Technical University of Denmark

Control Architecture Modeling for Future Power Systems

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Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

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Kongens Lyngby 2011
Elektro-PHD-2011-xx

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ELEKTRO-PHD: ISSN 0909-3192

Abstract

Uncontrollable power generation, distributed energy resources, controllable demand, etc. are fundamental aspects of energy systems largely based on renewable energy supply. These technologies have in common that they contradict the conventional categories of electric power system operation. As their introduction has proceeded incrementally in the past, operation strategies of the power system could be adapted. For example much more wind power could be integrated than originally anticipated, largely due to the flexibility reserves already present in the power system, and the possibility of inter-regional electricity exchange. Howerver, at the same time, it seen that the overall system design cannot keep up by simply adaptating in response to changes, but that also new strategies have to be designed in anticipation. Changes to the electricity markets have been suggested to adapt to the limited predictability of wind power, and several new control strategies have been proposed, in particular to enable the control of distributed energy resources, including for example, distributed generation or electric vehicles. Market designs adressing the procurement of balancing resources are highly dependent on the operation strategies specifying the resource requirements. How should one decide which control strategy and market configuration is best for a future power system? Most research up to this point has addressed single isolated aspects of this design problem. Those of the ideas that fit with current markets and operation concepts are lucky; they can be evaluated on the present design. But how could they be evaluated on a potential future power system? Approaches are required that support the design and evaluation of power system operation and control in context of future energy scenarios.

This work adresses this challenge, not by providing a universal solution, but by providing some basic modeling methodology that enables better problem for-

mulation and by suggesting an approach to adressing the general chicken/egg problem of planning and re-design of system operation and control. The dissertation first focuses on the development of models, diagrams, that support the conceptual design of control and operation strategies, where a central theme is the focus on modeling system goals and functions rather than system structure. The perspective is then shifted toward long-term energy scenarios and adaptation of power system operation, considering the integration of energy scenario models with the re-design of operation strategies.

The main contributions in the first part are, firstly, by adaptation of an existing functional modeling approach called Multilevel Flow Modeling (MFM) to the power systems domain, identifying the means-ends composition of control levels and development of principles for the consistent modelling of control structures, a formalization of control as a service; secondly, the formal mapping of fluctuating and controllable resources to a multi-scale and multi-stage representation of control and operation structures; and finally the application to some concrete study cases, including a present system balancing, and proposed control structures such as Microgrids and Cells. In the second part, the main contributions are the outline of a formation strategy, integrating the design and model-based evaluation of future power system operation concepts with iterative energy scenario development. Finally, a new modeling framework for development and evaluation of power system operation in context of energy-storage based power system balancing is introduced.

Preface

This thesis was prepared at the Department of Electrical Engineering, in the Centre for Electric Technology, at the Technical University of Denmark in partial fulfillment of the requirements for acquiring the Ph.D. degree in engineering.

The work on this thesis was part of the CEESA (Coherent Environmental and Energy Systems Analysis) project, partly funded by the Danish Council for Strategic Research, and related work was also supported by the iPower project, funded by the Danish Council for Technology and and Innovation.

The thesis deals with the control structure modeling of power systems for the purpose of planning and re-design to meet the challenges of a 100% renewable energy system. The dissertation is divided into two parts. Part I is focussed on conceptual modeling of control structure and resource allocation in power system operation. Results in Part II then contributes to planning methodology for long-term energy planning and re-design of power system operation.

The thesis consists of a synthesis report and a separate collection of ten key publications written during the period 2008–2011, and elsewhere published.

Arguments and methods in this work have been synthesized from so many domains, that I would not dare to point out a single discipline this thesis belongs in. Some of the ideas that appear difficult to grasp from an engineering point of view, in my experience, were immediately appreciated by persons with a very different academic background, such as psychology for example. The text could be read from a perspective of power system or control engineering, confirming common knowledge while developing a new perspective on well-understood control and operation aspects in the first part, and then, pointing toward models in integrated planning methodology in the second. From a perspective of energy planning and scenario design, a better starting point would be Part II, then Part I could be read as methodology background. I hope that, due to the level of abstraction, the text will be accessible throughout without the need for detail knowledge on either subject.

Kgs. Lyngby, August 2011

Kai Heussen

Key Publications

The following publications form the basis for the synthesis generated in this report and their central results have been incorporated. Reference to results reported in these papers is made in the respective chapters.

[MFM-I] Kai Heussen, Ashad Saleem and Morten Lind. Control Architecture of Power Systems: Modeling of Purpose and Function. In *Proc. of the IEEE PES 2009 General Meeting, Calgary*, 2009.

[MFM-II] Kai Heussen and Morten Lind. Decomposing Objectives and Functions in Power System Operation and Control. In *Proc. of the IEEE PES/IAS Conference on Sustainable Alternative Energy, Valencia*, 2009.

[MFM-III] Kai Heussen and Morten Lind. Functional Modeling of Perspectives on the Example of Electric Energy Systems. In T. Yao, editor, *Zero-Carbon Energy Kyoto*. Springer, 2009.

[MFM-IIIa] Kai Heussen and Morten Lind. Integration of Power Systems with other Energy Systems using Multilevel Flow Modeling of Control. Technical report, Technical University of Denmark, Centre for Electric Technology, 2009. *extended version of [MFM-III], unpublished*

[MFM-IV] Kai Heussen and Morten Lind. Representing Causality and Reasoning about Controllability of Multi-level Flow-Systems. In *Proc. of the 2010 IEEE Conference on Systems, Man and Cybernetics, Istanbul, Turkey*, 2010.

[MFM-APP-CP] Kai Heussen, Arshad Saleem, and Morten Lind. System-awareness for Agent-based Power System Control. In *Proc. of the IREP Symposium- Bulk Power System Dynamics and Control, VIII (IREP) 2010. Rio de Janeiro, Brazil.*, pages 1 –15, aug. 2010.

[MFM-APP-CIM] Kai Heussen and Daniel Kullmann. On the Potential of Functional Modeling Extensions to the CIM for Means-ends Representation and Reasoning. In *Workshop Energieinformatik 2010, Oldenburg*, 2010.

[PN-I] Kai Heussen, Stephan Koch, Andreas Ulbig, and Göran Andersson. Energy Storage in Power System Operation: The Power Nodes Modeling Framework. In *IEEE PES Conference on Innovative Smart Grid Technologies Europe, Gothenburg*, 2010.

[PN-II] Kai Heussen, Stephan Koch, Andreas Ulbig, and Göran Andersson. Unified System-level Modeling of Intermittent Renewable Energy and Energy Storage for Future Power System Operation. *IEEE Systems Journal*, 2011. Special issue on System Integration of Intermittent Renewable Energy. *forthcoming.*

Contents

Chapter 1

Introduction

The present organization and structure of power systems has been shaped by a technical innovation, economic opportunism and political drive over more than one century [105, 238, 239]. Power systems have been recognized as an important infrastructure, and electric energy is a critical foundation for modern societies. As a technical infrastructure, electric power systems are amongst the largest technical artifacts on our planet.

Power systems differ from other important infrastructures in that they can be considered one huge, complex and sensitive machine: cause and effect extend over the whole infrastructure within a time scale of milliseconds. Whereas severe disturbances can cause interruption of electricity supply affecting millions, this characteristic physical property is also fundamental to the design of alternating current power systems.

Distributed and Hierarchical Control. The power system is a network structure. Its physical structures enables enables the transfer of electricity from energy providers to energy consumers from and to any node in the power grid. As for any machine with such dynamics, the operating state of the power system must be controlled and supervised in order to maintain this functional behaviour. The control of power systems has both distributed and centralized characteristics. As a distributed system, it coordinates this energy transfer amongst controllable and freely varying resources, decentrally balancing surplus and deficit, managing grid constraints, the grid voltage is also locally controlled. Despite this decentralized character of fundamental control structures, alleviating network issues, etc. Technically as well as organizationally, a large number of control structures and responsible entities have emerged, controlling different regional and functional aspects of the power system.

Market-based Resource Allocation. On the basis of this functioning power system, market structures have been designed and introduced in power systems around the globe during the last decades, intended to facilitate the provision of electricity from the most economic source and to stimulate investments. The design of electricity markets requires a regulatory framework, including a conceptual definition of actors types with specified roles and responsibilities: there are 'natural' monopolies responsible for grid operation and market facilitation, and certain independent actors, trading energy on markets and providing predefined (control-) services for grid operation.
To name a few entities influencing power control in a liberalized environment today: Transmission and distribution operators, 'Utilities', plant operators, market operators, balancing groups, regulation authorities, standardization of components and controls ...

1.1 Challenges for Future Power System Control and Operation

The last decade has provided plenty indication that power systems will be operated differently in the future. It is, however, hard to say in short how exactly they should be different, or which operation concepts will prevail. In fact, one of the major challenges is 'drawing the big picture' or 'overall structure' of power system operation. Instead, we resort to metaphors and pars pro toto attributions, emphasizing the increased importance of new aspects in system operation. To consider a few of these, just try to picture the "horizontal", "intelligent", "renewable" and "distributed" power system of the future.

Some of these changes are well motivated. Recent developments and plans for the future energy mix induce changing requirements on the electricity infrastructure. The question is, whether those changes will actually mean a paradigm shift.

Energy Plans. There is a natural need to re-balance CO_2 levels in the atmosphere. Being responsible for the major part of the present imbalance, many industrialized nations recognize their responsibility to reduce, minimizing or neutralizing entirely their carbon emissions. The energy sector accounts for the larger part of anthropogenic carbon emissions, and together with other political risk-factors such as security of supply, this has motivated increased attention to long term energy planning.

Energy scenarios are being developed by different institutions, motivated by commercial, political or research interests, with different ambitions, with varying time horizons and at different regional scales: global (e.g. IEA REDT or the Bellona Scenario), continental (e.g. European 2020 , 2030 and 100% wind and solar [96]), national, local (regions, islands or communities). Sometimes the sector focus is exclusively on the electricity sector (e.g. [69]). Common to nearly all scenarios is an increased importance of the electricity infrastructure: whereas emissions can also be reduced in other energy sectors, renewable energy sources often are most effectively harvested by conversion to electricity. As hydro-electric resources have largely been exploited, mostly wind- and solar power are available for increasing the share of renewable energy.

A long-term energy strategy for Denmark was also developed in the CEESA project[1], which the present work was a part of. Overall goal of the project was the design of energy scenarios for Denmark with a 100% renewable energy supply in 2050. The final energy mix proposed for the 100% renewable energy system includes about 50-70% of wind energy in the overall energy mix – corresponding to 150-200% (!) of the conventional electricity demand.[2]

Being situated in Denmark, it was clear from the start that a major share of the energy mix would be supplied from wind power. Recent experience and studies have shown that around 20% of wind energy may be accommodated in a conventional power system [232]. The Danish government put forth a goal to supply 30% of its total energy need by renewables in 2025, which in turn was interpreted by the Danish transmission system operator (TSO) Energinet.dk as an objective of increasing wind power's contribution to electricity demand to 50% by 2025 [?]. More recently, the Danish government published a strategy for a fossil-free energy supply in 2050[3].

[1] CEESA: Coherent Energy and Environmental System Analysis. Project results: http://www.ceesa.plan.aau.dk/

[2] At time writing, the final numbers are not available yet. The results will be made available on the CEESA website, mentioned above.

[3] "Energistrategi 2050" (published in February 2011) – The plan can be found here: http://www.kemin.dk/DA-DK/KLIMAOGENERGIPOLITIK/DANSKKLIMAOGENERGIPOLITIK/ENERGISTRATEGI2050/

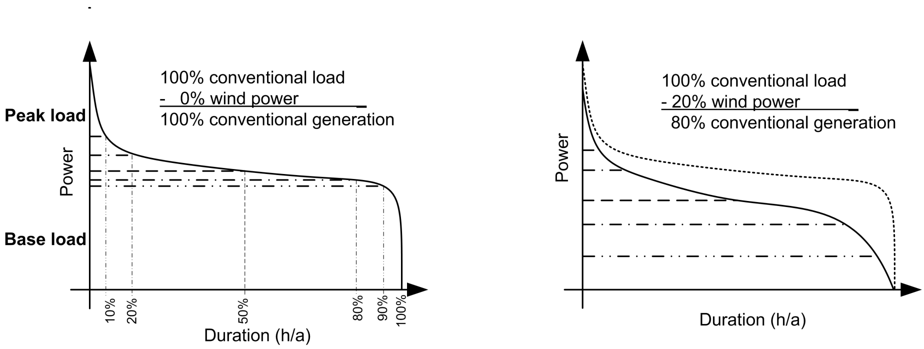

Figure 1.1: Sketch of duration curves for a conventional power system and for one with about 20% wind power. In conventional power systems, the distribution of electricity demand over a year defines a *demand profile* to be satisfied by dispatchable power generation [226]. As wind power is also undispatchable, the duration curve on the right is defined as *residual demand*: load-minus-wind ($P_{disp} = P_{load} - P_{wind}$). Evidently the there is less demand for generation units designed to operate year-around as "base load units" such as nuclear power plants, and more demand for flexible/mid-range units.

Fluctuating Generation. The challenge posed by wind power is that it turns power system operation on its head: in conventional operation thinking, load is assumed to be fluctuating[4] and generation to be controllable. The conceptual challenge of fluctuating generation in energy planning is motivated by means of a *load duration curve* in Figures 1.1 and 1.2 . Illustrating the impact of wind power, we can generate the *load minus wind* duration curve. Wind power, being uncontrollable and weakly correlated with load, reduces the total area by the energy it provides, but at the same time, it stretches the low end of the curve much more, ultimately to a negative value, whereas it reduces its peak load just a little[5].

The challenge illustrated here is obviously a planning challenge, to provide adequate resources for the significant amounts of energy that will either have to be shifted in time or balanced from outside the region of origin, and to provide balancing resources with reserve power plants that do not need to operate all year to recover investment cost. Not visible in the duration curve perspective, are other challenges more important for power system operation: in the time

[4]The terms "intermittent" and "fluctuating" are used thoughout this thesis to characterize the behaviour of non-controllable RES. "Intermittency", in particular, characterizes the property of time wise complete interruption of supply. Solar PV and single wind farms have this property. Wind in large clusters should be rather characterized as "fluctuating".

[5]This effect is ideally demonstrated on wind power, but it is also true - to a different extent and quality - for other forms of renewably generated electricity, such as solar photovoltaic or wave power.

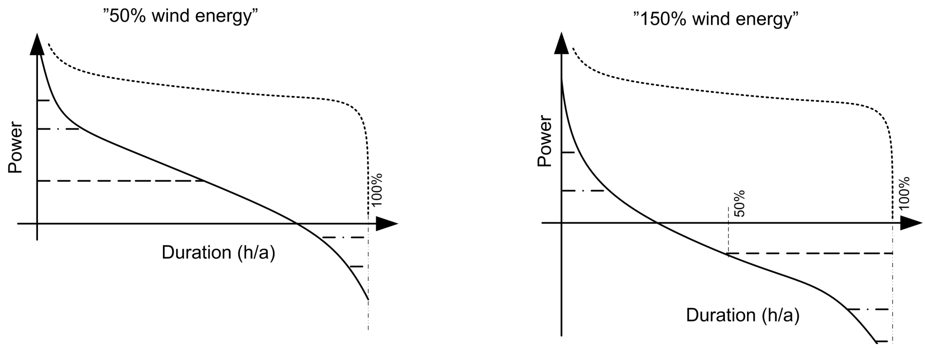

Figure 1.2: Sketch of duration curves for the residual demand where the annual electicity generation from wind turbines corresponds to 50% and 150% of the conventional electricity demand. The sketches thus correspond to the 2025 Energinet.dk and 2050 CEESA scenarios, respectively. Note that the duration curve, however illustrative it motivates the need for controllable demand or storage, only conveys a fraction of the operation challenges.

sequence, load has familiar behaviour patterns and predictable fluctuations; in contrast, the weather-dependency of wind and solar power imposes immense power fluctuations and due to the limited forecastability – critical grid loading can only be anticipated with a short time horizon and limited certainty.

Operationally, it may seem simple enough, to harvest wind energy and store it in a reversible form of energy, such that it may be dispatched as any other energy source in the conventional paradigm. However, for reasons of resource efficiency, such enormous scale of energy storage seems unthinkable, especially for regions with limited access to hydro storage capacity. Much to the contrary, it is desirable to adapt the operation paradigm in order to allow for the most economical or efficient resource allocation instead. The challenges Energinet.dk is anticipating and their mapping to current "smart grid" related projects has been investigated in a recent report.[6]

Distributed Energy Resources. One approach to accessing flexible power resources is based on dual-use: integration of the electricity sector with the heat- and transport sectors. Large-scale combined heat and power (CHP) is feasible and practiced in larger cities. Such a power plant can be combined with electric heat-pumps, consuming electricity when a surplus is available, to generate heat that can be stored until it is demanded. Just as important a resource will also be dispatchable distributed energy resources (DER), generation and consumption,

[6] http://www.energinet.dk/DA/FORSKNING/Nyheder/Sider/DendanskeSmartGridindsatskortlagt.aspx

e.g. with electric cars and small combined heat and power units (local- and μCHP). In addition to the challenges of fluctuating generation, the requirement for a more flexible power system lead to a higher complexity: Complexity is increased due to more and more small controllable energy resources. These units are smaller, more energy-constrained, have varying dynamic properties, and may be owned or operators by a larger variety of actors.

Proposed Future Control Structures. Both, increased demand for flexibility and the availability of DER require new, or at least an adaptation of, control and operation concepts. In future operation scenarios dominated by fluctuating renewable energies, the operating situation, such as power flows in the grid as well as balancing requirements will be continuously in flux. How can such a system be operated in a secure and efficient manner? Future control structures for power systems enable coordination and control of a more complex power system which is able to handle both more fluctuations and varying operating conditions as well as more distributed energy resources. Keywords such as Virtual Power Plants, Microgrids, Cells or Autonomous Power Systems have been coined to promote alternative control structures that are aimed in particular at facilitating the integration of DER. These structures are characterized by increased reliance on automation, information and communication technologies. A central feature for the control of these systems are aggregation concepts, which simplify the coordination of the diverse energy resources with the control functions required for power system operation [33].

Revision of the Market Paradigm Energy markets have been introduced on the basis of existing operation practice. As power system operation was a long-standing practice, the operational frame of reference for the introduction of electricity markets was firm and well established. As a result, the design of markets for power systems could be performed by experts in economy in collaboration with experienced practitioners.

The situation is different for power system operation in anticipation of the outlined operation challenges. At present, ongoing research on the adaptation of market rules to facilitate the market integration of renewable energy, flexible consumption and the enablement of more small-scale resources in the ancillary service markets is performed in parallel to technical research in anticipation of the operation challenges. In particular with regard to ancillary services, this situation presents a complex – chicken and egg-type – problem: the definition of a (new) service requirement influences the resources the market-size for this service. At the same time, the utilization of, and demand for, this service in operation practice is also influenced by the market prices.

The Concurrent Design Challenge. Both the challenges and this objective are widely acknowledged. The paradigm, design for change, is motivating research and development in many areas. However, power systems are too large, too complex to be redesigned as a whole and simply "deploy" them after redesign. However, to avoid the chicken/egg problem introduced above, we should also understand the design problem for future power system operation as an integrated control and market design problem.

Non-commercial research efforts therefore tend to be grouped into two research perspectives: *institutional adaptation* and *technological revolution*[7]. Each approach provides a different foundation for research activites, and each advances the state of knowledge in a different way.

The former approach is 'realistic', as it acknowledges the present institutional framework of power systems. Based on an institutional framework, opportunities and costs for technological advancements can be quantified and evaluated. It is top-down in the sense that it focuses on adaptation of institutional frameworks (to facilitate integration of technological advancements or to foster desired developments). An example of this approach is the activation of distributed energy resources by means of a (commercial) virtual power plant (e.g. [199]).A significant design challenge is encountered at the distribution level: the present institutional framework only offers the so-called "fit and forget" approach, and both technology and institutional adaptation are required. Such an adaptation can only proceed incrementally.

The latter perspective focuses on technological advancement, independent of present institutional constraints. Advancements are created bottom-up, on the basis of technological opportunities which have 'obvious' benefits in an engineering perspective. In a sense this approach may be considered 'utopian': concepts and technologies that are developed independent of present institutional frameworks cannot be evaluated in terms of the 'real-world' – benefits can only be evaluated in an 'island perspective'. Such advancement cannot immediately be applied, nor do they support 'real-world' decision making. However, if a transformation of energy systems is required in the long run, such technological advancement and engineering is essential.

As long term energy planning does not depend on given institutional frameworks, it can incorporate this utopian perspective. A central big-picture challenge thus remains: how can these gap between this "utopian" engineering, energy senarios and institutional advancement be closed? How could these independent forms of advancements be integrated in a common framework?

[7] Commercial research and development aims at providing technological solutions that can be employed (sold) in present institutional frameworks.

The challenges for the operation of future power systems may be summarized as:

- *More fluctuation and stochastic influence create more dynamic operating situations.*
  - renewables fluctuate, inducing continuously varying operating points as well as an increased need for balancing reserves.
  - balancing resources vary and become subject to relevant energy contraints (e.g. How many cars are parked? Battery full?)
- *System coordination is getting a lot more complex.*
  - More active participants need to be coordinated – ownership vs. responsiblity; who may control what?
  - Varying control capabilities of distributed energy resources (e.g. active or reactive power control.)
  - In adaptation, new "roles" in addition to the conventional categories are needed. What are those roles and how can they be defined?
  - Further market development and market redesign (e.g. ancillary services, real-time markets).

As clearly visible from this list, the challenges are not merely technological in the sense of efficiency and performance, but much deeper. If the re-consideration of power system operation should be supported by models, then such models need to reflect the coordination and control structures in a form and at a level where these challenges can be meaningfully related.

1.2 Approach

This work approaches the design challenge for future power systems from a perspective of conceptual design and representation. The challenges outlined above include issues that would typically be adressed in separate modelling domains (e.g. economic, communication, electric power, control...).[8] It is the goal of this work to develop a modeling approach that enables to break some

[8]This separation is a necessity motivated by the mathematical and analytical formalisms each domain provides. The mathematical perspective makes it difficult to step out of one's box.

of the isolation, by providing modeling concepts that enable more inter-related ways of thinking.

Planning, Design and Tinkering As part of CEESA project, this work aimed at identifying mutual requirements of scenario design (feasibility conditions and qualitative relations between power system resources) and control architecture (design requirements; how could the scenario's resource mix be accommodated by altering the control architecture?).

A fundamental approach to redesign from scratch consists of definition of overall design objectives, identification of specific requirements, and then 'ideally' a top-down design of the new system, based on known and anticipated solutions. New systems are not necessarily developed in this architectural fashion. Bottum-up processes ("tinkering"), which involves working with parts of a system and solving partial problems one at a time. Naturally, as this process is closer to implementation, it is also closer to practical solutions.

Solutions development could either be based on these current operation structures or on a greenfield approach, solving challenges that occur only in some future scenario. Often the relation between overall system requirements and these possible alternative solutions is not straightforward. The former tend to relate well to current system requirements but may be challenged by future requirements, and the latter, aimed at satisfying future requirements may not relate well to current operation paradigms. Current operation structures have grown out of historic institutional and technical arrangements. Future power system operation is confined to these paradigms only to the extend that a smooth transition ought to be feasible.

This 'big picture' may not always be present in the development phase. However, once developed, alternative solutions need to be evaluated in a common frame of reference. The value of an innovation can be judged only within such a frame of reference. In a practical world, both, tinkering with solutions and top-down design and evaluation are necessary. This co-development of top-down conceptual integration and bottom-up problem-solving constitutes the *formation* of power system control architecture.

Models Needed. This work aims at supporting this control formation by providing *a)* a qualitative representation for the formulation of control structures for power systems, and thereby *b)* a conceptual framework for the evaluation of operation strategies.

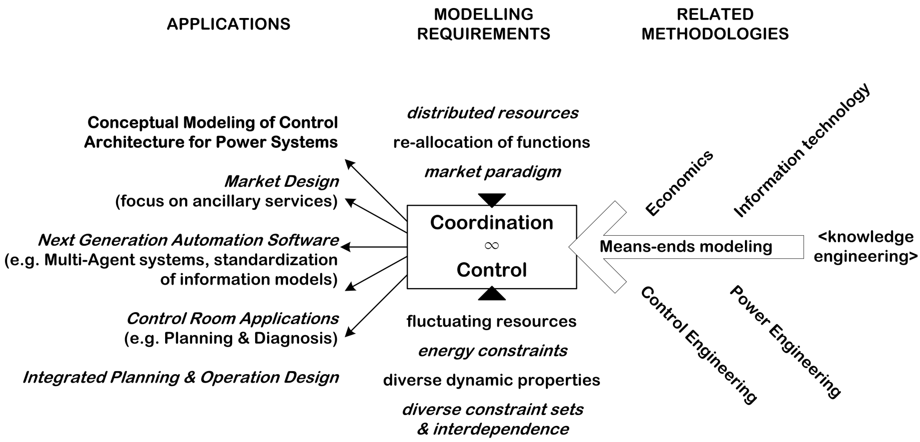

Figure 1.3: Illustration of modeling context.

Figure 1.3 illustrates a contextual perspective for control architecture modeling. Coordination and control of power systems is the object of representation. The modeling requirements are considered both from a perspective of future power system requirements: can those new requirements be meaningfully represented or evaluated as changes in the modelling approach? Model applications do not directly influence requirements of the modelling approach, but serve as a reference for evaluating the advancement of the method.

What properties should such a qualitative representation provide? It should...
- clearly formulate the "overall structure" of the power system control.
- provide different levels of decomposition such that more or less detailed views of the system can be studied
- enable the formulation of alternative control structures
- support the specification of control-relevant *requirements*, independent of their implementation
- provide a formal structure enabling the evaluation of solutions against those requirements
- include formal relations enabling the analyst to check consistency of objectives, control- and process structure.

As control functions can be formulated relatively independent from physical components, one further important property of this conceptual framework for valuation of (control) functions is a flexible assignment of structure to function. A qualitative and formally precise representation of control structures can facilitate the description and analysis of control structures in a number of ways. The representation for control architecture should enable systems designers to clearly define roles and responsibilities of participants in power system control. As abstract framework rather than implementation model, it leaves freedom to design and implementation of possible future innovations.

1.3 Objectives and Structure of Thesis

As the title suggests, this work adresses the modeling of control architecture for future power systems. Here, *modeling of control architecture* is not a given of well-defined subject area, and it is one of this work's objectives to arrive to an understanding of what architectural modeling for control could be. The term *future*, is, on the one hand, part of the motivation for choosing this architectural, design-oriented perspective. On the other hand it has a concrete context in this project's background of energy planning. This background formed the idea that energy planning and power system control and operation have mutual roles in the advancement of electricity systems: one is creating design requirements and the other would be assessing what is feasible based on available operation strategies. As of now, the advancement of operation strategies is not typically considered part of this relation.
Power systems, as they are seen today, are a vital infrastructure that supports the trade of energy, but also a complex engineering system. The challenge of re-engineering this system to support the integration of vast amounts of renewable energy, while at the same time maintaining and further developing functioning market structures is a central motivation for this work.

The introduction so far conveyed a sense of the main challenges considered for future power system operation and thus can be seen as attempt to answer the first reseach question:
Q1. *What aspects of power system control need to be represented to support the evaluation of control structures?*
As motivated, our approach to the control of future power systems should be "architectural", which is illustrated in Figure 1.4 as a somewhat uncertain domain description "Control Architecture". The main perspectives that have been considered to contribute to the challenge in this introduction are Energy Planning, Power System Operation and Resource Allocation by Markets, which can be viewed as perpectives on the control architecture domain. Chapter 2 thus investigates "control architecture" to clarify the notion:
Q2. *How could the analogy to "architecture" guide our understanding of the role of representations in design, and what would thus be required of an 'architectural' representation for control structure design?*
And Chapter 3 then asks,
Q3. *What conceptual representations are available to this modelling purpose?*,

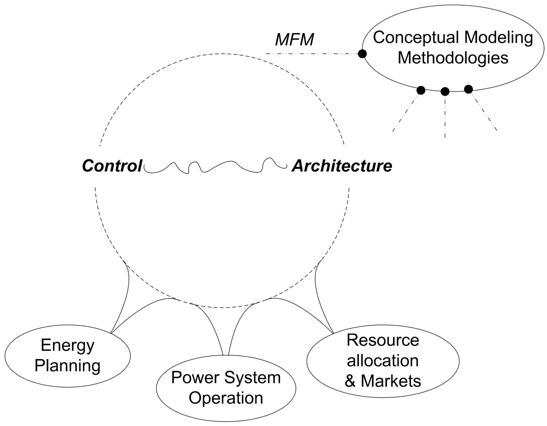

Figure 1.4: Conceptual overview of the research domain. Control architecture is the central subject, although it still requires some definition. The lower bubbles are contribute requirements to the problem formulation. The upper bubble, conceptual modeling, contributes methodology.

providing a discussion of conceptual modeling approaches and an introduction of the main methodology: Multi-level Flow Modeling (MFM).

Once a perspective on control architecture has been established, and the role of conceptual models is clear, we begin developing in-roads to the domain, by approaching it from different perspectives in the remaining Parts I and II. This mental picture is illustrated in Figure 1.5.

Part I focuses on conceptual modeling power system operation and control. The central Chapter 4 develops MFM modeling for power system control, adressing the question:
Q3. *How can a control architecture for power systems be modeled, also in view of a market-based allocation of energy and control resources?*
Once the conceptual modelling approach is made available, an application perspective is needed. Chapter 5 assumes the perspective of power system operation:
Q5. *How can the real challenges power system operation will be facing in the future be attacked from the perspective of this modeling approach?* and
Q6. *How can the conceptual perspective be used to support system operators in their supervisory responsibility?*
To finish Part I, Chapter 6 applies the methodology to case studies:
Q6. *Which concrete cases can methodology be applied to and what kinds of insights can be gained?*

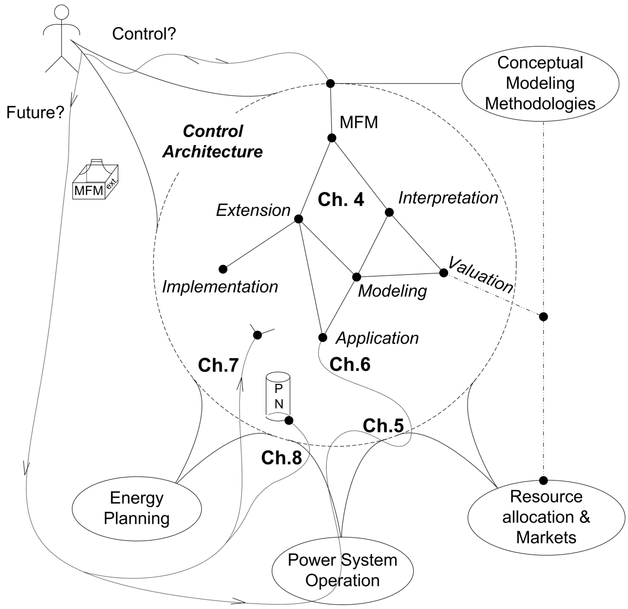

Figure 1.5: Different routes and inroads to the subject area. Chapter numbers are indicated in relation to the respective stations on the path.

Part II focuses on establishing the relation between operation and control design for power systems and long-term energy planning. In Chapter 7, we take a broad and methodological approach, discussing:

Q7. *How do changes in power system operation map to energy scenarios and vice versa?*

The relation between operation and scenarios is mediated by models. Chapter 8 answers the question:

Q8. *Can we identify a concrete model that reflects both central operation challenges and solutions, and is sufficiently generic to be adaptable to varying energy scenarios?*

Chapter 9 concludes on the results and highlights several avenues for future research.

Chapter 2

Control Architecture

A good design usually has a strong aesthetic appeal to those who are competent in the subject.
H.H. Rosenbrock in "Computer-Aided Control System Design" Academic Press, Inc., 1974[1]

Get the habit of analysis - analysis will in time enable synthesis to become your habit of mind.
Frank Lloyd Wright, Architect

Architecture is the "science and art" of conceiving a complex structure before its realization. The conscious process of architecting starts long before the first lines of a solution can be drafted, with the identification, analysis and interpretation of requirements. As all this happens before the first bricks are laid, architecture only deals with representations complementing a systematic design process. This can be said for building architecture, which originates the approach. In a generalized sense, architecture is also practiced today in a variety of disciplines.

Control engineering also deals with complex problems and utilizes a variety of representations. In fact representations, or models, are at the heart of control engineering – but mostly in form of mathematical models describing the signals

[1] Quote found in [223].

and behaviour of the control and the controlled system. Control design, however, also starts long before the first mathematical models are made, and it is not only on the level of signals and behaviour that control objectives and structures are decided. But what should be represented to enable a systematic approach to control architecture? How can domain-specific requirements be identified and control structures be drafted, for example to identify the level of detail needed for the respective mathematical models?

Whereas power systems and their control are already in place, the challenge of re-designing their control structure to meet future requirements can be viewed in a similar perspective, in analogy to renovation and modernization of a century-old house: any alterations must be well understood in their consequences for the system as a whole before they can be safely applied. Also in planning for future power systems, a sound conceptual understanding of power system control is a foundation for realistic planning. Yet, control architecture is not a well-understood concept readily defined in the literature.

We shall therefore first approach an understanding of the architectural design process and its associated representations. Then theory and practice of control engineering will be reflected on, and finally we review some related results on control structure design and concepts applied to the high-level description of control architecture.

2.1 Architecture and Representation

Architecture deals with the conceptualization of the whole and its parts, well before the first existential parts are created, then guides construction, continuously relating parts and details to a whole. By the architectural method, buildings are devised in anticipation to meet the needs of its users. Representations thus have a dual role in architecture: they support the design process as a conceptual model and they instruct construction as template. This section explores the forms and utility of representations in architecture. First, we shall review architecture in its original domain, to develop an intuition about the role of representations in the architectural process. Then we investigate a central issue in all design: the structure-functions relation and its role in representations. Finally, we review “architectural” perspectives in general engineering domains.

2.1.1 The Uses of Representations

Building architecture is the conception of spatial form, characterized by design constraints, such as:

a) domain-specific constraints, 'physics';
b) client-specified constraints, 'requirements', and
c) constraints associated with its embedding in an environment.

The following paragraphs analyze the role of representations in the identification and representation of these direct and indirect requirements; their role in synthesis by design; and their role in the realization of a design. Design is not a 'decomposition' of requirements, but always a synthetic act. Design thinking, however very much needs the decomposition of requirements for the conceptual development.

Requirement Analysis: Representation Domains. *Requirements analysis* comes before design. Analyzing requirements means to understand the nature of needs, and to interpret their meaning with respect to potential designs. Requirements or constraints are not properties of a design, but they are the aim which the design strives to overcome by synthesis.

The most typical representations in building architecture comprise geometric abstractions, conceptualizing the the design toward more concrete plans and drawings. The design domain of construction is characterized by spatial and material properties, thus the 'drawing' and other spatial representations are central to the development and communication of a design. Some design constraints are formulated in terms of those spatial and material properties. Most types of constraints, however, are characterized by an indirect relation to those spatial and material properties. They are no less important but they require consideration, analysis and interpretation. For example, requirements can be formulated in terms of a certain domain of interest, such as physical domains regarding energy or lighting, or other purpose-related (functional) concepts such as, e.g. 'common space', 'classroom', 'reception', etc. In these cases, alignment and conflict amongst requirements is not only based on spatial or material relations. Requirements analysis thus needs to consider relations that are primarily oriented on the character of the respective requirements – not on the design.

A formal and conceptual understanding can inform and guide requirements analysis and design. In case of complex requirements, analysis can be supported by formal representations in the requirements domain, mapping for example physical relations of heat or sound, or functional relations of building infrastructure or organizational function.

Finally, also the relation between requirement and design needs to be considered in order to reflect and validate the design on requirements. If the relation is immediate, as a spatial or material constraint, it is easily evaluated on the drawing board: by simply 'mapping' the constraint information to a design. A first degree of 'indirectness' is where a formalization and development of logical relations between design constraints and the central design representation is possible. Building on these relations, the design can be facilitated by providing information about "mismatch" and "fitness" of a given design by such formalized requirements, or by specifying a direct mapping of these requirements into the design[2].

Design: Patterns, Analysis and Reflection. Evaluation of relations between design and requirements first requires the existence of a form, an initial design.
An architectural design includes for example:
– functional elements (e.g. floor, doors, windows, roof, walls, etc.),
– distribution, relation and interconnection of functional elements,
– relation to substance (e.g. building materials),
– multiple views and illustrations of the design object, including functional and symbolic relations between building, environment and users.
The "functional elements" listed above correspond to characteristic geometric patterns in the spatial representation; not all functions of a building directly have a geometric equivalent, but certain relations can often be identified as a design pattern without detailing its geometric realization [17]. The identification of these needs, however, is associated with other domains. We should therefore distinguish between the "architectural domain", the space, the materials and its functional decomposition into design patterns, and an "application domain" or "requirements domain", where all sorts of requirements can be formulated that may or may not contradict each other. Design is to create a synthesis out of overlapping of requirements [15, 17].

Common representations facilitate architecture in several stages. Design may require both a bottom-up, experimental, and a top-down, drafting, approach. The explorative ways of design are supported by representations that allow the conceptualization of abstract ideas as well as details in context of the same architectural framework.

[2]Building information models facilitate architectural design by integrating functional or physical-contextual information into the 'native' architectural domain representation. Parametric architecture is a form of mapping "requirements" algorithmically to the design domain.

Planning: Representations for Evaluation of Requirements. Whereas architecture is typically associated with a design process and the final result, it is also embedded in a planning frame. Alternative designs need to be evaluated on hard and soft criteria, including cost, timing and fitness to design constraints. The evaluation is also based on representations in the design-domain: construction plans, 3D models, physical models, etc.

From Architectural Representation to Implementation. Architectural representations are blueprints for implementation. In granulation and detail, an architectural representation should be sufficiently specific to leave no space for misinterpretation. The construction plan should be 'implementable'.

In summa, architecture is inherently a top-down design process that, after some requirements analysis, begins with a rough sketch of the central ideas, uses iterative, and in the final stages of development creates highly specific details and plans. For most of this process, a coherent spatial representation is employed, in different perspectives and with different levels of detail.

2.1.2 The Function-Structure Distinction

Buildings satisfy complex functional requirements: they integrate structural support, shelter, space for social gathering, regulation of a local climate, access to energy and communication systems, and many other functions. Note that the mapping between function and space is manifold: the realization of a function need not reserve space, it may share space with other functions, and it may enrich a space. In building architecture functions naturally overlap in space/form. Physical form is not bound to functions. Yet, there is a human tendency to attribute function directly to the physical form, to a specific implementation. Today it is understood that a mistake of functional thinking in urban planning was the direct translation of conceptual, functional, categories to spatial differentiation. The result were cities without overlap, as C. Alexander put it [16].

In power system, as typical for engineering systems, function and structure (form) seem fully aligned. This is, however, a misinterpretation, an illusion, which is particularly evident when control functions are considered as their form expresses little about their respective function.

Need for Conceptual Trees. In the world of experience, anything can be interpreted as one thing, or as another. Conceptual "trees" are required as a tool

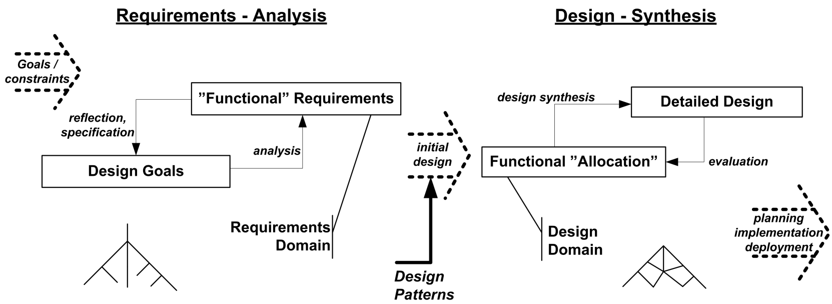

Figure 2.1: Requirements analysis and design. Arrows indicate a process and boxes indicate states of knowledge.

of conceptual analysis, such as the analysis of design requirements, because "the tree is the easiest vehicle for the mind" [15, 16]. A concept is only clearly defined if it can be said to mean one thing and one thing only. Conceptual analysis is a characterized by hierarchical decomposition, without internal overlap. It creates the clarity to form intentions. The analysis of functional requirements provides a conceptual decomposition of what is needed in terms of what is required to satisfy the need. In that way it must be domain-specific, and, conceptually, it must result in "trees" from a clear analysis and prioritization of objectives.

Functional analysis is a powerful method. In power system control, we must acknowledge here, that structural decompositions can therefore hardly be meaningful as conceptual models of control functions.

Design as Mapping between Domains. The two notions, the tree of functions, and the "semi-lattice" [16] of overlapping functions in a final design can be decomposed into two facets of the design process: *requirements analysis* and *design*.
The functional analysis informs design, e.g. about wanted and unwanted overlap, but it does not justify form [16], function motivates form [15, 17]. In architecture, "form" implies a reference to the design domain.

The architecting-process of two domains is illustrated in Figure 2.1. Here, the word 'functional' has different interpretations in the requirements and design domains. The 'Functional Requirements' are characterized by the 'tree-shaped' results of requirements analysis. In the design domain on the right, the word 'allocation' indicates a mapping (including overlap) of requirements onto the (e.g. geometric) concepts in the design domain, forming the semi-lattice structure that characterizes the allocation of functions to the 'form' (or whatever represents the design).

Of course, functional requirements can originate from several technical or social contexts, so that the conceptual, analytical, classification of requirements can be applied to several domains. The design-domain is, however, unique to each design process.

Design Patterns. A strategy for reducing the creative burden on this intuitive transition from requirements to the design domain is the strategy of resorting to *design patterns*, which are characteristic aspects of a function, formulated as patterns in the design domain. In building architecture, such patterns could be elementary geometric shapes or more abstract and 'soft' (sketched) patterns of characteristic spatial relationships [17]. Such patterns are drafted from experience and their sketching character is important to conceive overlap. Also in engineering, complex templates drawn from previous designs can be employed. Such previous designs can be formalized and qualified by certain properties and stored in design libraries (e.g. [227] in the mechanical engineering domain), to be searched by means of algorithmic approaches, automating the design process. Even though such formal shortcuts from requirements to design exist, it should be recognized that they could indeed be taken as *shortcuts*, suggesting parts of 'old' solutions as complete building blocks, which would be all but good design. The abstract, sketching, representation that characterizes a family of solutions seems more difficult to conceive in the engineering domain.

Once an initial design is drafted, an iterative process of adaptation could fit the design to satisfy the (functional) requirements – this process is referred to as the "Design" phase in Figure 2.1.

2.1.3 Systems Architecture

The term 'architecture' has long found its way into engineering domains. It is particularly used to refer to a high-level conceptual models of engineering solutions in context of systems engineering. A review of uses of the terms 'system engineering' and 'systems architecture' shows that there are different schools with related but different applications, approaches and issue areas. Let us refer to one of them as 'systems engineering' and to the other as 'software engineering'. Systems engineering is focussed on high-level guidance and evaluation of 'conventional' engineering processes with respect to organizational performance; its 'design domains' are thus the engineering domains relevant for the respective system. In contrast, software engineering is tied into organizational performance from another perspective: software systems support and facilitate organization, thus typically require formalization of organizational processes in their requirements domain – however, their design domain is software. As both approaches

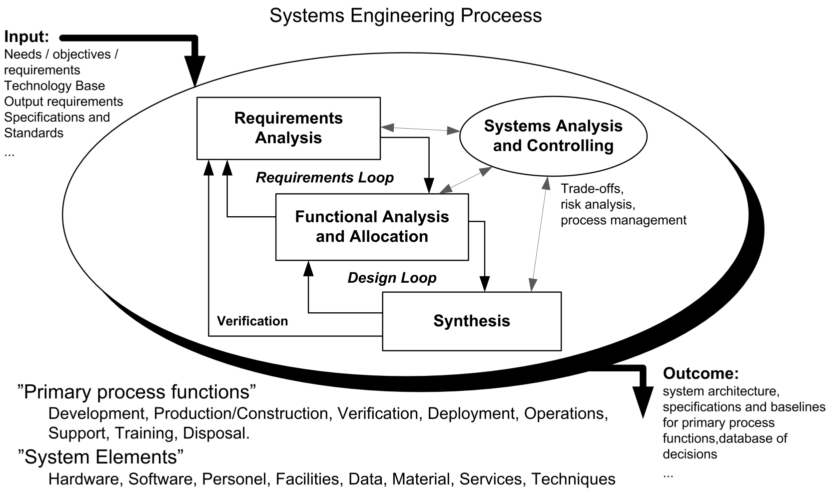

Figure 2.2: The systems engineering process, adpated from [197]. The term "Primary Functions" comprises all actual engineering functions: Development, Production/Construction, Verification, Deployment, Operations, Support, Training, Disposal; as "System Elements" are considered: Hardware, Software, Personel, Facilities, Data, Material, Services, Techniques (*ibid.*).

utilize formalization of processes, there is overlap in the modeling apporaches utilized. The third domain is closely related to the software engineering domain, but it is distinct in that its stated purpose is "Organization Architecture". However, its focus is on requirements engineering and thus its design domain is not necessarily organization structure itself, but rather information models and processes that can be formalized in software systems.

Systems Engineering and System Architecture. Systems engineering is a method of addressing organizational challenges in complex engineering processes (examples of such engineering processes include: spacecraft design, aerospace engineering, militatry command & control). Such challenges are associated with barriers of complexity, such as information management, functional complexity and process guidance from requirements to implementation. A pool of high-level methods support systems engineering, and several standards have been developed in support of specific systems engineering challenges[3] [197]. Whereas systems engineering is here understood as the umbrella concept, "systems architecture" is considered a sub-domain associated specifically with conceptual modeling of the engineering domain. Whereas the overall method

[3] An overview of standards and tools is provided on the homepage of the International Council of Systems Engineering (INCOSE): http://www.incose.org/.

thus remains to be considered ‘engineering’, the term ‘architecture’ is mostly referred to a representation of knowledge, not a process.

The systems engineering process presented in [197], defines three forms of ‘architectural representations’:

- **Functional Architecture**: a structured presentation of “functional and performance” requirements allocated to system functions.
- **Physical Architecture**: illustation of system breakdown *into subsystems and components.*
- **System Architecture**: the *products* necessary to support the system[4]

Models used in context of the ‘functional architecture’ also tend to be relatively distant from the domain, mostly aimed at organizing information, into ‘functional specification’ and ‘performance specification’, e.g. by high-level function models such as IDEF0, or process-sequence representations. Sequential processes are supported by powerful diagrammatic representations (e.g. also the flow-chart). For non-sequential processes, there is generally a lack of good conceptual modeling approaches that are sufficiently concise to support both organization and *analysis*. Process-relevant information is thus typically presented in form of domain specific, usually structure-oriented, schematics, such as: piping and instrumentation diagrams, one-line diagrams, or other domain-specific diagrams. Further detail (or generalization) would then be conveyed by mathematical models of varied forms.

Within the systems engineering domain, the term referring to what would be the equivalent of a building is a “system” or a “complex system”. A more recently developing discipline in systems engineering considers “systems of systems”, which could thus be considered the equivalent to discipline of urban planning. Systems of systems engineering thus shifts focus the further away from the implementation domain toward requirements evaluation and methods of systems alignment. Here in particular, it becomes essential to consider representation of the new “whole” that is formed by that system-of-systems.

Failure of, for example a communication link, within these technical structures could imply a failure of a control systems, with potentially harmful consequences for humans and the technical systems. Engineering for safety, including a conceptual understanding for the propagation of faults is thus a necessity for such systems.

[4] “...and, by implication, the processes necessary for development, production/construction, deployment, operations, support, disposal, training, and verification.” [197]

In contrast, failure of software systems within the organizational structures considered below, imply a fallback to social systems composed human interactions. This may imply a loss in efficiency of operations but does not imply the same harmful consequences. As a result, most software security is rather concerned with the domain-internal issue of blocking access to information and controls, not with modeling the consequences of such failure.

ICT Systems and Software Architecture. Mostly in the software engineering domain, "systems architecture" has developed into a well established approach that is associated with a collection of methods and representations. It is in the nature of information and communication systems to deal with – often complex – information and data whose structure and content is closely aligned with the domain the software is to serve. Software systems are indeed very complex systems with respect to the number of users, the different application domains they span and the informational complexity they integrate.

ICT systems architecture, is therefore concerned with both, representations of its internal structure and interfaces (the ICT domain), and a conceptual understanding and representation of the domain it serves, the "application" domain. Tools and methods developed around the purpose of systems architecture are thus aimed at acquisition of (application) domain knowledge (some conceptual representations employed in different domains are introduced in Section 3.1.1) and its mapping into IT concepts, which form representations of the solution/design-domain (software architecture). The situation is comparable to a challenge in architecture of buildings: the mapping of (functional[5]) requirements into the spatial and material domain of the design is not straightforward. Such non-software requirements are referred to as "Non-Functional-Requirements" or quality requirements [173, 47]. This design-mapping issue has been identified with respect to object-oriented software design (e.g. Object-oriented Analysis (OOA) [174] or IDEF4[6]), where the adaption of software functions to the respective application domain can be intuitive and straightforward. Here the danger of confusing application requirements and design domains occurs – a drawback which "goal-oriented" requirements analysis strives to overcome [52, 174, 240]. The issue is partly beeing circumvented by developing more flexible and generic software concepts that are more closely adaptable to application domain requirements, such as agent-based software (focusing on

[5]The word "functional" here plays a pivotal role in creating misunderstandings across domains. "Functional requirements" as understood in the IT domain refer to requirements decomposition of the *software architecture* [47], not of the application domain. In contrast, the word 'functional' is here employed to refer to the analysis and decomposition of varied *application domains*, not the software implementation domain. The appropriate term for this in the software context term would be "goal-oriented" requirements [240].

[6]http://www.idef.com/IDEF4.htm

organization, roles and behaviour [263, 70]) and service-oriented architectures [237].

Organization Architecture. Organizations may be viewed as living organisms [206]. But their operations also require massive amounts of data and very large software systems. The organization of software architectures is thus often closely interwoven with structure and processes of actual social organizations, such as bureaucracies or corporations.

Development of such software systems requires a formalization of types of information as well as processes. And while these methods of formalization of processes are required from a software engineering perspective, they also stabilize, mechanize and coordinate organizational processes. Here, the formalization of software follows along with organizational formalization and vice-versa. The management of organizations becomes a practice of formalization and redesign, supported by conceptual models that formalize relationships, activities and evaluation criteria. Within these organizational methodologies, architectural formalization of organization does not explicitly distinguish computerized from social interactions, thereby becomes a tool of shaping the social interactions required for collaboration [20].

The “Zachman Framework” (Framework for Enterprise Architecture) describes a matrix of “perspectives” (six rows: from governance to operation) and “abstractions” (six columns: What, How, Where, Who, When, Why) to define a complete set of views within an organization that should be considered in ‘architecting’ an organization in analogy to the architecture of buildings [262]. Here the focus is on taxonomy and completeness, rather than to focus on an instructive sequence. This framework is a reference for instructional “architecture frameworks” which have been developed to guide the definition and deployment of enterprise information systems, focussing on the *process* of architecting including conceptual representations. The Open Group Architecture Framework[7] (TOGAF) is an example for these frameworks, an overview is provided by [220]. Such frameworks however are rather complex in themselves. The utility of combining several conceptual modeling perspectives in a more ad-hoc fashion has also been recognized and demonstrated in context of the development of business cases for e-businesses [6, 191].

We observe that commonalities between the discipline of an architect and the ideas leading to architecture frameworks are, again, rather associated with representations as well as requirements analysis. Central are methods for the identification of needs, provision of conceptual models including varied perspectives

[7] www.opengroup.org/togaf/

(views) in the analysis of domain requirements, and training targeted at the tools provided.

2.2 Control

Control is the power to influence or direct behaviour. From the word's origin, 'to check or verify accounts'[8], the deep connection between normative direction and observation of deviant behaviour is clear.
The control of technical processes has been a crucial aspect of engineering since the onset of industrialization. Since cybernetics and the formulation of mathematical control theory it became an engineering discipline in itself. It is in the nature of control engineering, however, that any application of control systems is tied to another engineering domain, defining the object of influence. Control is an enabling technology also for electric power systems, enabling the adjustment of power generation in response to changes in demand and the maintenance of voltage levels in spite of changes in loading of the grid.

This section aims to review traditional perspectives on control engineering and mathematical control theory. There are some basic concepts common to most control systems and they form a common understanding of 'what control is about' amongst control engineers. A coarse overview of control concepts and representations will give a sense of the common tools and methods in control engineering. Approaching the architectural perspective, a first discussion of control structures and control in several domains should then motivate the need for different conceptual perspective of control systems.

2.2.1 Basic Control Concepts

Figure 2.3 presents the constituents of a control system. The control object is a some form of *process*, also referred to as 'plant' or 'system', whose behaviour should be influenced by the control toward an *objective*. Control and process interact by means of *instrumentation* that transforms signals into actions and observables into signals, usually by means of separate *actuators* and *sensors*. From a control perspective, actuators form an *input* to the system and sensors form an *output* from the system. Whereas the internal structure of the control is subject to the specific control design, *signal processing* functions, *control laws* and *internal models* are a valid decomposition of most control systems. The process interacts not only with the controller but is also embedded in and

[8]Source: Oxford Online Dictionary (http://oxforddictionaries.com/).

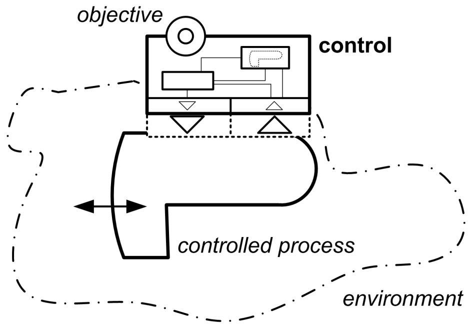

Figure 2.3: Some central components common to technical control systems. Process, instrumentation (actuators, sensors), and interactions with the environment are the (physical) objects of control; control itself is typically considered non-physical, separate from its environment. Control is best understood as a function rather than by its physical form.

interacts with an *environment*, which influences the process for example by imposing *disturbances* on it.

In principle, control influence toward an objective only requires to compute an input signal by means of a process model and to perturb appropriately the system by means of actuation. Apart from actuation, observation of the system is an important feature of control, mainly because of [223]:

- Unknown disturbances
- Model uncertainty
- Unstable process

Feedback thus can mitigate deviations from an objective caused by:
– other unknown influences that may cause the process behaviour to deviate;
– uncertainty of the process model and a resulting incorrectness of the input pre-computation.
Dynamic *stability* is a central concept of control engineering: an unstable process can only be stabilized by feedback, modifying the dynamic behaviour of the integrated system of control and process.

Control design methodologies focus on the (mathematical) description of dynamics of process and control. The main design criteria are stability, robustness and (dynamic) performance. Control objectives, sensors and actuators as well as performance requirements comprise an interface between process- and control design: they can only be chosen in coordination between process requirements and control capabilities. The weighting of these requirements leads toward the choice of an appropriate control methodology.

2.2.2 Control Methodologies

Control (design) methodologies can be differentiated by types of objectives (functions), classes of system models, stability concepts, forms of control structures and algorithms they support. The field is wide and we shall only give a compact overview.

Control Functions. Common functions of control described in the literature include but are not limited to: disturbance rejection (encapsulation); tracking control (offering a 'reference' input); maintaining an operating point (setting the system state to a normative value; toward an 'external' objective); input decoupling (offering independent inputs); stabilizing an unstable system; shaping the behavior of a system (e.g. to satisfy some functional requirement); enhancing the agility of a stable system. (e.g. by extending the range of dynamic states by nonlinear control); confining the behaviour of a system (to a stable region, to a linear domain); and various forms of optimizing control (objective is formulated as a cost function, e.g. Model predictive control).

System Classes. The main system classes can be divided into continuous, discrete and hybrid systems. *Continuous systems* are typically modeled as ordinary differential equations (ODE), $\dot{x} = f(x, u)$, with $y = h(x, u)$; here x denotes the vector of state variables, u the input and y the output. Also differential algebraic equations (DAE) are considered, such as in power systems, adding a constraint of the form $0 = g(x, u)$[9]. Control design methods are mostly focused on special forms of the model corresponding to conceptual simplifications, such as *linear state space models*, $\dot{x} = Ax + Bu$ with $y = Cx + Du$, or input-affine nonlinear models, $\dot{x} = f(x) + g(x)u$ with $y = h(x, u)$. Modeling of *time-discrete systems* is often oriented toward continuous systems (e.g. for digital control of continuous systems [46]).

Control modeling approaches have also been developed for system formulated as implicit differential equations, $0 = F(x, \dot{x}, \ldots, u, \dot{u}, \ldots)$, with special struc-

[9] Power systems are often described in this general DAE form, defining dynamical states for the synchronous generators and an implicit algebraic equation representing the electric coupling.

ture. Notable here are behavioural modeling [251] and more specialized port-controlled Hamiltonian systems [107].
Discrete event systems (DES) are systems with discrete states and labelled transitions between states. Such systems are typical for e.g. supervisory control or fabrication processes. A number of modeling approaches are available for such systems, including automata or petri nets. A well-developed control theory is formulated for in the Ramadge-Wonham theory [200, 252].
Hybrid systems combine discrete-event and continuous system modeling, which allows the study of the combined behaviour of e.g. switched continuous systems. Also hybrid control theory is particularly considered in context of supervisory control [118].

Stability Concepts. A review of stability concepts for non-linear control is provided in [117].

Planning and Optimizing Control. Optimizing control[10] is a type of control function that generates control signals toward minimizing an objective function within a planning horizon. It has evolved from a mere feed-forward planning control to a feedback-capable control methodology, called model-predictive control (MPC) [202]. The optimization capability has become very important for in several industrial processes, in particular when a process needs to be operated under varying conditions or when state constraints are to be considered. A number of applications of MPC in power systems have emerged.

'Intelligent' Control. The broad term 'intelligent control' summarizes a range of control methodologies which cannot be categorized under the above classification conventional control theory. Most of the work in this field can be classified as applications of methodologies from the field of artificial intelligence (AI) to control problems (e.g. neural networks, fuzzy logic, knowledge-based and expert systems), including a number of hybrid methodologies combining low-level continuous control and high-level supervisory and planning control. The focus is here rather on automation of the complete control hierarchy toward the creation of 'autonomous' control systems, robots in particular [183]. This focus required the departure from the behavioural paradigm toward approaches that integrate semantic concepts, enabling higher-level planning and reflective control levels. The domain also includes non-conventional approaches

[10] Note: Here we distinguish 'optimizing control', from 'optimal control', which in the literature are both referred to as 'optimal control'. In optimal control, an optimization problem is solved as part of the control design, but the control objective is a standard control problem, such as disturbance rejection or setpoint tracking.

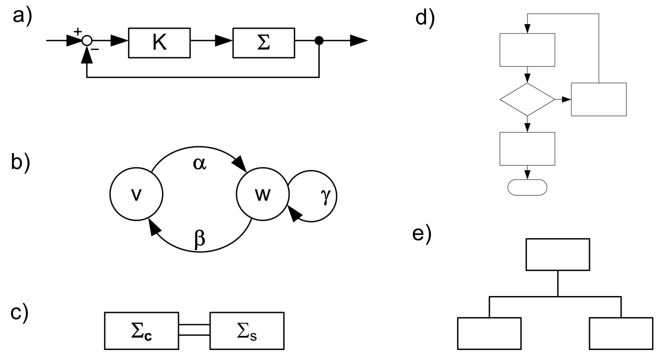

Figure 2.4: Some common representations associated with control systems: a) signal flow diagram, b) discrete-event system (automaton with two states), c) interconnection of systems by variable sharing, d) flow-chart and e) organigram. Representations a)-c) are associated with specialized behavioural models, d) relates to an algorithmic perspective and e) is derived from an organizational perspective.

on the lower control levels, which may be summarized as the neuro-fuzzy control domain. An overview of intelligent control approaches can be found in [97]. A number of successful applications also in power systems [247] demonstrate the practical utility of approaches from this domain. The term "intelligent" is less pronounced today as a wide area of subdomains have emerged as independent research areas, including, for example, the study of hybrid systems. However, the consideration of AI concepts has been proven particularly powerful for developing an organizational perspective on control architecture. A recent example is the application of intelligent software agents, which, in coordination with conventional control systems, provide a convincing modeling approach for the organizational coordination in power systems [205].

2.2.3 Common Representation in Control

Representations employed in control engineering are mostly either oriented toward a mathematical formalization, or oriented toward an implementation perspective, displaying algorithmic, data or communication aspects. Here both control- and process domain are modeled by the same formalism. Intentionality (goal-orientation) of control systems is mostly implicit, but not expressed semantically by stating its function. Some common diagram styles are shown in Figure 2.4 and explained below:

- *Block Diagrams* are most commonly employed to represent a signals &

systems perspective: In signal-flow diagrams arrows are *signals* and the boxes are *systems* which generate or transform signals (corresponding to a transfer functions, motivated by Laplace transform), thus tend to be interpreted as causal map from input to output (as causal signal transformation). This type of diagram originates from signal processing and is often used to both decompose a process and to explain the composition of control systems.

  – In the 'standard' feedback control loop presented in Figure 2.4 a), K refers to the controller and Σ denotes the system.
  – an 'architectural view' of signal flow diagrams is often used: boxes and signals are labelled to to ascribe meaning to elements and relations. The diagram semantics, limit the meaning of arrows to signal flows, or information exchange, and the box's functions to signal or information processing functions.
  – a variation of the signals and systems perspective where the arrow enters the box from the top is often employed to indicate purpose or command more explicitly.

- Discrete event systems are modeled as Automata (Figure 2.4 b)), with graphical representation as circles and arrows, where circles indicate states and arrows transitions between states. The labelling of transitions allows the interpretation of automata as symbol-generators [200]. Another popular representation for sequential, event-based processes is the Petri-Net (not shown). Discrete event systems are commonly associated with "supervisory control" and hierarchies [252], but are also employed in combination with ODEs, e.g. to model hybrid systems for mode-switching dynamics in a domain-model.

- In the general case, a signal-oriented representation with pre-defined causality is not meaningful. In a view of 'control as interconnection', [251], signal-arrows are removed and replaced by shared variables as subsystem interfaces (Figure 2.4 c)). This view is useful to generalize problem formulations on the principle of duality e.g. in the energy domain [107], e.g. port-controlled Hamiltonian sytems. An important graphical representation associated with this system view is Bond Graphs (e.g. [251, 53], not displayed).

The mathematical formulation of optimization problems is also suited for the formulation of control problems, and its structure explicitly contains an 'objective' (or: cost function). For example in [223], in particular optimization is distinguished by an explicit "objective" signal entering a function block from the top.

Hierarchies, layers, and embedding of processes are generally considered important fundamental patterns in control engineering. Their representation however is typically modeled either as signal cascade or embeddings of blocks. One structure employed to depict hierarchical relations is the organigram (Figure 2.4 e)),. Organigram type representation implies a relation of downward command and upward reporting (implied symmetry of signals); this type of diagram is borrowed from organizational structures and does not reflect any physical interconnections and constraints.

Some more design oriented representations are derived from a rather superficial concept of function, and are oriented on process level and communications such as the "structured analysis and design technique" (SADT) [162](utilized e.g. in IDEF0[11]. Here, also the concepts of horizontal process interactions and of vertical command appear. Explicit formulations of control-process-relations would enable a conceptual integration of process domain- and control representation necessary for a conceptual design, but are not widely available. One such representation is Multilevel-Flow-Modeling, which will be presented in Section 3.2, and is further developed in this work.

2.2.4 Control Needs and Architecture in Different Domains

Industrial scale control systems include hundreds or thousands of single control loops, are structured into several levels of hierarchy, and interact with the environment and human operators in a variety of ways. In application of control to industrial systems, the interaction between process- and control design, as well as implementation, deployment and operation become more relevant. The challenges encountered in the design of automation and control structure are often specific to the application domain, and are not covered by (conventional) control design methodologies. Specific architectural approaches are used in several industrial domains, where experience has been build around common control design patterns to provide solution templates.

To get an overview of the variety of requirements that motivate the development of domain-specific control architecture, we can draft some references from other disciplines.

Control Architecture in Robotics. Robots are machines designed to act with relatively high level of autonomy and to perform a versatile set of oper-

[11] http://www.idef.com/

ations. Instances range from: industrial special purpose robots (mounted or mobile), over unmanned (underwater, ground or aerial) vehicles, to humanoid robots. They can be designed to operate as individuals or in collaboration. Common to all robot control systems is that they are not tightly bound to external process constraints – focus is on behaviour, autonomy and task execution, rather than predefined functions. Generally speaking, robots have to “survive” a range of possible external circumstances, while achieving its goals. The internal structure of a robot is rather stable and its internal structural complexity small in comparison to the complexity of the world surrounding it. A robot's control architecture therefore reflects the complexity of the external environments it is designed to deal with. An ‘autonomous’ (arial or ground) vehicle with a complex mission plan naturally requires more sensory, world modeling and planning capabilities than a stationary manufacturing robot designed for a limited set of tasks.

Naturally, research in robotics has been closely associated with different conceptions of (artificial) intelligence. It is rather common to discuss control architecture in the field of robotics, but not that 'control' here is considered in the wider sense as goal achievement, including e.g. task-decomposition and deliberation. A number of architectures have been proposed to organize the generation of goal-directed behaviour of robots, which are also frequently referred to as 'cognitive' architectures (e.g. [14, 12, 82]). Two quite different types of control architecture for 'intelligent' robots have been established early on, and serve as reference for much of the following work: the task-oriented and hierarchical RCS (real-time control system, also: NASREM) by Albus and Barbera [14, 157] and the 'subsumption architecture' proposed by Brooks [36].
The RCS, developed as architecture for a tele-manufacturing robot, was expected to be sufficiently generic to serve as a standard reference for applications in other domains [157, 10]. The architecture utilizes a strictly hierarchical set of layers (from servo-control to high-level planning), each composed of interacting sensory processing-, world model-, task decomposition modules. This architecture has been further developed and extended for autonomous ground vehicles (4D/RCS) [13, 11].
The subsumption architecture is a control system where all layers have direct access to sensors and actuators, are mostly implemented as direct situation-action rules and coordination between layers is achieved by inhibition: lower-level signals have a higher priority than high-level signals. In this architecture layers are directly associated with a (task-achieving) behaviour, without complex representation or planning functions.

Whereas the relevance of robots for general insights in intelligence is contested, in particular in perspective of information systems [66, 100, 257], the field remains an active area of research generating, possibly generic, insights into the 'how' of building intelligent control structures [166, 82].

Control Architecture in the Process Industry. Industrial plants encompass a wide range of processes, including for example chemical processing plants and power plants. In contrast to the general requirements to robotics, industrial plants present a structured (internal) environment and the interaction with the environment is determined mostly by exchange of energy, materials and goods. Design methods are strongly oriented on representation of the specific processes that occur in the respective domain. Common to industrial plants is the shared purpose of all subsystems: to support the economic and safe operation of the total plant.

Industrial automation systems, their structure and design have been repeatedly discussed in the literature, for example discussing their vertical (hierarchical) and horizontal composition [165, 170], automation and computer control structures [196], control structure design [128]. Most design knowledge, though, remains informal engineering practice. Control systems support operation at many levels and most processes are of continuous nature. Low-level systems directly control on continuous process variables, where choice of input and output variables is crucial for the overall system performance. Higher-level structures are oriented toward optimization, and methods of optimizing control such as MPC are increasingly applied. Discrete-event and hybrid systems' methods are employed in supervisory process control, where discrete events can be interpreted as operation mode transitions. Yet higher levels are oriented on scheduling and resource procurement, which are part of the control architecture, but not typically considered part of control design [222].

Control Architecture in Assembly Plants. Fabrication processes are also structured environments, but, in contrast to the processes considered above, can generally be organized into discrete units and sequential processes. Robotic manipulators work in parallel or in sequence with human workers. Also for robots that operate on a factory floor, a more structured environment than e.g. in case of a in-house service robots, is given. Higher-level automation supervises the behaviour of such processes as discrete-event systems, and Petri-Nets, a natural domain representations for such processes, is a method typically employed also for process automation.
If flexibility and versatility is a requirement for manufacturing systems, such a system would reorganize its production processes, e.g. in response to new production demands or workstation failure, etc. This requires the ad-hoc generation of manufacturing schedules, dependent on available resources. This type of challenge is addressed by so-called holonic manufacturing systems. Here computer-agents, associated with manufacturing resources self-organize in response to different types of demands [37, 4]. The concept of holons enables

various organizational structures, such as distributed or *heterarchical*[12] configurations. Holons can also be aggregated. In perspective of such systems, 'hierachies' are source of organizational rigidity rather than optimal performance.

Control Architecture in Power Systems. Power systems are very complex machines, structurally and behaviourally. In the systems-engineering perspective presented above, they are systems of systems, interconnecting other complex systems, such as power plants or factories. On the other hand, power systems provide a very structured environment. Internally and externally, types of disturbances can be classified, and their effects, in spite of complex in their technical nature, have limited degrees of freedom. One major source of complexity in power systems is only visible in the course of system failures, when coordinated normal operation conditions are no longer fulfilled and un-intended interactions of local protection equipment cause unpredictable behaviours such as cascading blackouts. Control hierarchies have frequently employed to explain power system control [165, 219, 68, 106]. Schematic decompositions into control levels use criteria such as level of detail in representations or relevant time scales.

Control hierarchies are, however, insufficient to describe formulate control architecture of power systems. Understood as an infrastructure, power systems are different from the above in one important sense: as a whole, they are not owned or operated by a single entity and the interests associated with their reliable operation tend toward a public good [104]. Yet, many independent, self-interested, entities contribute to and rely on their operation. This observation is all the more true since the deregulation of power systems, and the separation of grid operation monopolies and energy conversion providers. This development is unique to power systems: it raises the challenge of interfacing markets and control structures. The trade of energy is considered independent of system operation, and except for transmission constraints it can be performed decoupled from the operation. Energy producing and consuming actors are thus not subordinated to a central control entity, so that one may speak of power system control being organized in a *heterarchy* rather then in a hierarchy. The entity (or entities) responsible for the operation, including the real-time balancing between supply and demand, do not necessarily own the assets required, such that the operation of ancillary service markets becomes a part of the control architecture. Beyond the various hierarchical aspects of control, modeling control architecture for future power systems thus also requires a representation of this heterarchical nature and the coordination of independent actors. Here is where the requirement of an efficient resource allocation meets the requirement of a stable and secure system operation.

[12] A *heterarchy* is a hierarchical structure with several (independent) top-level objectives.

2.3 Coordination and Control Architecture

In the first section in this chapter we have described two fundamental aspects of architecture: a) the methodology of architecting (design) and b) representations for requirements-analysis and design-synthesis. Such representations support reflection in an iterative design process, the communication of a design, and its verification against requirements. Further, design patterns have been found to be important in operationalizing the design process. How do you “sketch” or “draft” control architecture for complex processes as those listed above? Are there domain-specific or general design patterns that constitute control architecture?

There is an overarching consensus that hierarchies and layers play an important role in control structures [165, 223, 215, 106]. However, many concepts of hierarchies, but also distributed and ‘heterarchical’ control structures have been proposed.
The systems literature speaks of two dimensions of composition (e.g. [105]): A horizontal composition associated with common functional properties and a vertical composition, denoting a layering structure where higher layers are associated with goals and lower layers are associated with the process means. In this perspective of systems we could speak of two kinds of organizational activities: *coordination*, as an activity aimed at *horizontal organization*, and *control*, as an activity aimed at *vertical organization*.

This section aims to present a very compact overview of methodologies and representations for control structure design, control and coordination architecture. Here we also take note of the increasing relevance of organizational structures for coordination of control activities.

2.3.1 Control Structure Design

Most of the above theory and methods describe analytical techniques that suppose the availability of a process model, and a well defined control problem including inputs outputs and control objective. There is a gap between mathematical control theory and control engineering practice which is mostly filled by practical domain knowledge. Whereas control design is a common challenge and a well understood problem, in industry and academia, control architecture is not well understood as a problem formulation [75, 223]. The challenge is referred to as ‘control structure design’, ‘plantwide control’ or ‘overall process control’.

Control Structure Design in Process Control. Process control has some properties in common with control in power systems, including the highly functionalized process organization and continuos dynamics on multiple time scales. Some recent advancements in the systematic design for such control systems shall be reviewed. The first step in the development of plantwide control structure is the identification of the overall process goals. When process objectives are considered given, the realization of a control structure still requires further analysis and synthesis. In application to chemical process plants, Foss, Morari and Skogestad *et al.* [75, 170, 223, 222] identified the following tasks within control structure design:

1. selection of *manipulated variables* (inputs);
2. selection of *controlled variables* (outputs) and additional measurements, e.g. for stabilization;
3. *control configuration*; and
4. *controller type*, including design methodology.

A step-by-step methodology for control structure design for complete process plants is then described in [222]: The paper defines several control levels, including several optimization and scheduling layers, but focuses on the (lower) process-level, supervisory control and local optimization. The methodology proposes a combined approach of top-down analysis and bottom-up design. The analysis part aims at identifying control objectives, degrees of freedom, primary controlled variables and a central "production-rate" definition. The latter aspect shapes the process structure and requires considerations of disturbance propagation with respect to inventory control. For illustration, the paper uses hierachical command-layers and combines conventional piping & instrumentation diagrams (PID) in connection with multi-coloured arrows indicating causal- and flow-directions. For the bottom-up design, the approach describes a strategy for low-complexity control design with focus on single-input single output control. The main objectives for the low-level control design is 'stabilization' of the process and local disturbance rejection. Supervisory control then aims at controlling the primary variables either by decentralized- or by multivariable-control.

The methodology was outlined to highlight some central aspects of control structure design: *control objectives*, *degrees of freedom analysis*, *primary (vs. secondary) controlled variables* and the importance of *disturbance rejection and -propagation* for the control structure. The translation of these design considerations to the power systems domain is partly subject of this work.
We also note that no specific design-oriented representation was employed, but

that the common PID diagrams were employed as domain representation, extended by a notations indicating degrees of freedom and causal influence.

Some Control Structure Representations. On lower control levels, the composition of control structures is strongly characterized by the controlled process. The focus on one domain allows the identification of a certain logic and formal representation by which control structure and process can be co-composed. For example, a specialized domain representation for "multi-machine-multi-converter systems" is introduced and utilized in [30]. Here both the controlled system composition and control logic are identified as basic patterns, represented as puzzle-like diagrammatic elements. The authors apply these representations to the discussion of varied process- and control configurations.
A domain-independent approach to the conceptual design of control systems has been proposed in [228]. The formalization is based on a categorization of control-related signal-processing functions, which enables the discussion of high-level control and planning functions, but hardly supports the combined process and control design.

Toward Automation Design for Dynamical Processes. One important aspect for plant operation which is mostly treated as separate from control systems design is a more complete 'automation' perspective, which also includes *safety systems*, *fault detection and diagnosis* and *instrumentation design*. For example a methodology for the definition of discrete control modes for safe process design seems missing in the literature. The lack of available representations is partly a result of the complexity of the challenge, but also results from the almost exclusive focus on quantitative/mathematical methodology in the control-related research domains. For example, in the domain of fault-tolerant control, Zhang and Jian [264] provide a recent, comprehensive and clear review, qualitative modeling is hardly utilized, even though it is important for the related fault diagnosis methodologies. In fault diagnosis and safety analysis, qualitative modeling has been more common, which is also discussed in a review by Venkatasubramanian *et al.* [243] (more recent results in means-ends modeling and related model-based diagnosis in context of MFM are listed in Chapter 3). These qualitative models are then mostly considered independent of control applications. A perspective integrating and mapping the qualitative representation of control systems to behaviour and computational implementations would be required for the design of reconfigurable and flexible process control.

Research focussed on specialized controller synthesis rather than general design methodology, can lead the direction toward understanding the modularity of such control architectures. To provide a foundation for conceptual modeling, experience with reconfigurable control architectures [176, 175], but also more modular control concepts, such as task-oriented control design [250], are required. An example for the possibility of integrating diagnosis and reconfiguration based on qualitative models could be [198] (here applied to a network with discrete states, using causal graphs).

2.3.2 Control Levels, Layers and Hierarchies

The above mentioned results included some instructive methodology adressing the conceptual design of control structures. Such instructive results are sparse in the academic literature, and a more descriptive, analytical, treatment of man-made complex systems in general is more common. There appears to be some consensus that modeling in terms of levels, layers and hierarchies offers a meaningful analytical decomposition.

Automation Hierarchy. A common and practical decomposition of industrial process control defines the following layers [196]:

- Enterprise Resource Planning (ERP)
- Manufacturing Management System (MMS)
- Supervisory control
- Process-level control

In principle, this intuitive layering can be obeserved in many industries and processes, and it is instructive in the sense the each layer seems to have a separate purpose. It can be observed that the hierarchical ordering of layers could be motivated by a number of different concepts (from bottom-to-top): from means to ends, from process to management, internal communication: from signals to symbols, time-scales: from milliseconds to weeks, stability of structure: from hard to flexible, planning horizon, et cetera. Also with regard to safety, fault-propagation and -impact can be quite different.

Both job specializations and academic research tend to focus on problem formulations within such layers. When a new plant is designed, it can be developed from a practicioners perspective and experience, without much consideration for the motivation of this layered structure. A deeper conceptual understanding of these practical layers may be desirable, in particular to support the synthesis and integrated design of process and automation system.

Concepts of Vertical and Horizontal Decomposition. More could be said about the generic "horizontal" and "vertical" composition concepts. Mesarovic [165] introduced three types of decomposition concepts – strata, decision layers and echelons – and suggested that these were, at least implicitly present in all process organization. The associated characteristic properties were:

- *Strata*: a vertical decomposition into separate domains, e.g. communication, computing, electricity, economics etc.
- *(Decision) Layers*: a vertical decomposition of decision and control processes, with increasing deliberation, learning and goal-seeking capacity at the top and direct process control below;
- *Echelons*: horizontal decomposition into parallel control hierarchies, with weak interactions on a process level and some coordination and information exchange.

Mesarovic's generalization was motivated in reference to process control and power systems.

The *stratum* notion is commonly understood. Stratification corresponds well to a 'platform' concept where one layer is a means for another other layer, e.g. the OSI layers in communication, or the communication layer as a means of control. Stratification, however, is not necessarily equivalent to hierarchy. The *echelon* terminology was well-coined, and also adopted in the control community, for example by [170], possibly because it clearly isolates control hierarchies from another, which is well-aligned with a perspective of hierarchical control and conceptual decomposition. The decomposition into decision-layers was not so well adopted, but relates to later work on the internal organization of planning systems in artificial intelligence (such as discussed in relation to Robotics in Section 2.2.4). It also relates to Rasmussen's decision ladder [201], cf. Section 3.1.4, which models a cognitive problem-solving process.

Mesarovic illustrated the layering conceptually by boxes and arrows, which alludes to signal exchange, and thus the graphical pattern would strongly hint toward control hierarchy. However, instead of simply recognizing a hierarchy, we can focus on the labelling of these signal-arrows. In case of strata, the layers are symmetrical, indicating a downward "intervention", and upward "performance feedback". This labelling indicates a control-relation in terms of signal-exchange. However, the means-end relation between strata should not necessarily be seen as a hierarchical control-relation, as layers are not necessarily supervised in this monolithic sense, and also the hierarchical encapsulation of strata does not hold in many applications. Echelons, instead, exchange "coordination" and "information feedback", which, as a labelling for signal arrows,

seems a little forced. But it indicates the interpretation that horizontal relations represent *coordination* activities, whereas vertical information exchange is considered *control*. The decision layers exchange downward "strategies", and upward further unspecified information.
Criticism in other literature emphasizes that Mesarovic's decomposition is non-instructive for design considerations. Often the stringent hierarchical conception is eased up, so that both Strata and Decision Layers are simply referred to as layers (e.g. [223, 161]).
All in all, it can be recognized that several types of hierarchies seem relevant for control structures and complex processes in general. Further, in particular the horizontal composition of a system is difficult to frame in a signal-oriented model.

Arguments for Hierarchies. There are deeper arguments for the value of hierarchical organization of levels in several domains, which shall only be listed here:

- hierarchical control motivated by an entropy-based argument: the principle of increasing precision and decreasing intelligence (IPDI) [215];
- aggregation of similar properties reduces control complexity [165];
- supervisory control and cognition: abstraction hierarchy [201];
- planning/decision levels [201] and representations for planning [11];
- structural stability and resilience [221];
- emergent (useful) properties of a whole and difficulty of reduction [241, 91]
- ...

The list could be continued to many further arguments, domains and abstract considerations. In a review of concepts of hierarchy, Lane [122] further recognizes researchers different perspectives in considering either hierarchies of process or hierarchies of structure.

However, as hierarchies already seem natural for goal-oriented control structures, and conceptual decompositions are "trees", the understanding of overlap and interaction between hierarchies becomes, conceptually, the bigger challenge.

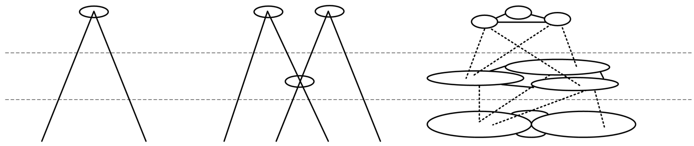

Figure 2.5: Hierarchy, heterachy, and a holon-based organization structure. The circles indicate spheres of deliberation. For the holon-pictogram on the right, the dotted lines suggest allocation & control, and the solid lines coordination.

2.3.3 Coordination Architecture

In control, hierarchies are static structures designed to enable a goal-oriented configuration of dynamic processes. The rigidity of the hierarchy supports internal stability, however, it also makes it inflexible to adapt to changing external requirements. Adaptation to new external demands requires adaptation from the top: adaptation of objectives.
For flexible production units like the fabrication plants mentioned in the previous section, a strict hierarchy is more a hindrance than a help. Heterarchical- and holon-structures [37] are more flexible, because they enable deliberation about objectives at several levels in the process structure (Figure 2.5). In a holon-architecture, deliberation is associated with all levels of the production chain, so that resources and tasks can be dynamically matched to production objectives.

This increase in flexibility also creates new challenges. In fully hierarchical processes, the coordination problem is addressed in process design and is therefore resolved. In these flexible organization structures, the coordination problem has to be addressed at each level where deliberation and re-organization is possible. A "self-organization" process requires an explicit understanding of these coordination problems.
Order is only maintained by certain patterns of interrelations. As human organizations naturally include deliberation capabilities for each individual, the identification of co-ordination patterns within organizations, an understanding of their functional purpose and their emerging stability are subject of organizational research.

Coordination Patterns in Organizations. In [167], Mintzberg identifies five types of coordination patterns, or systems, within organizations, which are overlaid and together stabilize an organization:

- The formal system of authority (the hierarchy),

- a regulating system of activities,
- an informal system of communication,
- a system of work-constellations, and
- an ad-hoc decision system.

These patterns cut across organizational functions and each follow different pathways through the organization. One should note that some of these coordination patterns also have control character: organizational theory does not use the same clear distinction between vertical control and horizontal coordination as introduced above, but rather views control as a special form of coordination. The interaction patterns in organizations tend to be multi-layered and with varying emphasis in different organization forms. Mintzberg further distinguishes six stereotypical organization forms (from formal bureaucracies to ad-hoc organizations), with six corresponding dominant coordination and control mechanisms.

Organizational Flexibility in a Control Perspective. Organizational flexibility can also be formulated from a control perspective. As discussed in [130], a meaningful interpretation of flexibility requires the alignment of several perspectives. The authors introduce a number of systems-theoretical concepts to facilitate the definition of these perspectives. Firstly, one should recognize several possible decompositions of an organization into *part-systems*: *subsystems* (structurally disjoint subsets), *aspect-systems* (a conceptual decomposition, without 'structural' sectioning), and *phase-systems* (time-wise decompositions). Any of these part-systems can be perceived as subject to some form of control. In relation to the previous discussion on hierarchies, the concept of aspect-system can be used to realize a distinction between structural and functional system decompositions and to conceive overlap of control hierarchies; and phase-systems could be relevant to understand controlled transitions, for example. The authors formulate a *flexibility game* between a controlling organ (CO) and a target system (TS), the controlled system.
To understand the control perspective two cognitive viewpoints are distinguished: the analytical view, from an environment onto the system, which, according to the authors, leads to the perspective in which seeks to stabilize a system's behaviour in response to environmental changes (corresponding to a conventional control design perspective); the other viewpoint, motivated with reference to Goguen and Varela [91], is from the system into an environment. Here, the autonomy of the system with respect to its behaviour in the environment is recognized and notions of identity, ownership over parts and components and

resilience[13] become meaningful. The assumption of these two perspectives with respect to CO and TS enables the identification two key aspects of flexibility: *control capability* of the CO and *controllability* of the TS.
Note that these concepts have been discussed with respect to human organizations. However, it seems that an obvious analogy can be drawn to the more autonomy-oriented control architectures in robotics on the one hand, and the more analytical perspective applied in process-control on the other hand.

Coordination Patterns for Multi-Agent Systems. The social study of organizations indentified patterns of organization and coordination. The further formalization of these coordination patterns enabled the synthesis of software concepts that mimic these social patterns. For example, van Aart [236] proposes organizational patterns for multi-agent systems derived from Mintzberg's patterns. These formalized patterns enable varied forms of adaptivity of software structures, including also numerical algorithms as in electronic market places [249]. Electronic/software-services are common technology today [237], and also their application in power systems is deemed feasible [98].

The conceptual formalization of social coordination patterns has a central role of in the synthesis of such software coordination systems, their analysis and deployment as a business. This is well illustrated in the developments since the HOMEBOTS concept of Akkermans, Ygge and Gustavsson [6], which also outlined a research agenda leading to the present PowerMatcher [115] system which provides an electronic multi-commodity market for the coordination and control of distributed energy resources in power systems. In [260], Ygge and Akkermans explicitly describe their market-algorithm as derived from socio-economic theory, which is further anchored in socio-economic theory (and control theory) in [5].
In the meantime, conceptual modeling of business processes, the "e3value" methodology, was developed by Gordijn [92] and later applied to the distributed balancing system by Kok, Derzsi, Gordijn, Akkermans *et al.* [95, 116].

Note that failure of these organization patterns would imply failure of the software system: In relation to electronic markets, both Wellman [249] and Ygge [259] emphasize a careful design of decision process and selection of price-commodity pairing is essential. Therefore, not only software quality and security needs to be guaranteed [98], but also the consequences of software failure on the electric power infrastructure should be accounted for.

[13] *Autonomy*: the ability to adapt to an environment while and maintaining an identity; *resilience*: ability of a system of interactions to persist while absorbing environmental change. Resilience is thus a rather persistence of a configuration, whereas autonomy is associated with persistence of identity.

2.4 Chapter Conclusion

The need for and uses of representations in the design of complex systems have been introduced in Section 2.1. A need for conceptual models in support of requirements analysis, as well as the role of functional patterns with respect to design has been observed. Section 2.2 explained how control structures are typically represented – mostly in terms of signal-oriented block diagrams. Semantic differentiation between 'control' and 'process', between objective and disturbance, between control function and target system, can only be implicit in this type of representation. But for control structure design, the mapping between process structure and the objectives of a control system is essential, and thus requires explicit consideration.
A review of control architectures in several domains showed characteristics of power systems control requirements differentiating it from other domains: it involves a dynamic, non-sequential, process (comparable to process plants), but also a multi-owner, multi-purpose structure which requires several types of coordination (which could be compared to some modern fabrication processes).

Approaching an architectural perspective on control systems in Section 2.3, we identified some domain-specific, instructive results. Other, more generic, description in terms of layers and hierarchies are less instructive, but provide a conceptual understanding of the related concepts of vertical and horizontal system composition. Some known coordination concepts for flexible and adaptable systems were reviewed.

In particular, it showed that for the modeling and control of processes, little concepts and modeling methodologies seem available that would support a concise formulation of process-type control structures and at the same time enable abstraction to support a heterarchical formulation of power system control in terms of coordination layers.

Such an "architectural" representation will be developed and applied to power system modelling in Part I of this thesis. The methodology will be based on Multilevel Flow Modeling (MFM).

CHAPTER 3

Conceptual Modeling

This chapter provides an overview of methods and applications of conceptual modeling in general, with a developing focus on goal-function oriented modeling. Then a compact introduction to means-ends modeling with Multi-level Flow Modeling (MFM) and closely related modeling concepts is provided. But first, the two central notions, conceptual model and function, shall be clarified.

Conceptual Modeling was motivated in the previous chapter, in context of requirements identification and analysis in relation to a design problem. To have clear conceptual understanding of requirements enables further design steps, and on the contrary, the use of unclear and ambivalent concepts in the requirements-analysis is fatal for the design process [15]. Conceptual modeling is relevant for the development of a problem statement, it enables coordination with respect to both requirements identification and solution development, and it serves further as documentation. A conceptual model can also be representation of a solution in the design domain. Common to all conceptual modeling is the possibility to iteratively approach a formalized, clear "concept" of whatever is to be modeled.

The development of a conceptual model can be a formalization process in two layers. The foundation is a group of domain concepts and interfaces, which form a logical basis for the further modeling. The modeling process is then the analytical process in which the "problem" is analyzed in terms of these domain

concepts.
The formalization of domain concepts enables logical reasoning. If the conceptual model is fully formalized, the reasoning rules enable various forms of model assessment, such as checking for model consistency, or deriving conclusion on the basis of model-related propositions.

Conceptual models are often associated with diagrammatic representations. The graphical approach supports description and analysis by model concepts, and their clear separation from 'soft' natural language descriptions and other concepts associated with a certain modeling problem. Further, the development of a concept basis is often a slow and iterative process in which domain concepts are established and isolated in their meaning.

The Function Concept. Functional modeling – or function modeling – is a specific form of conceptual modeling that aims to represent the (design) functions of a system.
The word function[1] can have a number of different interpretations, but its root is ascription of a role in achievement of a purpose. To exemplify, a stone may have the function of keeping papers on the ground, or the function of a weapon, depending on its use. Or it may have no function at all. These functions of the stone are not an inherent property of the stone, but they are attributed to its use[2].
The *function* of an object is that *attribution of a purpose* in context of some action, and as such, a function names a *directed mapping* between object and purpose. The attainment of a goal may require the combination of a number of functions, and vice versa: in context of other functions, one funtion may serve several purposes.

The specific understanding of function in the mathematical context has confused the interpretation of this word. Purpose is not a mathematical concept. What remains for the mathematical concept of function is to capture one aspect of its meaning: given an input, a function *determines* the output. Functions are directed mappings. Mathematical functions can be employed, for example, to

[1] 1 : the special purpose or activity for which a thing exists or is used; 2 the job or duty of a person; 3 a large ceremony or social event; 4 a : something (such as a quality or measurement) that is related to and changes with something else b : something that results from something else (Source: Merriam Websters's Learner's dictionary). *Etymology*: Latin *function-*, *functio* performance, from *fungi* to perform; probably akin to Sanskrit *bhunkte* he enjoys.

[2] Closely related to function is the meaning of "tool": an object that is ready to assume a mediator role in achievement of a purpose. A hammer mediates the hammering of a nail. The function of a hammer with respect to nailing is that it mediates the force excerted by the hand to build momentum sufficient for the purpose of sinking the object nail into the (opposor) wood. In contrast to a *function* concept, a *tool*-word refers to a thing, and so the word can be used to refer to a thing independently of its design purpose.

model a sequence of goal-directed computations, or causal relations by mapping cause to effect, or observations to an interpretation, situation to action, etc. The relation to purpose is not connected to mathematical functions. Therefore the mathematical function concept needs to be distinguished from the (semantic) concept of function.

The function concept has an important role in modeling of technical systems, as it expresses the relation between objects or processes and the system's design objectives. When system functions can be expressed explicitly, performance requirements can be formulated, failure modes can be identified, requirements for alternate solutions can be formulated, independent of given solutions. It is important to note the difference between goals and functions: a goal states a purpose; a function states a performance that is associated with a purpose. A single goal may require a system of interacting functions in order to satisfy it.

3.1 Conceptual Modeling in Context

Modeling is an important practice in all analytical work. The word 'conceptual' is meant to summarize those modeling approaches where part of the modeling modeling effort is to avoid pre-conceived notions, and to aim at the development of clearer concepts and understanding. It is thus rather an approach than a specific domain, and the idea behind this approach shall be illustrated in a few different application-perspectives.

3.1.1 The Software Engineering Context

Conceptual modeling has become an established methodology in particular due to the needs and opportunities in software engineering [45].
From an application-perspective, we can distinguish three central uses of conceptual modeling in relation to software: Requirements (modeling/engineering), representation of software concepts and code generation, and domain ontologies (information modeling). The former two have already been adressed in Section 2.1.3 in terms of the functional vs. non-functional requirements discussion. A more general discipline originating from an artificial intelligence and expert systems context is called knowledge engineering (e.g. [218]), and its methodologies are often integrated in the above mentioned applications.

Domain Ontologies. A domain ontology, or information model, is a conceptual model of domain concepts, which is for example used to model the information content and context of data structures. Most domain ontologies today are formulated on top of a standardized conceptual basis, using the entity-relationship model [45]. Standards for these modeling concepts, including the "unified modeling language" UML [2], is provided by the Object Management Group[3].
The information model mainly facilitates communication and standardization of model-formats (supporting software "interoperability"). A specialized information model for power systems exists [48].

Representation of Software Concepts. Software concepts are a form of conceptual model in themselves. Whereas original programming languages were adapted to their sequential execution by a processor, advanced software concepts provide programming concepts (also called 'metaphors') adapted to modelling needs, such as object-orientation or agent-based programming.
A conceptual design of software can therefore be performed by developing a solution in the respective modeling paradigm. If the modeling is performed in the respective software environment, program code can be generated directly from the model [31].
A family of concepts is provided by UML (entities, relationship, roles ,...), on the basis of which a solution can be drafted from requirements, and to further specify such models independent of the implementation language.

Knowledge- and Requirements Engineering. Requirements engineering is a form of knowledge engineering [218, 217]. Knowledge engineering is the general methodology of formalizing (expert) knowledge to make it accessible to computer-based reasoning methods, including expert systems for example. It has applications in several engineering domains.

The term 'requirements modeling' already indicates its use in a design context. In software engineering, functional requirements are such requirements that can be directly formulated in terms of software concepts, similar to the idea of design patterns.
'Non-functional' requirements are those requirements that cannot directly be formulated in terms of software concepts. These requirements are more challenging to the requirements identification process as they can neither be formulated in the function-concepts of the programmer, nor would a client be capable of stating them in a structured manner.
A number of conceptual modeling approaches have been developed to facilitate

[3]Organization: http://www.omg.org/; UML related topics http://www.uml.org/.

the formalization of such non-functional requirements (e.g. Goal-oriented Modeling [52, 174, 240]). Such approaches tend to formalize notions of goals and goal-directed activities.

Another specialization for requirements modeling illustrates the increased relevance of conceptual definitions within application domains. For example the *e3value* family of conceptual modeling languages (e.g. [94]) provides concepts for modeling a business case in terms of value-constellations, rather than the business process. This example shows that the commonly used term "requirements" can also be misleading, as these business models certainly can also be viewed as a representation in the design domain (cf. Section 2.1.2).

3.1.2 Sequential and Discrete Processes

Independent of application domains, sequential processes are a special, very common, class of discrete processes. Algorithms can be stated in a sequence of commands; recipes, manufacturing processes and business processes can all be formulated as a sequence of activities and decisions. They have in common their teleological perspective: a sequence of steps leads to a final state which can be interpreted as goal. Achievement of the goal, or failure, terminates the process. Discrete event processes are a more general class, which does not require the alignment of teleology and process sequence.

The Flow-Chart. Most models of sequential processes are variants of a flow-chart (cf. Figure 2.4d), on page 30). The main concepts of a flow-chart are: *start*, *transition*, *function*, *decision*, *termination*. Due to the sequence, a function is always characterized by input and output, so that the transition between functions is also aligned with information (or product) transfer. Conceptually, this input-output view also aligns the state of activity with goal orientation and performance evaluation.
Several extended forms of flow-charts exist, often specialized to a given domain. The "activity diagram" of UML or business process models are such specializations, which also include adaptations to the modeling of actors or functional roles in relation to the process.

Discrete Events. The discrete states of activity and sequence is a useful perspective for many processes, but the direct alignment with goals and performance requirements is not always meaningful. Central discrete event concepts are *states* and *transitions*. Discrete event systems, automata (cf. Figure 2.4b)) or Petri Nets model the behaviour of this more general class of processes.

3.1.3 Engineering Applications of Conceptual Modelling

Knowledge and models are central aspect in all engineering. Conceptual modeling is therefore used in various engineering domains, in a wide range of applications and approaches. Engineering is about building for purpose, so that some form of function-orientation in the conceptual models is natural. The definition of concepts also enables the standardization of modeling methodology, which has led to the IDEF[4] family of modeling & design standards. The methods chosen for this review have relation to a formal requirements/design modeling and its evaluation.

Qualitative Process Modeling. Qualitative process modeling (QPT), is based on the idea that physical behaviour could be modeled and their interactions could be 'simulated' based on purely qualitative descriptions [73, 74]. The method allowed for example to generate linguistic descriptions, explanations and predictions directly from the qualitative model. One of the problems with qualitative simulation, however is that many dynamic situations cannot be decided based on qualitative information alone [255]. To adress this problem, the approach was improved and called Hybrid Phenomena Theory by Woods [254], who established a method for the generation of state-space models for simulation from qualitative process descriptions, using a categorization of physical phenomena.

Object-Oriented Modeling. The software notion of object-oriented modeling, was picked up in several engineering domains. It has been applied to the organization of simulation model-libraries. Here, the central concepts tree-structures, enclosure, etc. have been translated into requirements for the formulation of libraries for simulation models [22]. A simulation platform, Modelica [163], supports such models. The object-oriented modeling of physical systems favours the "behavioural" modeling approach and can be well-aligned with the Bond-Graph based models mentioned above [35].

The common use of object-oriented software, has, also lead to the need to establish design-methodology that would enable proper object-oriented design (e.g. IDEF4).

Mechanical Design. Mechanical design is, comparable to building architecture, about the creation of form, possibly with a stronger focus on function and

[4] http://www.idef.com

a more graspable set of these. Building on the idea of design patterns mentioned above, Stone *et al.* [227, 102] develop a "functional basis" for the functional description of a design. The functional basis is a group of function-concepts and logical relations that enable the functional description of a mechanical design. A design library can thus be build in which function-patterns can be searched to find design examples for the required combination of functions. The papers clearly suggest the "evolving" aspect of that functional basis., that is, it takes several iterations of concept definition, application and re-consideration of concepts for the right concepts to emerge.

Function Chart. More general purpose is the system/requirements-engineering related Structured Analysis and Design Technique (SADT) [162]. It is centered around a central function-concept with four interconnection relations (input, output, control, mechanisms). In modeling with SADT, the function is characterized by a single action verb, which cascaded in sequence with another function, or zoomed and further detailed using the same function concept. SADT forms the basis for the IDEF0 standard.

3.1.4 Conceptual Modeling for Supervisory Control and Safety

In supervisory control of processes it is important to have a clear concept of the process. Traditional supervisory interfaces (e.g. in control rooms) simply display structural subsystems of a process and single values for measurements. The problem for interface design for complex plant is that the number of single measurements by far exceeds an operator's focus ability , and that different combinations of values matter in varying operating situations [201]. Whereas stable plant operation is typically characterized by some primary control variables determined in the design phase (cf. Section 2.3.1), failure modes are not necessarily as simple to identify. A related research domain is that of reliability and safety analysis, which also requires an understanding of fault-propagation and diagnosis, and it has shown the some similar modeling approaches can be used in either domain.

At least two perspectives are relevant in the understanding and design of such human-machine interfaces (HMI): firstly, the perspective of the process, in which the events occur and faults escalate, and effective operator interventions are required so that, for example, a classification of alarms is possible; secondly, the perspective of the plant operator for example in terms of her situational awareness and problem solving support must be understood to define what is relevant process information. As this perspective obviously requires an understanding, of cognitive processes, the related research domain is called cognitive systems engineering. Third and forth possible perspectives could be the semiotic consideration of information content and that of (graphical) interface design. At present, there is no coherent theory for operator interface design. Here, conceptual models play an important role in the attempt to form an understanding of the relations between process, interface and operators.

Process Modelling for Operator Support. There are several types of operator support systems that can benefit from a both detailed and overall understanding of system goals and functions. The some central applications of this type include: alarm design and alarm filtering, fault diagnosis and counteraction planning.

Related concepts that have been established as fundamental to the required process understanding include: distinction of structural and functional process composition, means-ends abstraction levels, the relation between nominal (desired) and actual plant state, teleology and causality, representation of process objectives vs. operating procedures (e.g. [201, 141, 134, 184, 84, 169]).

The explicit "functional modeling" methods that have been applied successfully to such problems are "Multilevel Flow Modeling" and "Goal Tree–Success tree". Multilevel Flow Modeling is introduced in the following section. The Goal Tree–Success Tree methodology (GTST) [168, 169] is different from MFM in a variety of ways. It is more practice-oriented and uses more conventional engineering representations. Further it resorts to a fully hierarchical decomposition of operation goals, less from a process perspective, but more from perspective of threats and failure avoidance.

The main difference between the two modeling approaches is likely the strong orientation on operation practice (including operator interventions), physical components, available and required operation knowledge in the GTST, whereas MFM development has been more driven from a first-principles perspective, on modeling and understanding the abstraction levels in a process-composition.

The 'Cognitive' Perspective Apart from this process-perspective, such interfaces are also meant to support problem-solving by operators. This cognitive dimension should also be considered in the interface design. The *decision-ladder* introduced by Rasmussen [201], Figure 3.1, is an important consideration from this perspective. Rasmussen further introduced the so-called abstraction hierarchy, which was motivated in a means-ends perspective, which suggested to

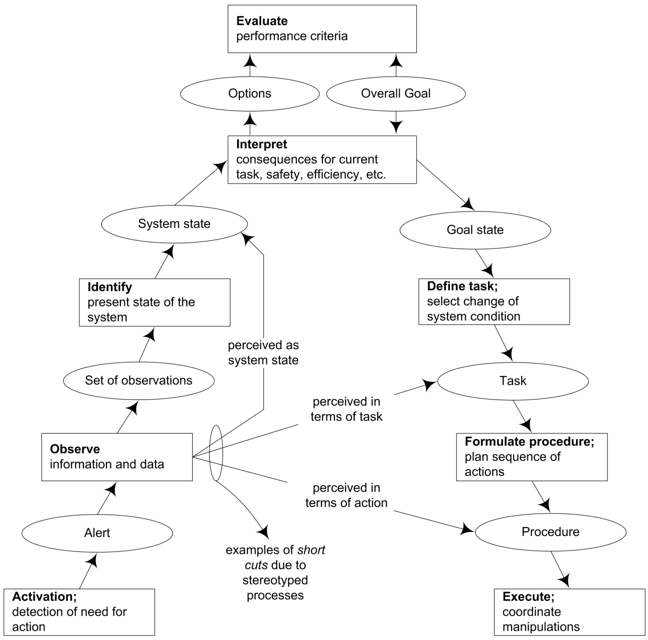

Figure 3.1: Decison Ladder [201], modeling different stages of problem solving. The *shortcuts* illustrate common, control-related, pathways through this ladder. For example a simple controller would 'solve' an observed deviation from its objective by directly computing and executing a counteraction. It takes higher levels of reasoning to deliberate about alternative objectives.

decompose a process into a sequence of layers: physical form, physical functions, generalized functions, abstract functions and functional purpose. The abstraction hierarchy motivated a variety of further developments in the cognitive systems domain, including the so-called "ecological interfaces" [27]. Whereas a relation between the abstraction hierarchy and MFM was originally intended, it became clear that some of the assumptions and loose definitions of the means-ends and whole-part concepts in abstraction hierarchy were problematic [138]. It should also be considered that representations (incl. displays) serve the coordination between operators of different plants, or with workers in the field, so that interfaces can be perceived as coordination instruments, which can be understood in a perspective of collaborative work [20].

Reliability and Safety Modeling. Most engineering methodologies are aimed at designing establishing and deploying a process. That is, they tend to have a positive/operational view on a system. Modeling for reliability and safety analysis, instead asks: What could go wrong, and what are the consequences?

Methodologies such as Fault Trees and failure mode effect analysis (FMEA) have long tradition in reliability engineering. Both are quite linear and intuitive, but do not support the analyst in checking consistency or completeness of a model. The Goal Tree–Success Tree tree methodology also was developed out of the practice of failure mode analysis and intergrates well with probabilistic failure mode assessment.

Functional modeling with MFM can support the mapping from an "operational" system description to possible fault combinations [114, 258, 125, 44]. Also the modeling of safety functions is supported by MFM [123], which has evolved over time, more recently also emphasizing the role of control functions as barriers [143].

3.2 Multilevel Flow Modeling

The basic insight underlying MFM is that the functions of a complex process are composed of several levels of means and ends and that it takes a group of system functions to form a whole. A domain model that offers only one abstraction level of system functions implies choice of the level of means-ends abstraction. The choice of abstraction level is implicit in the formulation of an objective and reflected in the modeling of functions associated with it.

Multilevel Flow Modeling provides concepts for the composition of multiple levels of means-ends abstraction. It combines goals, goal-relations, generalized functions, function-relations and whole-part concepts with several classes of means-ends relations. Altogether MFM provides a rich ontology for modeling purpose & function of complex processes. The basic core of MFM has been stable, but new modeling aspects, functions and relations have been introduced over time, such that the overall methodology is evolving toward more powerful and concise representations. MFM is supported by knowledge based tools for model building and reasoning: a graphical modeling environment and a rule-based reasoning environment with graphical user interface, which is referred to as *MFM Workbench* in the following.

3.2.1 MFM Concepts

Multilevel Flow Modeling (MFM) is an approach to modeling goals and functions of complex industrial processes involving interactions between flows of mass, energy and information [132, 133, 135, 139, 144, 145]. MFM functions

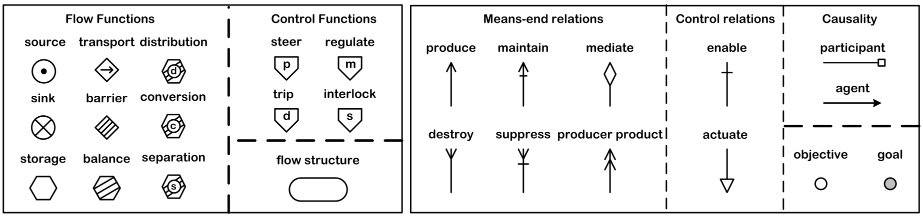

Figure 3.2: MFM Entities and Relations.

are founded on basic actions [148] and can be supported by function-structure relations [150]. A tutorial introduction to modeling with MFM can be found in [152].

Functions, Means-ends and Whole-part Concepts. Process functions are represented by elementary flow functions interconnected to form flow structures representing a particular goal oriented view of the system (Figure 3.2). Flow structures are interconnected in a multilevel representation through means-end relations, causal roles and control functions and structures. MFM is founded on fundamental concepts of action [144] and each of the elementary flow and control functions can be seen as instances of more generic action types. The views represented by the flow structures, functions, objectives and their interrelations comprise together a comprehensive model of the functional organization of the system represented as a hypergraph. It should be noted that MFM is a formalized conceptual model of the system which supports qualitative reasoning about control situations [137, 212].

Control Functions. A representation of control systems based on action theory has been introduced more recently to MFM[142, 144, 149]. The four elementary control functions, which are based on elementary action types (based on vonWright's action theory), are found in Figure 3.2. A tutorial introduction to modeling of control functions can be found in [151]

In contrast to the classical signals and systems perspective, control functions have a special role in the perspective of mean-ends modeling: Whereas a *flow-structure* is a functional abstraction of a process, the *control-structure* is a representation of the intentional structure realized by a control system[5]. That is,

[5]In the control literature, the 'intentional system' is sometimes referred to as 'active' structure, whereas the the controlled system, here '(multi-level) flow-structure', is referred to as the 'passive' basis. This wording does not apply exactly for multilevel-flow-structures, as energy sources and sinks may well be part of the system.

the control functions in MFM are explicitly modelled separate from the process and are formulated as elementary actions in relation to their respective control-objective.

3.2.2 Example Model

Application of the MFM concepts is illustrated in the following by a simple example that has been introduced by Lind in [MFM-I]. The model in Figure 3.3 represents the objectives and functions of a water circulation loop in a heat transfer system. It is assumed that the water is circulated by an oil lubricated pump. The example illustrates how the MFM model provides a comprehensive understanding of the purpose and functions of the circulation loop and its subsystems. On an overall level the model can be seen as composed of three sub-models representing different views on the water circulation system.

The first view (starting from the top) represents systems aspects related to water circulation and comprises the flow structure labeled **MFS1**, the *produce* relation and the objective **O1**. This part of the models represents the overall objective of the water circulation, which is to produce a flow of water. The *flow structure* contains the functions provided to circulate the water. In this simplified model, the *transport* function **T1** is the means used for water circulation.

The second view is partially overlapping with the first view because what is seen here as a means (the transport **T1**) is in the second view seen as an end. Transport **T1** is related to the means of transport which is the pumping represented by the energy flow structure **EFS1**). **T1** and **EFS1** is therefore related by a type of means-end relation called a producer-product relation in MFM. The flow structure **EFS1** is decomposed into the flow functions representing the services provided by components of the pump system (including the energy supply) in order to achieve the end, the transportation of water represented by **T1**.

The third view is related with the second view through an *enabling* relation and an associated objective **O2** which is the end to be achieved by the functions contained in the flow structure **MFS2**. The flow structure **MFS2** represents the functions involved in the lubrication of the pump and the objective **O2** represents the condition that should be fulfilled in order to ensure that the pump is properly lubricated. A condition which should be satisfied in order to enable the pump to provide its functions. The flow functions inside **MFS2** accordingly represents the functions of the pump lubrication system.

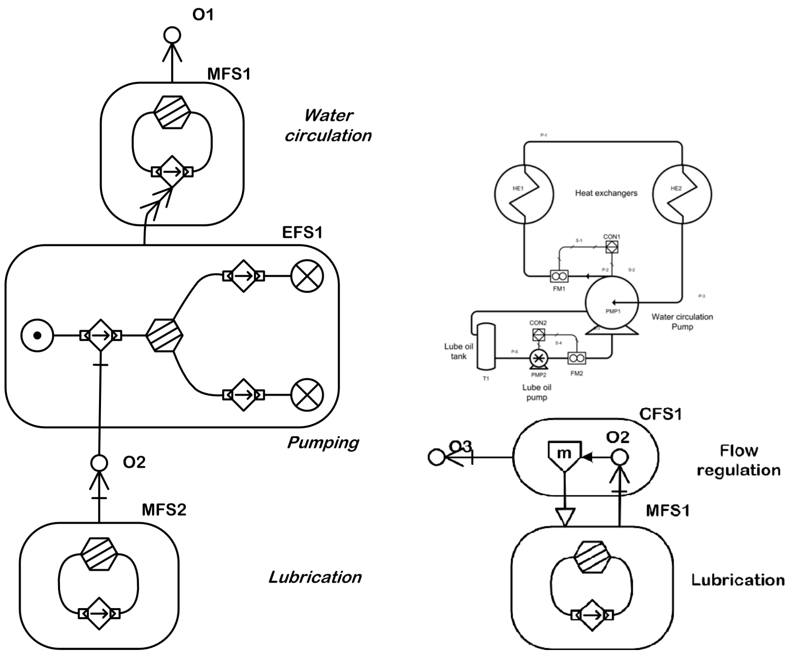

Figure 3.3: MFM model of a water circulation loop (as part of a heat-exchange process). The model on the right includes an explicit model of the flow regulation.

Example with control function. In the modeling example above, no consideration was given to the purpose and function of control systems in meeting the overall objective. MFM has a set of functions which can be used to represent control system functions.

Assume that we need to keep the lubrication flow in the pump within specified limits in order to avoid pump problems. An engineering solution to this problem could be to use a regulator measuring the oil flow and controlling the speed of the oil pump. The function of the regulator is to maintain oil flow within limits. This function can be modelled in MFM as shown in Figure 3.3 on the right.

Note that we have introduced a new objective **O3** in addition to the original objective **O2**. It is important to emphasize the fundamental difference between these two objectives. **O2** is a *process* objective specifying the value range within the lubrication flow should be kept. In contrast, **O3** is an objective specifying the *performance* required of the regulated process, such as stability margins and other control attributes specifying the desired performance of the regulator (see also Lind [135]).

It should be stressed that the “loop” formed by the maintain and the actuate relations connecting the mass flow and the control flow structures are conceptual relations of intention and causality and is therefore not a representation of the function or structure of a feedback loop. The concept of feedback is connected with signal or information flow. Control functions shown here do not describe information flow but the purpose of the control action (to regulate).

3.2.3 MFM Software and Applications

MFM has been used to represent a variety of complex dynamic processes including fossil and nuclear power generation [123, 182, 155, 154], oil refineries [89], chemical engineering [212, 189] and biochemical processes [80].

Applications of MFM include model based situation assessment and decision support for control room operators [186], hazop analysis [208], alarm design [234] and alarm filtering [126] and planning of control actions [123, 88]. It has been used for knowledge representation in AI planning for supervisory control systems [54]. A recent revision of the inference rules for cause- and consequence reasoning is provided [153].

MFM has been applied in power systems by Larsson [127] without explicit representation of control functions. Here we show that the capability of representing control is essential for capturing the functional complexity of power systems.

Application of MFM in power systems is envisioned to further intelligent agent solutions in power systems control. MFM models could support situation-awareness of agents, for example to enable reasoning about appropriate responses in fault situations [213].

MFM Workbench and Workflow MFM is supported by knowledge based tools for model building and reasoning [145].

MFM models can be drwawn graphically using a template for MS Visio. The Model concepts and relations can then be translated automatically into a file of JESS facts. In the MFM Workbench, a software based on Java and JESS, this model file can be read and employed for further applications.

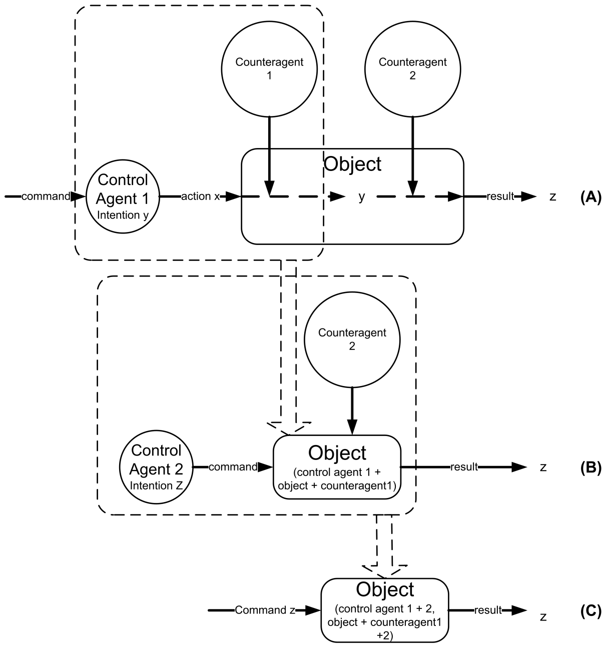

Figure 3.4: Modeling execution levels. The disturbances, or counter-agents are incrementally encapsulated by system in higher-level system compositions (B)+(C) [146].

3.2.4 Related Concepts

In the development of MFM and its applications, several related concepts were identified and other strong concepts have been developed. The *decision ladder* mentioned above, as well as two unpublished concepts, *execution levels* and *action phases*, by Lind [146, 147] have been found useful for the considerations presented in this work.

Execution Levels Execution levels enable a conceptual decomposition of a conventional control hierarchy such as e.g. a cascade, including the distinction between primary and secondary control variables. The model concepts are *system* (object) and *agent* (control- and counter-agent), and the relations are simple input-output relations [146]. In addition, there is a recursive whole-part relation that implies that any system can be composed of further such arrangements (comparable to the function concept in SADT). The concepts and encapsulation process are illustrated in Figure 3.4. In contrast to the SADT core concept, this model is designed specifically to model the control structures. As Lind discusses in the related lecture, the execution levels can also be interpreted in an 'inverse' fashion to represent levels of defense against threats.

Action phases. Action phases, illustrated in Figure 3.5, model a sequence of conditions that constitute successful execution of an action. MFM functions are formulated as (goal-related) actions, this action model provides the interpretation of several stages of possibility and realization for every function. This fine-grained, logical, decomposition enables an in-depth analysis of interdependencies of functions. Based on the identified action dependencies, for example to systematically develop a startup procedure. MFM concepts model intended structure and relations of actions in the performance stage. We distinguish therefore two perspectives on MFM concepts, a *performative* perspective, for modeling and investigating the interactions of functions in the execution-phase only, and a *modal* perspective, where the function state could also be in-active, faulted, or in some different action phase.

3.3 Chapter Conclusion

The overview of conceptual modeling applications in was presented to provide some context to MFM as a conceptual modeling methodology. It is positioned uniquely in relation to process modeling and is by far the most advanced of its

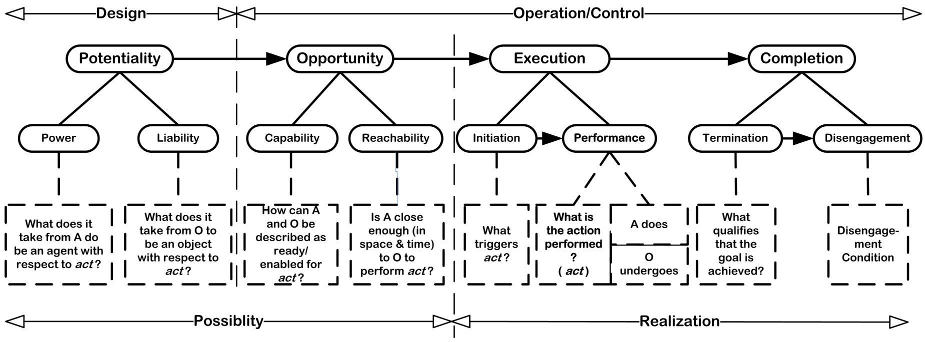

Figure 3.5: The Action Narrative [147]. The phase-descriptions have been adapted to modeling questions in relation to agent- and object-roles of the action, which are denoted as A, O and act in the graphic.

kind. However, it has not been applied to power system control before and it is, at this point, unclear whether the flow-concepts are meaningful for electric power flows – and how superficial or formal the representation should be understood.

Another motivation for creating this conceptual modeling context is its role in architectural and design thinking. Clearly, conceptual modeling has an important role in modeling requirements as well as in the development of representations in the design domain. In fact, the role of a representation as requirement model or as representation in the design domain is not defined by the representation, but by the design perspective involved. MFM can thus be viewed as an analytical tool for conceptualizing control requirements. At the same time, it becomes a means of representing, analyzing and detailing a conceptual design.

Part I

Power System Operation and Control Modeling

Chapter 4

Means-ends Representation of Power System Control

It has been motivated in Chapter 2 that control architecture should be supported by domain-specific representations, also called conceptual (domain) models. These model the main concepts of architectural solutions and allow to convey how architectural requirements are met. A specific and concise domain model for power system control should capture characteristic functions and interactions of electric power systems as well as its control.

In this chapter, we will explore the representation capability of means-ends modeling to serve as domain modelling approach for power system control architecture. Layered MFM models are proposed for:
- power system balancing and area control,
- active power flow and congestion management
- voltage control and reactive power flow.

In the process, the MFM method will be extended, in particular to serve reasoning about explicit and implicit modeling of control structure performance:
- motivation and introduction of bi-directional flow-functions,
- consistency of MFM causality with system's degrees-of-freedom,
- classification of flow-structure domains into flow- and balance-networks,
- behavioural roles to model external influences on flow-structures,
- an algorithm for the identification of control-influence capability.

Earlier version of the models presented in this chapter have been reported in the [MFM-I, MFM-II], some of the MFM extensions and the control-influence algorithm has been developed for [MFM-IV]. Further, to enable the modeling of actors and a service-oriented decomposition of control structures, a conceptual mapping between MFM models and a value-oriented modeling perspective is discussed. The underlying interpretation of the action-concept to model perspecives was presented in [MFM-III, MFM-IIIa], and application considerations with regard to agent-based control in power systems and information modeling were discussed in [MFM-APP-CP, MFM-APP-CIM].

4.1 Why means-ends modeling?

It will be helpful to share the motivation for the chosing a means-ends perspective for conceptual modeling of power system control. We shall therefore explore the motivation by seeking answer to the following questions:

1) *Why is "means-ends" modeling suitable for control?*
2) *How does means-ends functional modeling become an instrument for developing or evaluating control architecture?*
3) *How can means-ends modeling be employed in the power systems domain?*

4.1.1 Why "means-ends" and "causality" in control?

Overall goals, process- and control-objectives are achieved by performance of relevant functions. These functions are, in turn, realized by behaviour and structure of system components. This ordering holds for any machine. And it forms a direction of means-ands abstraction:

Overall goals
||
process- and control-objectives
||
control- and process-functions
||
realization (behaviour-structure)

Consider two specific control functions: *In order to* save a specific power line from overloading, a respective relay is programmed to open its circuit-breaker, *causing* a separation of the power line from the grid. Or: *In order to* keep the system frequency at 50Hz, power system frequency control alters the generators' power infeed to *cause* synchronous generators to accelerate/decelerate frequency. Any control action is described by: an *intention* to achieve a certain state of the system, a goal, is realized *by means of* manipulating one aspect to *cause* the desired state using the system's internal structure. Every control action entails concepts of means-ends and causality [141].

The interfaces for a control function modeled by an explicit means-ends representation are [143]:
- *"upward"*: the purpose it serves by formulating the goal it achieves
- *"downward"*: the (functional) means it employs to *bring about* (i.e. to cause by intentional action) [188] its purpose.
Here, the word "function" implies an ascription of purpose to an action (e.g. [190]). Functional modeling thus explicitly connects objectives (purpose) with behaviour and structure [135, 150].
From a perspective of overall goals it provides modeling context by intermediate levels of abstraction along the means-ends dimension: breaking down goals, specifying subgoals and concrete objectives which are then related to specific functions; from a perspective of physical components, MFM functions model the purpose ascribed to a component in dependence of the relevant level of detail – one component is often associated with different functions, depending on the objective considered.
Each objective is thus associated with a particular view on the physical system. The choice of an appropriate level of (means-ends) abstraction for modeling the controlled domain is thus an essential design step in developing control structures. For example, a high level of abstraction (i.e. a simple model) is often sufficient to model the aspects relevant for a specific control problem: in power system frequency control, the power balance and a single dynamic state, the system frequency, are sufficient to model the physical domain relevant for frequency control (e.g. [120]).

The decomposition of (control) objectives is based on engineering principles applied to the physics of the electro-mechanical phenomena employed. In power systems, overall goals are decomposed into a number of control objectives such as: maintaining reserve margins (secure operation), power-balance (frequency stability), optimal transmission operation (voltage stability, reactive power management), and so on.

Representations of control in terms of signal diagrams directly model causal input-output structures. They do not distinguish means and ends, and thus cannot be used to develop the control structure. Instead, such a model presupposes the choice of an abstraction level, as well as a pre-alignment of ends (as output) and means (the input-to-output causality).

As the input-ouput structure of a process is thus determined by the choice of control structures, it has been suggested that physical systems should better be modeled in a purely behavioural perspective and that interactions with a system are better understood as 'variable-sharing' [251]. This perspective also enables an object-oriented modeling of physical systems, e.g. by Bond Graphs [78, 34]. Here, the system definition does not specify a causal (input-output) structure, but instead an (equation-based) approach modeling implicit relations between variables. By specifying an input as constraint (shared variables, interconnection), input-output causality can be recovered from this 'acausal' model of the controlled domain. In particular, the Bond-Graph methodology offers a fully graphical notation for causality assignment. By tracking *degrees of freedom*, consistency and input-output causality of a model can be assessed. This feature enables formulation of physical domain-models independent from a given control configuration, which is very useful for control structure design [34, 53].

The focus on physical modeling does not support abstraction of models to different control levels, or the encapsulation of control functions. Apart from that, the development of a physical model pre-supposes the choice of relevant physical phenomena [254, 256], which is part of the control structure design. A meaningful multi-level perspective of control structures thus requires an explicit formulation of means-ends relations between control functions and the process it is controlling. For the functional process representation, the useful aspect of causality assignment should be recovered (further discussed in Section 4.3 and 4.4).

4.1.2 The utility of means-ends functional models.

Control is understood to be about assignment and achievement of objectives by means of influencing the behaviour of a (technical) system. A combined means-ends and causal representation is truly "architectural": because it is based on these two essential relations it enables a drafting of control structures with a sketching approach toward refined control structures and requirements specifications. As a design domain representation it supports the process of problem formation – in contrast to design-oriented methods that pre-suppose a given problem formulation.
Explicit formulation of means-ends relations provides a symbolic representation that defines levels of system decomposition, independent of the engineering domain or mathematical modelling approach. Moreover, the means-ends enclosure specifies whether a control system serves at a higher or lower level of decomposition. Only if the purpose of a control function is in this way specified in a system-context, the failure mode of a control function can be modeled. Information about the significance of a failure is thus embedded in the means-ends

relations.

The means-ends formulation of control patterns offers a framework to support a purely functional perspective on power system control. The framework is logical, independent of specific technology domains or mathematical representations. In this way, a stepwise abstraction from device-level to system-level representations becomes possible.
The 'fitness' of a control solution is a means-ends concept [57]. A formal model of control structures based on means-ends perspective thus provides the framework and interfaces that allow the formulation of 'fitness' requirements, such as performance requirements or reliability.

4.1.3 Practical uses of functional models.

As mentioned in Section 3.2, functional modeling in MFM has been used in particular for *model-based reasoning* applications, root-cause analysis, startup planning or fault-tree generation. All of these applications, however, so far employed MFM without explicit consideration of control functions.

MFM applications in support *control design* have also been suggested [172], and MFM models have been utilized in the generation of sequential control commands for plant start-up [123]. Description of control structures or their 'design purpose' independent of a particular implementation can be a valuable means for general automation design purposes. In this work, MFM models are primarily employed to this end: conceptual modeling and analysis of control structures for future power systems. Further applications in the power systems domain will be discussed in Section 4.6.

The information embedded in a means-ends functional model relates specific actions to their context and purpose. This type of structured, goal-related, information is relevant for any agent in a complex environment, because it establishes a norm, an expected behaviour, in which unexpected disturbances, can be related to as "deviations" [136, 186]. In this situation, the functional information reduces the apparent complexity. It can relate the deviant behaviour and provide contextual information that helps judging the severity of a given malfunction. Only from a limited list of alternatives, right actions can be chosen [190]. In this sense, it can be employed to support *situation awareness* for human operators and computer agents [139, 186].

A fourth application aspect is the understanding of functional models as a formal language to support communication and coordination. It may serve as a *means of coordination* by providing the 'background' citeREF means of coordination of a specific action one agent performs in context of a system of multi-agent interaction, providing a means of representing the "field of work" as well as relating it to process and state information. Because it specifies roles (REF MLI ANS-paper!) it also may provide a background for defining the roles which need to be filled in any particular "work arrangement" (the "what" and the "who" of coordination). Last but not least, the language properties makes it also suitable for formal *information modelling* in context of applications where control services need to be exchanged.

As with other diagrammatic models, means-ends models can be formulated in a more or less formal form. Models can be analyzed purely as formal construct, or used as a form of presentation to carry further contextual information. During model development formalization can incrementally be increased, along with model detailing. How formal the a model should be formulated depends on the modeling purpose – for example it is often acceptable, not to detail the causal relations in a model, when only the multi-level perspective and means-ends relations are concerned. More formal models are more likely to serve computer reasoning applications. Formalization of human knowledge is key to knowledge-based artificial intelligence. MFM can thus also be seen as a method of knowledge engineering, such as requirements modeling.

4.2 Models of Power System Balancing

The flow-functions available in MFM offer representations for mass-flow and energy-flow. For MFM modeling of power systems, causal roles, energy-flow functions and control functions are utilized. It is easily anticipated that some functions are not relevant in this domain and that some technology aspects cannot be explicitly represented with the given functions. The modeling in this section is therefore primarily aimed at exploring the representation capacity of MFM with respect to power systems.

Power systems require a continuous balance between power in-feed and consumption. The organization of power balancing, is therefore of major relevance for system operation.
Generation is responsible for the system balance, following demand variations, which is modeled by a high-level MFM model in Figure 4.1 by the *energy flow structure* $\mathbf{S_1}$ and its associated *goal* $\mathbf{g_1}$: The flow functions *source* (Generation) and *sink* (Demand) mark system boundaries; the energy *transport* (Delivery) indicates the nominal direction of power flow and the associated *causal roles* model thej influence of the neighbouring functions on the flow-state of the transport. The causal roles express: Demand is the *agent* causing the en-

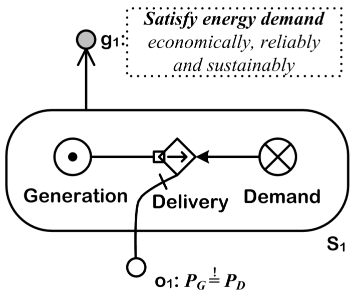

Figure 4.1: High-level view of the conventional electricity system. The diagram is a MFM model in semi-formal notation with descriptive annotations.

ergy flow, whereas Generation is a *participant* supplying demanded energy. In other words: generation follows load demand. This organization of allocating the balancing function to controllable generation will be referred to as "conventional paradigm" of power system operation. This distribution of causal roles is *enabled* by the power balancing control functions that will be analyzed below.

4.2.1 Frequency Control

Generally modeling with MFM does not require equations. In this section equations are included to illustrate a close analogy between modeling in the familiar equation-based form and MFM based modeling.

The flow-structure $\mathbf{S_1'}$ in Figure 4.2 presents a more explicit model of a power system in which the kinetic energy of the system inertia is modeled by an *energy storage*:

$$\dot{E}_{kin,sys}(f_{sys}) = P_{G,mech} - P_{D,el} \quad , \tag{4.1}$$

where the kinetic energy corresponds to the aggregate synchronous inertia in the system, and the power balance is formulated across the generated mechanical power $P_{G,mech}$ and the respective electrical net-load $P_{D,el}$ on the machines. A mismatch between energy provided to the system and the energy removed from it will result in a change of the storage-level in the kinetical energy storage, but the storage level does not (immediately) influence generation or demand[1]. This is a more 'physical' view of the electricity system as it does not reflect a controllability bias between generation and demand, which is reflected in the modified causal role of the energy source.

[1]System self-damping and other self-regulating effects can be ignored at this stage.

The main control objective for this system has been associated with the previous model (Fig. 4.1)[2]:

$$\mathbf{o_1}: \quad P_G \stackrel{!}{=} P_D \ , \tag{4.2}$$

In large power systems, this objective is decomposed into sub-objectives. The separation is based on a decomposition of the power injection P_G:

$$P_G = -K_{sys}\Delta f_{sys} + P_{disp,t} \ , \tag{4.3}$$

where $\Delta f_{sys} = f_{sys} - f_0$ is the frequency deviation, $K_{sys} = \frac{1}{R_{sys}}$ is the (imposed) system droop constant and $P_{disp,t}$ is the total power dispatch. This decomposition of the power injection together with the ubiquitous observability of the system frequency enables a decomposition to the objectives $\mathbf{o_{1a}}$ and $\mathbf{o_{1b}}$ of droop control (frequency containment) and system balancing (frequency restoration).

Droop control, or primary frequency control, is a control structure shared within the complete synchronous region of a power system, utilizing the frequency both as control reference and load-sharing mechanism. The control response is coordinated by the settings of individual generator droop constants such that a required system droop constant is achieved. The control objective is to achieve the droop characteristic:

$$\mathbf{o_{1a}}: \quad \Delta f_{sys} \stackrel{!}{=} \frac{1}{K_{sys}} \cdot (P_{disp,t} - P_D) \ , \tag{4.4}$$

From a system perspective, this objective corresponds to a proportional relation between frequency and power dispatch. The primary frequency control is represented by the *control flow structure* $\mathbf{S_2}$ shown in Figure 4.2. The control requirements are characterized both by control objective $\mathbf{o_{1a}}$ (Equation (4.4)) and the performance requirement $\mathbf{o_{1a,p}}$.

The resulting stationary frequency deviation reflects the mismatch between demand and dispatched power. The power dispatch is to be adjusted by the frequency restoration $\mathbf{S_3}$, in order to relieve the droop control. The control function thus also aims to restore a nominal level in the system's energy buffer $E_{kin,sys}(f_0)$ corresponding to returning the frequency to its nominal value:

$$\mathbf{o_{1b}}: \quad f_{sys} \stackrel{!}{=} f_0 \ , \tag{4.5}$$

This objective can be achieved in different ways:
a) by regulation, control function [m], observing the frequency deviation and actuating the power dispatch, or

[2] The notation (1) $\stackrel{!}{=}$ (2) implies an assignment intention: (1) *should match* (2).

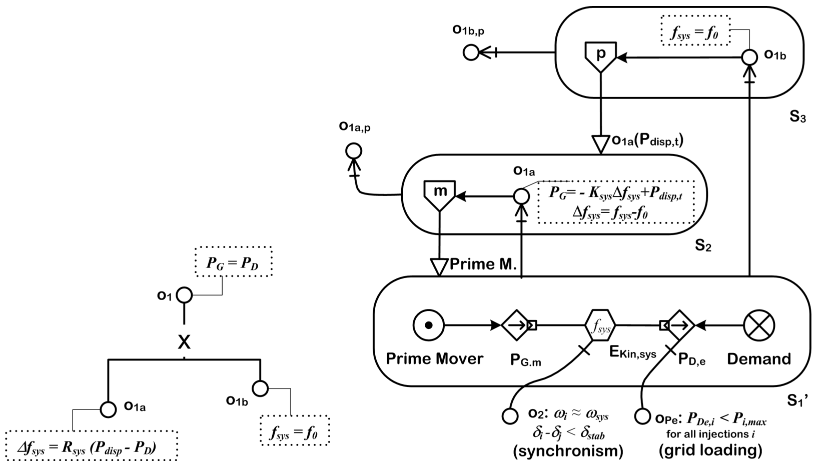

Figure 4.2: Objective decomposition and MFM model of frequency control. The synchronism of all connected generators is the condition required for this flow-structure with a single energy storage to be valid.

b) by steering, control function [p], as the steady state power imbalance can be computed from the steady state frequency (by Equation (4.4), objective $\mathbf{o_{1b}}$). Option a) is typically practiced in context of area control (also called AGC) in large scale systems (e.g. the former UCTE [230]), whereas option b) is more common in smaller systems that do not practice area control (incl. the former NORDEL [177]).

The performance objectives $\mathbf{o_{1a,p}}$ and $\mathbf{o_{1b,p}}$ specify *how* the control structures $\mathbf{S_3}$ should achieve the control objectives $\mathbf{o_{1a}}$ and $\mathbf{o_{1b}}$, respectively. This performance requirement is central to the coordination of control functions especially in large systems. If performance requirements are not considered in detail and controller tuning is not coordinated, this can be detrimental to system stability. For the former UCTE, for example, such information was specified in the Operations Handbook [230], based on the specification of a nominal contingency.

4.2.2 Area Control

The power balance is not just a technological requirement, it can also be motivated organizationally: it can be established with repect to a local area, a whole synchronous network, as well as with respect to interconnections between synchronous networks. Larger power systems are organized into control areas. Control areas are organizational constructs and their boundaries do not necessarily represent physical bottlenecks. In contrast to frequency control, there is also no physical 'distributed observability' of a mismatch between intended and actual exchange value.

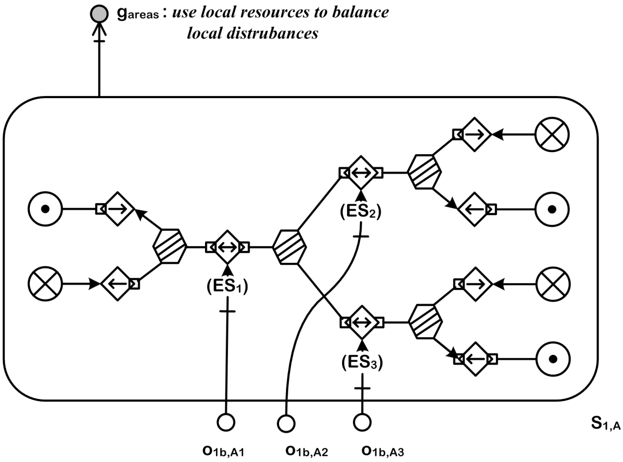

Figure 4.3: Abstract MFM model of the system balancing with three control areas, indicating causal relations. The small boxes and arrows at transport functions indicate the causes of influencing the power flow though transport.

To formulate the purpose of control areas, another high-level (abstract) model is introduced (Figure 4.3). It has been expanded from Figure 4.1 to account for the definition of the boundaries of control areas. The step-wise expansion is included in paper [MFM-II]. The organizational boundary of a control area also marks the boundary of responsibility between separate TSOs. Ideally, the flows across the boundaries of control areas are fixed to pre-scheduled levels (either import ot export flows). Therefore, objectives $\mathbf{o_{3,Ai}}$ are modeled enabling a causal agent specifying the flow through the respective transport function. At this level, disturbances from one area would not pass through the area-boundaries. The purpose of control areas is thus to balance a mismatch between scheduled demand and supply within the area such that a pre-scheduled power exchange is maintained.

Within a synchronous area, the flow across AC power lines out of and into an area, however, cannot be controlled directly. Area control realizes the desired flows by measurement of the cross-boundary flow and actuation of generation output within the area. In Figure 4.4, the frequency control functions of a synchronous network with three control areas are modeled. The shared system frequency droop control is in principle modeled as in Figure 4.2. Here it becomes more explicit that the flow-functions really model the functional composition rather than individual generation units: whereas the primary (droop) and secondary (area) control functions may be executed on the same generator, the functions associated with frequency droop controller are modeled separately. The droop control performs relative (positive and negative) adjustments which are aggregated together for the whole synchronous region and functionally separated from the area-specific control adjustments and respective operating points of generating units.

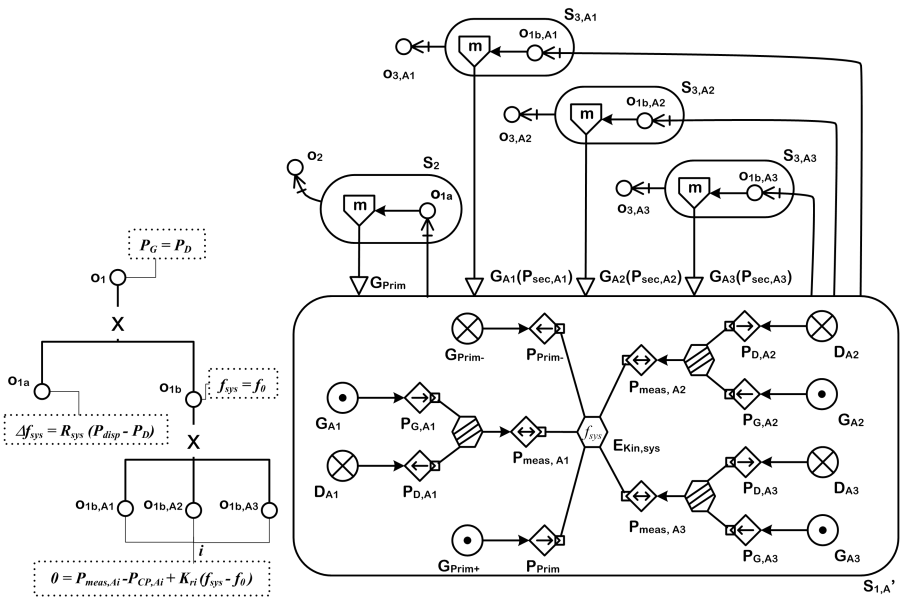

Figure 4.4: Objective hierachy, control and flow structure of the system balancing with control areas.

It can also be observed that frequency and area control, cannot be modeled as a 'cascade' (as in Fig. 4.2) any more. Instead, the droop control and area control functions aim at the two physically coupled, but organizationally separated, objectives: frequency droop (or 'containment'), and frequency restoration by area control. The representations of control function case are overlayed into the functional structure presented in Figure 4.4. Operationally they are differentiated by accounting, causal sequence (*1st* frequency change; *2nd* restoration), as well as time scales (response speed, stability concerns), which, again is a requirement formulated by the respective performance objectives.
Note that a new flow-function, the *bi-directional transport*, has been introduced inf Figures 4.3 and 4.4 to account for the inter-area exchange.

4.2.3 Bi-directional Flow Functions

Flow-functions model relevant states and intended behavioural ranges. The bi-directional transport utilized above is a sign that the set of flow-functions may have to be extended for power system modeling purposes. The current set of flow functions includes directed and undirected functions, but all flows are understood as directed. This implies the sense that a changing flow direction is automatically understood as a fault, because the functions represent *intended* behaviour. There are two reasons why bi-directional flow functions should be also considered in general and for power systems specifically:

- in systems where flows are induced from potential differences (e.g. water flows between 'communicating reservoirs', or current-flows following Kirchhoff laws), bi-directional flows *balancing* the systems toward an equilibrium condition are a normal situation. Here an abnormal (fault) situation is rather associated with extreme absolute values of flow (pos-hi; normal; neg-hi).
- in context of control functions, disturbances cause relative (positive or negative) *deviations* from a reference value (setpoint, equilibrium); also control actions compensating deviations would then be modeled as relative adjustments. An abnormal situation for an actuator could be of the sort 'saturation'.

If control functions can be modeled as in Figure 4.4, where positive and negative adjustments are modeled as separate functions from a system perspective, it should also be natural to model them in a single function that can both inject or consume power.

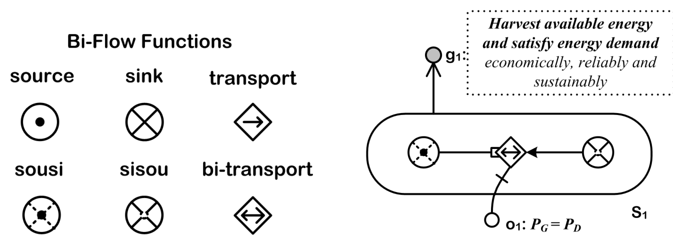

Figure 4.5: *Left*: Flow functions for bi-directional modeling in flow-structures. *Right*: Modeling example, here the difference between the source-sink on the left and the sink-source on the right is analog to Figure 4.1: the source-sink follows the sink-source.

The bi-directional arrows in Figs. 4.4 and 4.3 are symmetrical. To maintain a transparent sign convention and to keep the upstream/downstream notions

of flow-functions, a “normal positive” flow direction should be indicated. As bi-directed flow situations can be both internal (e.g. between balances or storages) or occur at the boundary of a flow-structure. A bi-directional transport function thus needs to be supplemented by corresponding system boundaries: a source-sink (sousi) and a sink-source (sisou). These functions are presented in Figure 4.5 on the left; in the following discussions, the bi-directional functions will be viewed as equivalent to their uni-directional counterparts.
The model on the right presents an example utilizing these new functions. With reference to Figure 4.1, the “conventional paradigm”, this “bi-directional” energy system can be viewed as the modern power system paradigm, where controllability and free variation are no longer tied conceptually to either generation or consumption.

4.3 Representations of the Power Grid

The power balancing functions modeled above require the simplification of lumped system inertia and it was intuitive to model this perspective in MFM. This view of the system is valid as long as synchronism between all generators' rotor angles can be maintained, the transmission system is intact and capacities of the grid are not exceeded. These issues relate to distributed system variables such as line flows, complex bus voltages and rotor angles. Control structures supporting such requirements are mostly distributed and formulated on the basis of such distributed variables as well.
This section aims to develop domain models for these control structures which require an explicit representation of the grid topology.

The distribution of complex voltages and line flows is often modeled in a structural/topological perspective of the grid in terms of a one-line diagram (OLD). Topologically, the one-line-diagram perspective can be mapped directly to MFM, with lines modeled by *transports* and busses modeled as *balances*, but care must be taken in the interpretation of the flow-variables represented. In order to support consistent modeling of causal roles, the following pages introduce a specific interpretation of flow-functions and causal roles.The interpretation can be viewed as a modeling technique for consistent flow-structures, rather than physical systems modeling.

4.3.1 Concise Flow-structure Modeling

The question whether a given MFM model is 'correct' may seem largely a matter of expert-intuition. However, experience has shown that experts tend to agree on some form of model as correct and another as not. In fact, modeling with MFM is quite formal and there are some underlying principles that are just difficult to formulate. This Section attempts to advance this formulation by way of analogy, and should therefore be taken with a grain of salt.

The Flow/Potential Analogy for MFM. In [MFM-IV], some guiding principles have been identified, which will be employed to develop further MFM models in this work. Let us review the motivation and application of these principles to the modeling of flow-structures in some more depth:

- Flow-functions can be defined as actions with respect to a common flow-object [185], which is *conserved* within a flow-structure; in the present context, this object is energy. Generally, the functions model a specific aspect of a physical phenomenon, so that assumptions about relevant and non-relevant physical phenomena are implied by the *choice of a flow-object* [254, 85].
- The *conservation-property* of flow-structures gives rise to a symmetry [23]. In analogy to the energy-oriented models of physical systems discussed in Sections 2.2.2, 2.2.3 and 4.1.1, we will view interactions between MFM flow-functions in a flow/potential perspective[3]. For states associated with flow-functions, this implies:
  - *storage*: potential (volume) – the storage accumulates the flow-object;
  - *transport*: flow – exchange of the conserved quantity is always a flow;
  - *balance*: flow or potential – balance is an intermediate; depends on causality assignment;
  - *source/sink*: flow or potential – as system boundary, the assignment of a state depends on the type of interface the modeled system has with its environment.

[3] Despite the notion of 'flow', this concept is only remotely related to the flow/effort notation in Bond-Graphs [78]: MFM has function-oriented model concepts that do not attempt to model physical behaviour. In MFM there is e.g. only one type of storage (integrator), physical flow/effort-variables are only implied, whereas causality is modeled explicitly. This reduced model complexity in MFM actually excludes the possibility of oscillating or unstable process models.

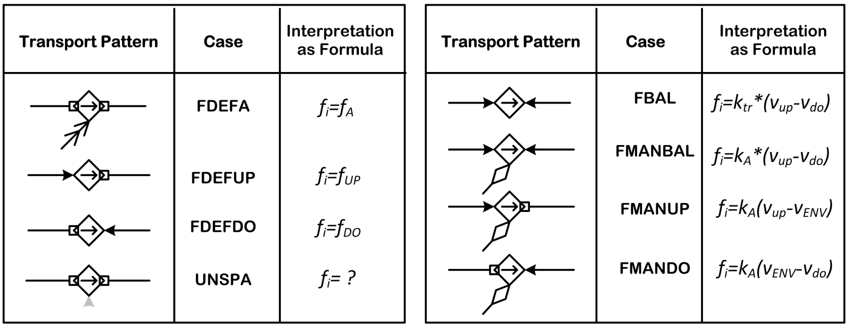

Figure 4.6: Patterns of influence on transport-flow. On the left, the flow is directly imposed (e.g. produced from other flow-functions); on the right, the flow results from a balance between neighbouring states and/or parametric influence. The "formula interpretation" suggests a simple constitutive relation corresponding to the type of influence pattern. The variables employed are: transport-state f_i, assumed neighbouring states: upstream/downstream -flows $f_{UP}/f_{DO}/f_A$, -potentials v_{up}/v_{do}). Influences originating external to the flow-structure: on the left, a determinant *producer-product* specifying f_A, and on the right a parametric *mediate*, modulating the flow-rate resulting from potential-differences. The FMANUP and FMANDO cases are modeled assuming an 'environmental' potential (e.g. atmospheric pressure), but could as well be any function $f_i = g(k_A, v_{up/do})$.

- Functions are associated with an internal 'state' and a 'constraint': the constraint connects causal and external influences to the internal state, and the internal state is the function's vehicle of influence on neighbouring functions.

A pressure gradient drives air flow, and a voltage-difference applied to a conductor induces a current. The analogy of voltage drops and waterfalls has been to developed into a consistent theory for multi-domain modeling of energy systems [107] and a graphical modeling approach, Bond Graphs [78], applies that thought also to control design [53]. In Bond Graphs, the assignment of causality is a further design step applied to an acausal model of physical interactions.
Multilevel Flow Models are not Bond graphs, but provide -in comparison- a more powerful architectural representation as they allow for multiple levels of abstraction and explicit modeling of control–process relations. MFM does not directly specify the physical variables represented by flow-functions, which is necessary to enable abstractions. Transport, balance, and storage functions aim to represent routing and storage of the flow-object. Causality-assignment then is performed from a perspective of process composition and analysis, not necessarily dependent on control-oriented input/output assignment. A methods of relating MFM functions with physical processes has been proposed by Gofuku et al. in context of a process design methodology [83, 85], utilizing Hybrid

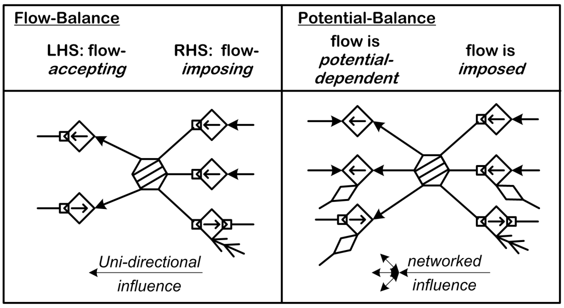

Figure 4.7: Two interpretations of Balance-function: In case of the *flow-balance*, the causality structure is that of input-output: a flow-*input* (RHS: right-hand-side) defines flow-*output* (LHS: left-hand-side). If the flow through the balance is not defined, it must be a *potential-balance*: The flow through the balance is a result of the total potential difference across the balance. To determine the flow in the respective transports, an "intermediate" potential is associated with the balance v^*_{bal}. In addition, there may be flows imposed to the balance, analog to the RHS of a flow-balance.

Phenomena Theory (HPT) [254].

The above notions of conservation and flow/potential-states (potential is often denoted as 'volume') are also aspects of standard MFM. However, as shown in the following, these notions can be interpreted to provide modeling rules for causality assignment and consistency-check of MFM models:

- *Causal roles* at a *transport* function determine the number of influences on its flow-state; in case of one influence (causal agent), it must determine the transport's flow, if more than one influence is present, the flow must result from a combination of those influences. A list of possible patterns is given in Figure 4.6. Note the case UNSPA (un-specified agent), which indicates a missing specification of agency; this situation will be discussed in Section 4.4.
- The storage-level (a potential) can, but need not, influence connected flows; storages add a degree of freedom as their 'feedback' is based on an integral of its in- and out-flows.
- From a perspective of flow-patterns, causality can be either "directed", i.e. determined by flows, or "networked", i.e. determined by potential-differences:
  - Networked causality is associated with potential-variables, such that the flow results from potential-differences; the corresponding transport-patterns are of the F*BAL variety;

  - Directed causality is associated with flow-variables and transport-patterns of the FDEF* variety, or FMANUP/FMANDO types.

- Balance functions, correspondingly, come in two varieties: Flow-balance and Potential-balance[4], which are illustrated in Figure 4.7, and further discussed in [MFM-IV]. A network of potential-balances with one or more FDEF* inputs, must either contain a storage or can be collapsed into a flow-balance.

- Sources and sinks connected to a transport of the FDEF variety, or downstream of FMANUP and upstream of FMANDO, imply the system boundary as flow-state.

- Sources and sinks connected to a F*BAL-transport, upstream of FMANUP or downstream of FMANDO represent a system boundary as potential-state.

In AC power systems, power, voltages and currents are often treated as complex variables. In relation to the established concepts, we can state already now, that the complex voltage (voltage & angle) has the character of a potential variable. Currents would be flow variables. This "physical" perspective is however only directly applicable if objectives and control mechanisms are actually also stated in these terms. By the analogy of power-flow calculations, currents could be mapped into power flows, so that power can be interpreted as the respective flow-variable if, for instance, losses are neglected.

Relation to previous work and implications for MFM modelling. The modeling perspective provided by flow-functions is not exact in the sense of the physical models presented for the analogy – but that should not be required anyway. It is common in engineering design to employ physical processes on the basis of some simplified perspective. Weak couplings may be ignored as design/modeling assumptions. The intent of functional modeling with flow-structures is to model the domain from a perspective of the objectives to be achieved. It can, however, be very useful to specifically identify the assumptions and simplifications that are employed for a process design. The close analogy between flow-functions and physical modeling is therefore not surprising.
The introduction of causal roles in [187] was partly motivated by comparison of MFM flow-structures to qualitative process theory (QPT) [73]. Hoewever, it is clear that MFM does not model 'qualitative physics', as Forbus explained QPT, and so the link to qualitive modeling of physic al processes is only indirect. As Gofuku *et al.* point out [83, 86, 87], a connection to physical phenomena it

[4] There is a close analogy with the concept of flow- and potential- junctions in bond graphs here: there is a constraint on the feasibility of connected causality patterns.

can be established by ways of HPT [254], which also allows the generation of mathematical models for numerical simulation.

In comparison to these previous formulations of causal roles, the interpretation presented here has been defined more concise and formal. Motivation for the formulation of flow- and potential properties and corresponding interaction rules (resulting in classification of causal patterns) has been found in analogy to the types of interfaces defined in the Bond Graph methodology. However, it has also been made clear that these flows and potentials cannot be interpreted immediately as those physical variables of the analogy. As argued in [23], we should acknowledge that the indetified interaction rules (if associated with the symmetry transformations of Noether's theorem), apply to a (mathematical) reference system, and that their identification with a specific "invariant structure" (what is conserved) is associated with another empirical layer. As hypothesis – suggesting further investigation – one may suggest that the symmetry and causation rules in flow-structures are fully supported by the conservation principle associated with flow-structures, and therefore domain-independent (which supports the perspective of [187]). On the contrary, the specific object of conservation is to be identified by empirical investigation on a case-by-case basis.

This more narrow interpretation of causal roles motivates an empirical modelling paradigm for MFM in which the identification of the conserved object is at the center of the modelling process. If the flow-object is not clearly identified at the beginning, a two-stage process is suggested: To first indentify intuitively required functions and function-connections. And then, by rigourously identifying the interactions/mechnisms which are actually need to be modeled by the respective flow-structure, to define the object of conservation.

A further point has been established. Networks of functions, the potential-networks, exist, within which cause and effect cannot be predicted in an discrete, rule-based way. This perspective supports Woods' argument [255], that a numerical simulation is sometimes required to compute cause and consequence (woods example was a tank with both inflow and outflow). Lifting the argument from this 'numerical' viewpoint, we conclude that a behavioural approach to the assessment and design of control structures remains a crucial part of control design.
On the other hand, it may be established that a non-physical approach to the modeling of behaviour could well be justified from the present functional modeling perspective. The mechanisms established above require, that flow-structures model relevant interactions of the flow-object in a flow-process, so that all process-relevant behaviours are either part of an MFM-model, or excluded by design-assumption. Contrary to [87], in this author's perspective, a behavioural interpretation of MFM flow-structures is feasible and provides sufficient information to frame the desired- or modeled behaviour. This sug-

gests that certain equations and parameters could be specified independent of the underlying physical phenomena. Hypothetically speaking, these equations would also enable the generation of (normative, unparameterized) mathematical models directly from flow-structures. With certainty, however, we can say that the MFM models *frame* behaviour in terms of purpose and performance. This framing will be revisited in Section 5.2.2.

4.3.2 Grid-Topology and Function

Power systems are composed of transmission elements (power lines or cables), distribution hubs (substations, incl. busses and transformers), and endpoints (power generation or consumption). One-line diagrams are a common representation of power systems connecting these central elements in a simplified structural view. This view can be mapped to a behavioural perspective by the formulation of algebraic power flow equations. It can also be mapped to functional views of the power system that account for the grid topology.

According to the above discussion, the energy flow functions of MFM can be employed to directly model a one-line view of a power grid. Bus bars and power lines, as passive components, would be modeled as balances and bi-transports, respectively. Power demand is a sink and power generation is a source. Whereas this assignment may seem intuitively sensible, the interesting question is how causal roles should be modeled with respect to active and reactive power flow.

A power flow solves both the reactive power and active power flows at the same time, but units may be required to control active power or reactive power independently. As flow-functions can only represent one causal pattern at a time, these to patterns should be modeled separately, if possible.
To identify this function-orientation, we should review the control objectives associated with distributed power system variables.

Power Flow Computation and Control Functions. In the most common analyses of AC power systems, the distributed variables of power, voltages and currents are treated as complex variables. For complex power flow calculations, four quantities are associated with each bus k: The complex voltage composed of voltage magnitude and (relative) voltage angle $V_k = V_k\angle\delta_k$ are the state variables; and the complex power $S = P + jQ$, where P and Q are active and reactive power 'injections', respectively. Two variables need to be specified for each bus and at least one reference-voltage and -angle need to be specified as a whole.

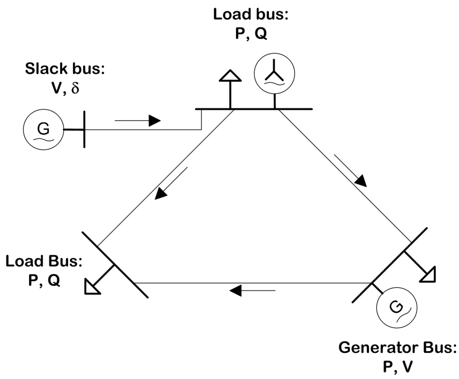

Figure 4.8: One line Diagram with load-flow specification of bus-types.

Based on the admittance model of the network $I = YV$, where Y is the complex bus-admittance matrix and I the vector of complex line currents, the power-flow problem is summarized in the following nonlinear equation:

$$P + jQ = S = V\bar{I} = V\overline{YV} \ .$$

The equation can be solved by a variety of numerical methods [81], most prominently the Newton-Raphson method. Complex voltage (Voltage & Angle) has the character of an effort variable, and current that of a flow variable. As currents can be mapped into power flows, power can be interpreted as flow-variable if, for instance, losses are neglected. The high X/R-ratio common in high-voltage transmission leads to a stronger coupling between voltage amplitude and reactive power than with active power. Correspondingly, there is a stronger coupling between active power and voltage angles. This is, for example, utilized by fast decoupled power flow methods (e.g. [120]).

As we will see now, this 'simplification' actually is a functional operation principle for power systems. Busses are classified by the combination of unknowns specified at the respective bus (P, V…"generator bus"; P, Q…"load bus"; V, δ … "slack bus"), as illustrated in Figure 4.8. The theoretically possible pairings (P, δ), (Q, δ), (Q, V) are not utilized. As a rule of thumb, causal roles model the system to indicate origin and propagation of disturbances with respect to the flow-variable. In relation to the functional purpose, the classification of bus types is interesting: The specification of fixed and free variables in the power flow calculation implies that voltage- and load-angle are functionally separate potentials, and therefore also causal structures should be assigned separately. Furthermore, the utilized pairings indicate that there is an asymmetry between the degrees of freedom assigned with control objectives: whereas the voltage angle is specified only once, in the 'slack bus', the voltage amplitude is controlled

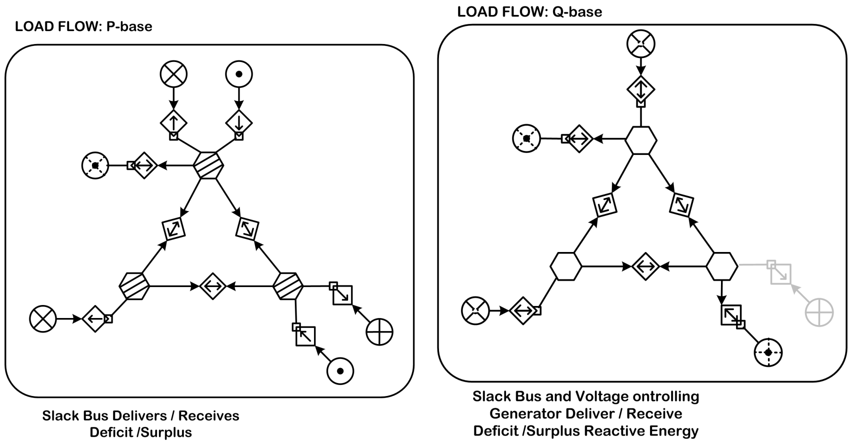

Figure 4.9: Flow-Structures representing a Active Power and Reactive Power view of the one-line diagram presented above in Fig. 4.8.

locally at several generator busses.
The following paragraphs present different topological MFM models associated with different operation objectives:

Modeling Active Power Flow. The functional model of active power flow corresponds to a behavioural system model only considering a linear power flow. A flow-structure model for active power flow corresponding to the above one-line-diagram is presented in Figure 4.9, on the left. The grid is modeled as a network of potential-balances. As in a typical power flow specification, all but one sinks and sources impose (inject) their respective power onto the system. To compensate active power mismatches there is exactly one slack-bus, and no other degrees of freedom are available in the model.
The network of potential balances corresponds to a linear vector-equation, similar to the load-flow equation of an AC electricity-network, with a potential-balance assigned to each bus. For a linearized power-flow equation, the 'intermediate potential' v^*_{bal} would correspond to the bus voltage angle variation $\Delta\theta_{bus}$.

This model perspective is equivalent to modeling the power system in terms of voltage angles, which has been suggested as a representation approach for analysing system stress across grid areas [59, 58]. This reference also provides a methodology for reducing the grid topology at area-interfaces, which directly maps to aggregation principles for balance-functions in this system view.

Modeling Voltage Control and Reactive Flows. A flow-structure model for voltage amplitude and reactive power is presented in Figure 4.9, on the right. Reactive power is interesting because it is not really power in the same sense as active power, but it is a very useful concept in power engineering. Technically speaking, it is an indicator of the reactive current contribution observed at an interface. Reactive power flow is the amplitude of that cyclic power exchange [71]. Because voltage in the AC grid is also associated with the charge level of inductance-capacitance pairs, we may speak of 'reactive energy' stored here as constituting the AC voltage magnitude. The additional degree of freedom of these storages enables a distributed voltage control. The control function *voltage control* is associated with a generator bus, specifying a potential variable. In the implicit control model here, this is modeled by an influence of the voltage-controlled storage on the associated source-sink.

Modeling Distribution Level Flows. Distribution systems are typically radial and in conventional systems, the power flow is unidirectional. Here, a much simpler causal structure can be employed on the basis of flow-balances. Reactive power is usually not considered in the distribution level.
If active and reactive power are controlled in the same fashion as in higher voltage levels, then causal roles would be the same and complex state variables would be correctly represented by MFM models. The higher relative resistance in lower-voltage levels, however, implies that the decoupling of active and reactive power cannot be performed in the same manner as above. In practice also control of voltage is not based on reactive power in low voltage grids, but based on transformer-rations. It is not clear at this time, how this situation should be modeled 'correctly' in MFM, but one may assume that the lack of decoupling capability means that causal roles should be aligned in these grids. The straightforward approach of modeling all influences, as shown in [211] (in case of distributed generation), can already yield meaningful diagnosis results in context of fault-analysis.
The main concerns in distribution system(/feeder) management are the avoidance of component overloading and the maintenance of an acceptable voltage along the complete feeder. As these issues cannot be entirely separated, it should be considered to model a mapping of complex state variables to MFM functions.

4.3.3 Dynamic Rotor Angles

The mechanism of keeping synchronism between generators on the grid results from the electro-mechanical interactions between the mechanical power balance at each individual generator and the electro-magnetic processes that form the grid. The process details are too complex to be modelled in a flow structure.

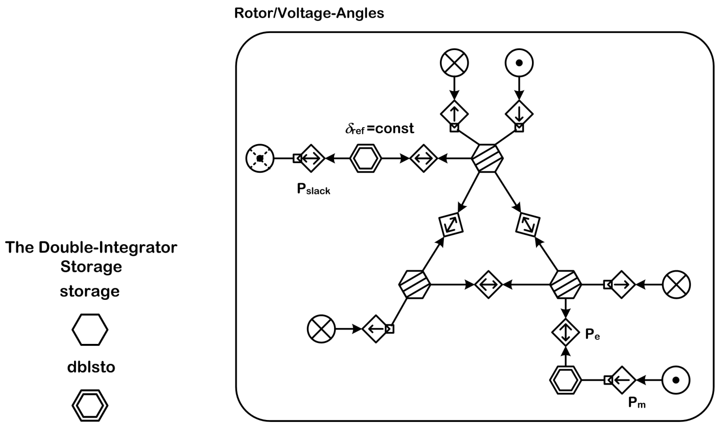

Figure 4.10: Introduction of double-integrator storage. The model example on the right shows utilization of the new function to model dynamic rotor angles and grid topology. Note that the causality assignment is 'integral' as in the case of the simple storage.

However, the mechanism is interesting and provides several modeling challenges that illustrate the achievable level of modeling precision by conceptual modeling with MFM.

The basic causal structure associated with the dynamic behaviour of the generator is an example of a specific type of causality: a double-integrator. To illustrate the situation, let us review the basic dynamic model of an unregulated synchronous machine [21]. The swing equation characterizing the dynamic behaviour of a single generator is

$$\frac{2H}{\omega_R}\frac{d^2\delta}{dt^2} = P_m - P_e \ . \tag{4.6}$$

Where H is the inertia constant, ω_R the rotor speed, and δ the machine's internal rotor angle. The mechanical power P_m is independent of the rotor angle and determined by the machine governor (associated with frequency regulation, Section 4.2). The electrical power P_e is a function of the mechanical power, the relative rotor angle (depending on the grid), rotation frequency, excitation (rotor field winding) voltage: $P_e = P_e(P_m, \Delta\delta, \dot{\delta}, \ldots)$. Equation (4.6) therefore models the mechanical swing of a rotor in response to changes in the grid as well as to internal changes such as excitation or mechanical power.

This second-order causality is typical for mechanical systems. It should not be modeled by a simple storage as the causal influence is relative to the angle. We introduce therefore a new function: the double-storage **dblsto** to model this

type of double-integrator situation.
Figure 4.10 presents the **dblsto** function and its application to a dynamic model of the one-line model presented in Figure 4.8. The synchronous machine is modeled in the lower right corner, where the mechanical input is independent of the **dblsto** state, but the electrical output is dependent. Note that the slack-bus is thought of as generator with reference angle.

In steady-state, the electrical and mechanical torque should be equal. This balance between electrical and mechanical power is maintained such that the aggregate frequency perspective applies. The load- and rotor-angles are closely associated with the power transfer capacity of the grid. If the mechanical power exceeds the power transfer capacity (maximum power injection of generator) of the grid, instability results [108].

The models presented in this section clearly illustrate the difference between modelling of structure and modelling of function, and they demonstrate also the importance of causality considerations when developing domain models. Note that the control functions have not been modeled explicitly in this section, but rather implicitly by modeling the functions and causal roles resulting from the flow. One difficulty associated with the modeling of causal roles is connected to the influences from non-flowfunction causal agents, such as actuator- and disturbance-influences on the domain. This issue will be adressed by the introduction of new roles in context of control modeling in the following section.

4.4 Modeling Control

The examples shown in Section 4.2 illustrate two important aspects of control representation in MFM: a) the clear contextual and graphical expression of control and performance objective, and b) the representation at different abstraction levels, in which the control functions are either explicit or implicit, that is, integrated in the modelled plant behaviour. This section aims at a deeper analysis of how control functions can or should be represented in MFM.

The control functions modelled in association with flow-structures throughout this work are viewed in terms of their intended performance. In this context, two alternative views of control in relation to MFM should be distinguished:

- *modal* control: control in relation to the possibility, enablement and triggering of actions, thus the constitution of an operating state [148]– this view is relevant to supervisory control, and also to the generation of control-sequences for start-up (e.g. [123]). Here, the MFM representation corresponds to a target configuration – modal control itself is not an object of representation in MFM. Disturbances in relation to this plan execution can also be considered 'faults', as they disrupt operation. MFM-based fault-diagnosis is also based on this perspective of disturbance.

- *performative* control: control functions are viewed in perspective of their goal-oriented behaviour. Control functions are modeled explicitly and the MFM model provides a framing for the control function performance. Disturbances in this view are part of plant behaviour, only degrading the *performance* of control functions.

The distinction between these different perspectives can also be explained in terms of their role in relation to the action phase model (Section 3.2.4): The 'performative' perspective of control models and adresses only the execution-phase, and is thus ignorant of the phase-model as a whole. The 'modal' perspective actually builds on the action-phase model and traverses its states.

In a control engineering perspective, we should therefore distinguish two types of disturbances: External influences representable as model-inputs and disruptions or faults modifying or invalidating the operating conditions. In the following, the former will be referred to as "disturbance"; the latter will be called "(disruptive) fault".

Representation of disturbances and controllability are essential for control structure design. As MFM reasoning has been primarily concerned with fault diagnosis, it does not yet facilitate the modeling of continuous disturbances. However, as will be shown, this facility can easily be added, along with other agent roles. Further, it will be investigated what control purposes can be represented in MFM. As the multi-level modeling capacity of MFM is one of its main features, we will investigate how MFM can support the representation of multiple control levels.

4.4.1 Functions and Action Roles

Petersen [185] elaborated the connection between the symbolic representations of functions and the semantics of action:

Definition 4.1 (Role, Function, Entity) A *function* of an *entity* E which is part of a *system* S, is specified in terms of the *role* R of E in relation to an action describing and intended state-change in S.

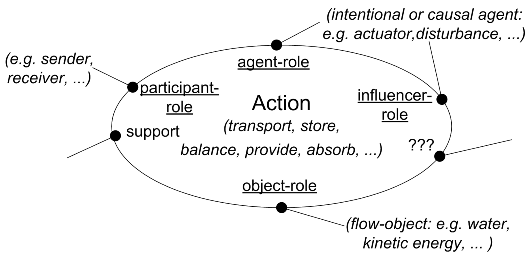

Figure 4.11: The purpose of an action with respect to a given context is its function. Action-roles define 'slots' for participation in the action. The action is performed by an *agent* on an *object*. The performance can be modified by an *influencer* and may require a passive *participant*. The underlined role-types can be modeled explictly in MFM.

Functions model interconnected actions or action-primitives. The actions can be associated with a "semantic deep structure" [185], defining roles of an action as slots that can be filled, which is illustrated in Figure 4.11.

Understanding a function as an action with a semantic deep structure implies that a number of roles can be associated with each function, such as *agent*- and *object*-roles. The object-role is particularly important for flow-functions and flow-structures, which can be viewed as interconnection of actions with respect to a common *flow-object*(which is conserved within a flow-structure[5].):

Definition 4.2 (Flow perspective [185]) The flow perspective on an action describes the state change that the object is undergoing without reference to the agent involved.

Flow-functions model actions in this flow perspective. A relation between two function-structures therefore also marks a perspective-shift, in which for example the flow-object of another structure turns into an external agent with respect to the related function [139, MFM-III].

4.4.2 Agent-Roles in Control

We have seen above, that the causal structure of a process is partly determined by control functions. When modeling control functions explicitly, however, the causal structure should reflect the controlled domain – not the domain including

[5]Note that the object may well undergo changes to some of its properties within a flow-structure. The conserved property would then be either mass or energy in various forms.

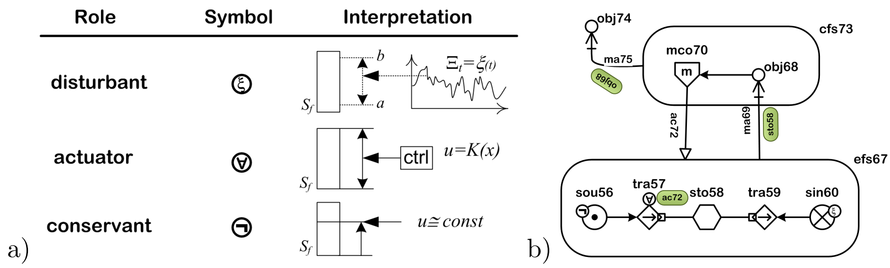

Figure 4.12: a) *External-Agent*-Roles and illustration. b) MFM model with agent-roles, based on the frequency control model in Figure 4.2 (with focus on primary control). Here, the *disturbant* models the causal influence of load variations, and the *conservant* corresponds to a setpoint for the source-potential (that could be the operating point, the boiler pressure, of a power plant). The actuator here acts as mediator, corresponding to the FMANUP case (Fig. 4.6), as it influences, but does not determine, the flow value of **tra57**.

the control performance. Actuators transform control signals into actions on a domain, and thereby cause an effect. They thus act as causal agents. We shall therefore refer to these agents as external causal agents, or simply external agents.

In closed loop control, the control system is supplied with information about deviations from the objective, which enables the rejection of influences contrary to the control objective. In an agent-perspective, a successful control agent has the ability to 'overpower' this disturbance agent by achieving the control objective within some given performance criterion – this could be called "successful encapsulation". Control design anticipates disturbance behaviour, and equips the controller with sufficient control resources and appropriate dynamics to defeat expected disturbances.
If flow-functions model actions and action roles (including causal roles) in the sense of Figure 4.11, the agent-role can also be modeled explicitly. For some functions the action performance is determined or influenced by an external causal agent, such as a control actuator. This influencer shall be represented explicitly to reflect its role in the process causal structure. Attachment of a role means that a free variable of the respective function, its state or a parametric influence, is now determined by the external agent that is represented by the role. Similar to the causal roles, the specific influence an such an agent performs depends on the overall influence pattern at the respective flow-function (as discussed in Section 4.3.1). In the context of control, we introduce three types of agent-roles: Actuator ⓥ, Disturbant ⓔ and Conservant ⊖, as shown in Figure 4.12 a). Figure 4.12 b) illustrates their application to a simple MFM example. An *actuator* ⓥ can adjust a free parameter, performing a commands it receives

from a control agent, explicitly represented by a control function/actuation relation.
A *disturbant* $\textcircled{\xi}$ represents a disturbance, i.e. a process modeled as uncontrolled and fluctuating.
The third role-entity, the *conservant* $\ominus$ ensures that the state or parameter variable is kept static, like a fixed setpoint. This role may for example represent a modeling assumption with respect to relative speed of variation, as the boiler-pressure in Figure 4.12 b), or explicitly represent a known stationary input.

Role-translations by Modeling Context. The roles model the relation between the source of influence and the present model-context: the actuator is an adjustable *control means*; the disturbance is uncertain- and *uncontrollable behaviour* in the model-context; and the conservant is *neutral*, as it does neither disturb nor help the achievement of an objective (which should not be confused with the situation of no role attachment, which presents a different causal pattern).

If the modeling context changes, for example due to consideration of a different control objective or time-scale (c.f Section 5.2.1), then the relation between influence and present model-context may change as well. For example, an active control function associated with an actuator could create a disturbance with respect to a another, then conflicting, control objective.In relation to this other control objective, the actuator could be modeled as a disturbance $\textcircled{\xi}$, because its behaviour is externally determined, likely fluctuating, and outside the control of the present control function. Thus, if an actuator is associated with a control structure other than the one in consideration, this can be understood as role-translation:

$$\text{internal} \mapsto \text{external}$$

$$\textcircled{\forall} \mapsto \textcircled{\xi}$$

where the uncertain behaviour represented by $\textcircled{\xi}$ is determined by the 'external' control objective and the disturbance it is counter-acting.

Modeling Flow-Structures with Agent Roles. A meaningful interpretation can be given for roles attached to these flow-functions: *Source*, *Sink*, *Transport*.
The agent-role changes the causal pattern of a transport function, in the sense discussed in Section 4.3.1. Here, the agent-role has the same effect as either a 'mediate' or 'producer-product' relation and the specific case is uniquely determined by the pattern of causal roles associated with the respective transport

(Figure 4.6).
As motivated in Section 4.3.1, the state of a sink or source follows from the causal pattern of the connected transport function. In context of this work, sinks and sources are interpreted as system-boundary. The character of this system-boundary (either as interface with the environment or with related flow-structures – see Janus-relation, Section 4.5)[6] thus depends on the model-context: either it is characterized by a flow or by a potential. An agent role attached to a sink or source means that the influence occurs at the system boundary (analog to variable-sharing in behavioural modeling,[251]), either by determination of flow, and therefore agnostic of the (relative) potential, or by determination of the potential, and therefore receptive for any flow.
The *Distribution* function is a specific flow-balance with an additional constraint determining the ratio beween output flows. This ratio is a free variable which may be determined by agent role-attachment. An attachment of external agent roles to *Storage*, *Balance*, *Conversion* and *Separation* does not seem meaningful as of now.

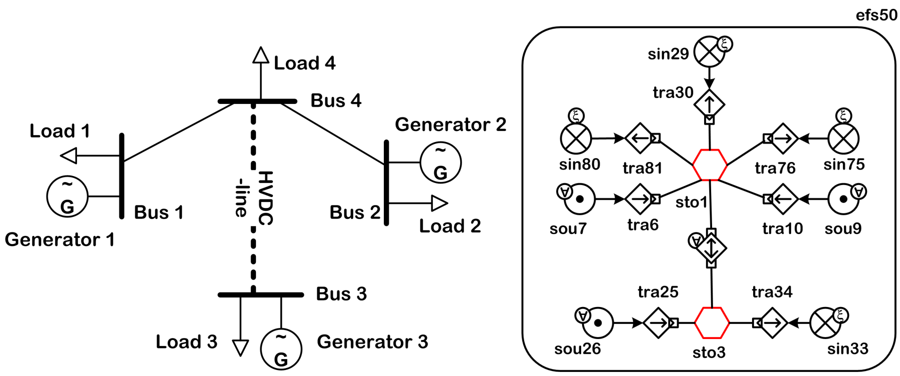

Figure 4.13: *Left*: One line diagram illustrating the example network. Note the combination of two AC networks (synchronous areas) with a DC link. *Right*: An MFM model of the power balancing problem for each area (energy storages representing the two frequencies are marked red), including fluctuating load, controllable generation, and controllable inter-area exchange (HVDC control). The allocation of controllable inputs to control functions is a control structure design problem.

Modeling Example. The case of two AC power networks interconnected by an HVDC-link is presented in Figure 4.13. Note how the influence of the different actuators are clearly modeled in terms of their causal influence. The

[6] There is a current discussion on how the status of sources and sinks should be interpreted, i.e. whether they should be attributed a state-variable. A slightly different perspective than that presented here is reported in [152].

flow across the HVDC line power can be controlled and may thus play a role in the overall control architecture[7].

4.4.3 Modeling Control Purpose

Control hierarchies often suppose a direct cascade of control levels, where the highest level control objectives correspond to plant-wide control objectives and subsystem controls operate at the command of higher level control functions (cf. Section 2.3, or [165, 106]). However, in actual control applicatons, it is often more appropriate to speak of 'layers' [223, 222]. In the following sections we aim to identify what constitutes such a layer or level, and identify a close relation between system representations and control purpose.

The agent-roles introduced above enable a control-perspective on the causality in flow-structures, which supports the selection of controlled variables; according to [222], the first three steps in control structure design (an algorithm to support this method is presented in Section 4.6). For control structure design, it is however equally important to identify, which purposes these control structures should serve in relation to the domain, corresponding to the "control configuration" (also [222]). In terms of modeling requirements, one should therefore be able to represent a) what the system 'looks like' without the control function, to specify the objective, – and b) what it should 'look like' if the control is successful in achieving this objective.

What purpose does a control function serve in context of a given system? This question is relevant for design specification of control functions, but also when the effects of a failure of a control function should be modeled. Modeling the control purpose forms the basis for understanding how control functions can either be modeled explicitly or implicitly in the formal framework of MFM. Implicit control modeling means to provide a system model of *successful control*.

Control Functions. Control utilizes available inputs, degrees of freedom and interconnections within the system to direct the system's behaviour, to *bring about* [188] the respective control purpose.

From a perspective of control design, different types of objectives lead to different design requirements. Some functions commonly referred to in the control literature include: *disturbance rejection*; *tracking control* (offering an input);

[7] This simple view also suggests that MFM can be employed in context of control design for HVDC interconnects.

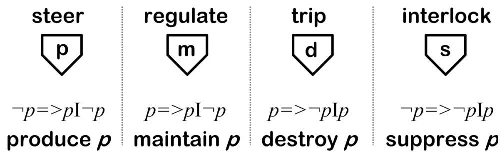

Figure 4.14: Control functions can be classified by their intended influence on the system, in relation to a considered system-state p. Read $p \Rightarrow p\mathrm{I}\neg p$ as "Given p, the result shall be p, else it would be *not* p". In the text, the control functions are denoted as $[p]$, $[m]$, $[d]$ and $[s]$, respectively.

input decoupling (offering independent inputs); *maintaining an operating point* (keeping the system state); *decentralized control* (one objective is decomposed and achieved by several controllers in parallel); *optimizing control* (toward a cost function, incl. Model predictive control); *stabilizing* an unstable system (active control, inverted pendulum); *enhancing the agility* of a stable system. (e.g. by extending the range of dynamic states by nonlinear control); or more generally *shaping the system behaviour* (to satisfy some functional requirement), and *confining the behaviour* of a system (to a stable region, to a linear domain). This list is quite long, but certainly not exhaustive. In mathematical control theory, this perspective leads to a classification of different types of control more from a point of view of the behavioural requirements and the mathematical approach to meeting these requirements.

The same control functions can be modeled in MFM, but based on a more essential classification from a perspective of control purposes: based on action theory and means-ends levels.
The *four types of control functions* introduced in [143] are classified by their intended effect on the state of a system (Figure 4.14).

The classification of control functions is based on the way a control intervention is related to an observable fact p. For example, if an operator requests a certain amount of power of a generator, e.g. in context of tertiary control, the operator command is executed as requested, but the power balance is observed independently of that command. In this case the $[p]$-function is used. The $[m]$ and $[s]$ functions are typically associated with closed-loop control, as they entail the monitoring of a given system state. In case of $[m]$, the objective is positively formulated. The control functions counteracting observed imbalances are of the *regulate* $[m]$-type. as shown in Section 4.2. The *interlock* $[s]$ corresponds for example to the function of a power system stabilizer, which is designed to locally suppress (dampen) specific oscillation modes.

The *steer* $[p]$ and *trip* $[d]$ functions are formulated positively or negatively as changes to a situation p. As the reference to the situation is formulated as transition, they are not as centrally considered in the standard frameworks of mathematical feedback control theory. However, these feedforward and batch control as well as safety oriented fault detection and avoidance techniques are important control functions. The [d]-function can be typically associated with protection equipment.

Control Objectives in Context. The purpose of a control function is closely related to its respective control objective. Therefore to the role of the control function in the system context can be characterized by the (functional) role of the control objective. Of course, an objective represents a goal with respect to a given domain model, but objectives can have a means-role as well: its achievement could *enable*, *mediate* or *produce* another function with respect to the same process. We therefore distinguish, temporarily, two types of objectives: *external objectives*, which have to be taken as a purpose in themselves; and *internal objectives*, which can immediately be related to a further purpose in the model context.

External Objectives. From a functional modeling perspective, a high-level control aims at achieving a purpose that serves some external requirement[8]. Two categories of objectives should be distinguished:

a) Objectives specified in terms of constraints on state variables, where the constraint is
   - a specific value (e.g. secondary frequency control), or
   - a relation of several variables, determining a specific behaviour (e.g. primary frequency control)

b) Objectives specified in terms of a cost function (e.g. minimize production cost).

The former type is common in conventional control systems. The latter type is often perceived as a design objective and subject to decomposition, until it can be replaced by the former type, for example by means of precomputed lookup tables [223]. Since optimizing control has become more common industrial practice, b) also became more attractive for direct implementation, however, opti-

[8]Here, external refers to all those objectives whose purpose is not (yet) related to the present model context. We will see that when expanding the model-context, previously 'external' objectives often turn 'internal'.

mizing control need not replace the simpler process-stabilizing controls[9]. In fact, optimization, is its own type of control function: it is a way of exploiting available degrees of freedom in a system.

Some *internal objectives* are identified in MFM by relations that can employ objectives on the means-side:

a) *enable*-relation: objective-achievement enables a function (e.g. oil circulation enables energy transfer in a pump)

b) *mediate* and *producer-product* relations: control-objective can be formulated to act as means-function (e.g. to produce a barrier against overflow).

c) *actuate* relation: the objective can include a degree of freedom, "offered" as new input (e.g. cascaded control systems, tracking control, decoupling control)

For a) and b), the existence of the objective itself and the relation is sufficient detail to model the control purpose. Therefore, the enabled, mediated or produced function represents a *full encapsulation* of the supporting control structure. As c) is *directed toward* the present flow-structure as a means, an encapsulation of the control purpose could here take the form of an actuator-role, attached to the objective's mainfunction (i.e. attaching the reference r to the respective output/objective value $y \overset{!}{=} r$). Parts of the former flow-structure should then also be transformed, depending on what aspect of the system has been encapsulated by the control function. What aspect is to be encapsulated follows from the influence path of the control function, and enables us to define a discrete abstraction level.

Abstraction Levels and Disturbance Encapsulation. Whether internal or external objective, it models an encapsulation of a control structure, and thus fully or partly also of a flow-structure.

This encapsulation aspect has been formalized by the concept of *execution levels* in [146]. The concept is illustrated in Figure 4.15. In a means-ends framework, control structures can be understood as fact-producers, that is, they transform a goal (intention Z) into an observable fact (result Z') – as integrated system, *Object"*, it behaves like an actuator $Z \rightarrow Z'$. It need not be however, that

[9] A theorem in [222] states that process-level controls introduces no new control limitations for the higher level control as long as (amongst other conditions) the output is available as new degree of freedom. Then, of course, the 'external' objective would be overridden by a higher-level objective in the sense of a cascade.

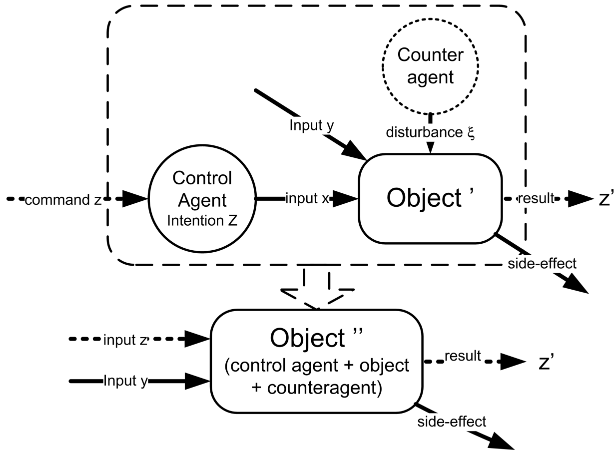

Figure 4.15: Encapsulation of disturbance by a control agent. The introduction of a control agent implicitly assumes a counter-agent originating the disturbance.

the lower-level control is directly controlled by a higher level control-loop (no z). The lower-level control-system modifies the system's behaviour in order to encapsulate some local dynamics or to modify the causal structure (e.g. for disturbance propagation or encapsulation). Consider a disturbance that is causally associated with the same mainfunction as the control objective: Successful control means that its influence on the system is mitigated and it therefore may disappear. Figure 4.15 illustrates this concept of control as disturbance encapsulation[10].

Here it is important to note the transformation of the controlled *Object'* into the, abstracted, *Object"*. Not only the control- and counter-agent disappear, but also the controlled system appears different from the uncontrolled system. For example, its behaviour and causal structure may be modified and it may have less degrees of freedom. A higher level control would be designed with respect to *Object"* under the assumption that the lower level control is successful. This pattern of control-integration may occur at several levels.

Experience with the execution-level modeling pattern of Figure 4.15 showed that multi-levelled control structure for a combined-heat-power (CHP) plant could be developed, even with very limited detail knowledge [25]. The control structure and encapsulation could also be re-organized to satisfy either of the control modes illustrated in Figure 4.16.

[10]The term "disturbance rejection" of control engineering is equivalent, but supposes a control-perspective. In a process-perspective, successful control actions render the respective disturbance irrelevant.

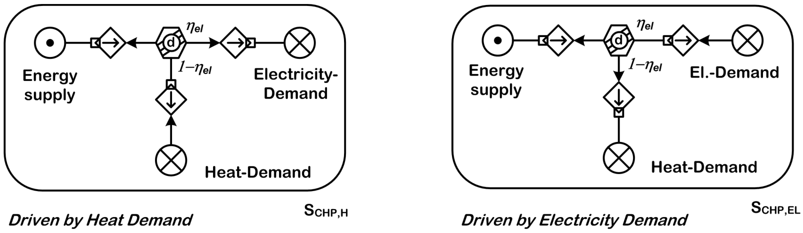

Figure 4.16: Control modes of a CHP plant.

Causal Roles for High-level Process Organization. Apart from eliminating the effect of disturbances, a control structure may specifically be designed to organize disturbance propagation; that is, to modify the causal structure of the process. Common organization patterns can be characterized as *supply-driven*, *demand-driven* or *bottleneck-driven* [140, 222].

This intended effect of the control organization can be reflected by causal roles, as demonstrated in Figure 4.16 and in Figure 4.1 high-level view of the power system. In both cases demand changes cause a modification of fuel input. In case of the CHP, it can either be following heat demand or following electricity demand.Without detailing the power plant further, these control modes are reflected by the distribution of causal roles in this abstract representation of the plant. A more detailed view of the process organization is provided by the example in Section 4.4.5.

4.4.4 Defining Abstraction Levels

Complex processes are usually composed of several levels of encapsulation. Reasoning about control levels thus requires a representation of this encapsulation. It is essential for this reasoning that causal influence is modeled at a consistent level of abstraction.

Explicit and Implicit Control. It had previously been observed that by means of model transformation, details of a process could be left out or expanded and thus allow dynamic model development and placing focus in system analysis. This process corresponds to an incremental extension or reduction of models for detailing and simplification is achieved following simple transformation rules [67]. Incremental model transformation can also be employed to develop the process representations that reflect control *implicitly*, as the intended plant behaviour, and *explicitly* by representing those functions of a system that a controller is to act upon. The model transformations have been discussed in [MFM-II].

The choice between explicit and implicit control representation, however, is not as incremental as in the transformation rules of [67]. As in the 'internal objective' example discussed above, the model is adapted in a discrete step that transforms both functions and causal patterns. We can observe the transition from explicit to implicit control ("folding") on several examples:

1. from *frequency control model* (Figure 4.2) to the high-level view of the power system (Figure 4.1, storage eliminated, causal structure determined);

2. from *rotor-angle model* (using the dblsto function, Figure 4.10) to the active power-flow model (dblsto eliminated, causal structure of source propagated, Figure 4.9; combined in Figure 4.23)

3. from *explicit voltage control* to implicit reactive power flows (cf. Figure 4.23, causal roles determined.)

4. inventory control of power plant feedwater: storage becomes flow-balance (Example, Fig. 4.18).

The list may be continued. Without generalizing further, some aspects can be concluded for explicit/implicit patterns:
- causal roles reflect the intended process organization,
- control objectives can be treated separately, unless coordinated decentralized control is considered (e.g. power system stabilizers)
- often, but not always the dynamic state is eliminated (and "replaced" by control performance assumptions)
- when the objective is stated in terms of a potential (e.g. voltage/reactive power model), the storage remains. One should also note that some abstractions listed here are actually formulated as conditional on a lower-level view of the system (here 1), whereas other formulations maintain the objective, but simply 'hide' the control structure along with the actuator and some other modifications in the causal structure (2,3,4).

Abstraction Levels in MFM. The MFM models of system balancing developed in Section 4.2 were presented with different levels of abstraction. The enabling condition of one level was provided by control functions on another level. This abstraction/detailing process is continued by the topological models of the previous section: their respective objectives are associated with the other representations by enabling conditions. This means-ends organziation does not model a cascade, but rather process layers, different views of the same system. Yet, they are organized in some form of vertical arrangement.

Summarizing our observations, we can say: control-related abstraction levels resemble modeling steps that are directly associated with modelling abstractions established in the process design, where the individual control purposes are formulated.

The following types of model-expansions are considered for expanding toward explicit control representation:

- expansion of agent-role (–> reveal cascade-pattern)
- expansion flow-function-pattern (causal roles included)
- expansion of condition-objective, and other ends-function relations.

Note that some case are analog to means-ends expansions, and other patterns are rather more detailed views of a given abstract flow-structure.
We further identify three effects present when the abstraction-level is increased:
- modified causal roles,
- reduced a degree of freedom in the system,
- disturbance encapsulation.

Here the degee of freedom offered by the controllable system variables is utilized to a) constrain the behaviour of (a subset of) dynamic states and b) to reject the disturbance observable "at a higher abstraction level". The abstraction levels thus correspond also to analog to time scales in cascaded control. However, also non-cascaded/parallel abstraction levels, as in the case of droop control and area control, require time-scale coordination to guarantee dynamic stability.

Learning from the results of this investigation we conclude with two modeling guidelines:
- be careful when modeling control systems: what is the abstraction level you are modeling at?
- it is ok to ignore control systems, as long as your model properly encapsulates their intended behaviour.

When control of power systems is described in the literature, the notion of "hierarchical control", e.g. in [219, 106], is common. It implies a necessity of central control and coordination. A model-hierarchy with different views of the same physical structure, as outlined in Figure 4.23 on page 129, seems a more accurate description of the means-ends organization of power systems, both in terms of levels and layers. This view supports the possibility of partly independent actors and definition of clear interfaces and responsibilities. The 'soft' and 'approximate' character of MFM models characterizes engineering

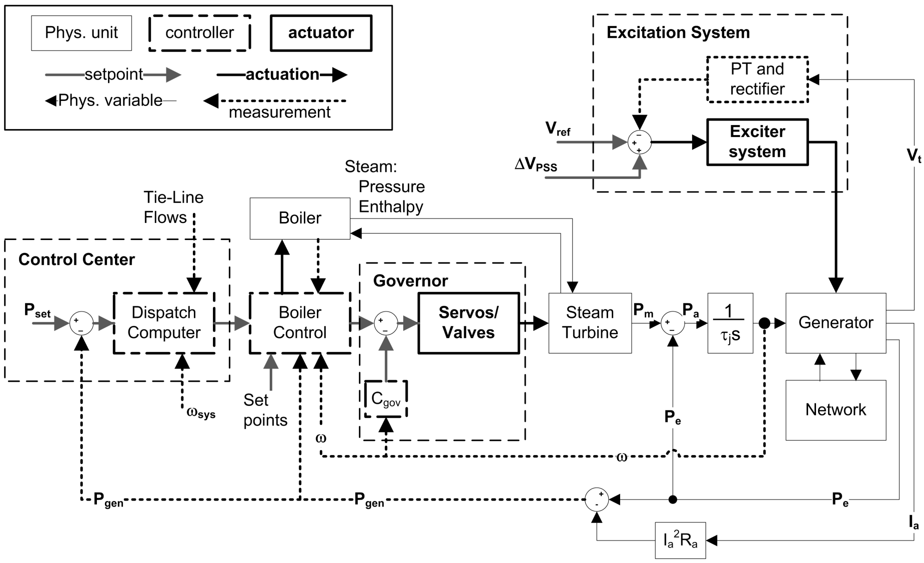

Figure 4.17: Signal-diagram view of a power plant (adapted from [21]). The diagram has been adapted to reflect qualitatively different signals and functions by different line styles. The physical units modeled here are: boiler, steam turbine and generator; and the control structures: boiler control and governor.

design intentions, both in relation to the objectives and in relation to behavioural requirements of the domain.

4.4.5 Modeling Example

In this example we model the main control loops of a thermal power plant supplying a varying electrical load in island mode. The example illustrates both the use of agent-roles and explicit/implicit control representation. The modeled process and controls are illustrated in Figures 4.17 and 4.18. The power plant model is simplified by assuming a fixed cooling- and smoke-power loss (excluding energy-recovery through the feedwater) - other than that, the model simplicity is due to the high-level perspective.

An MFM-model of the process is presented in Figure 4.18. The model comprises two flow-structures, modeling the process at the relevant abstraction level, and two control structures representing the main control objectives of the power plant: fresh-steam pressure setpoint and frequency control, which propagate the “disturbance” of varying power demand to the energy source.

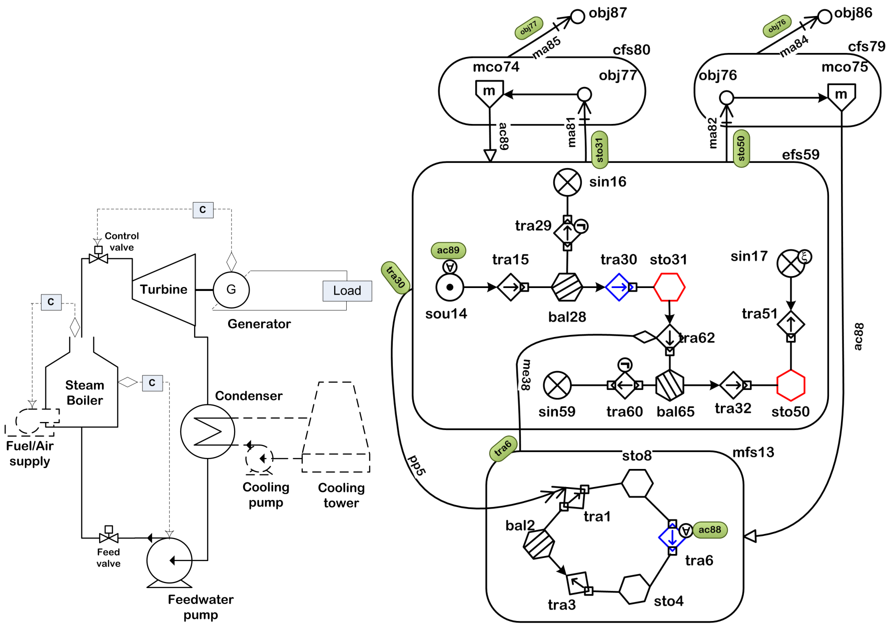

Figure 4.18: *Left:* Process diagram of the thermal power plant; for simplicity of illustration, the material flow of dashed components as well as the energy recovery in the feedwater are not modeled here. *Right:* MFM model for the main control loops of a thermal power plant. Note that the green bubble at a relations contains a reference to the associated entity.

The objective of the boiler-feedwater-pump control loop is to maintain a constant water-level (pressure) in the boiler. The evaporation rate thus implicitly determines the mass flow through the feedwater pump. In the MFM model, this control function is not modeled explicitly, to illustrate the consideration of control-"folding". The functions **bal2** and **tra3** and their causal relations, capture the effect that always as much water is pumped into the boiler as is being evaporated. The feedwater pump control is modeled implicitly as a flow-balance instead of explicit level-controlled storage and flow-actuated transport.

The lower flow-structure, **mfs13**, models the mass-flow of the main water-circulation. There are two mass-storages in the loop: **sto8** and **sto4**, representing fresh steam mass and cold-steam/condensate, respectively. Balance function **bal2** represents the balance between evaporation **tra1**, driven (**pp5**) by the heat transfer **tra30**, and feedwater flow (**tra3**), which is enabled by the underlying feedwater pump control. The controlled turbine inlet valve is actuated by **ac88** to determine the mass-flow of steam to the turbine (**tra6**). This mass-flow mediates the inflow of energy to the turbine (**tra62**), as represented by the mediate-relation **me38**.

The energy flow-structure **efs59** models heat-inflow from the combustion of fuel (**sou14**), heat-loss into exhaust gas (**tra29**, **sin16**), heat-transfer to water (**tra30**) and the steam enthalpy in **sto31**. The energy-transport to the turbine is influenced by **sto31** and **me38**, mass-flow and energy-content. Assuming a static energy-loss (**tra60**, **sin59**), a fraction of the energy-flow is transferred by the turbine (**tra32**) to the inertia of the rotating turbine-generator (**sto50**), which receives and provides energy to the load (**tra51**, **sin17**) without influence from the rotation speed.

Five external agent-roles are attached to functions in this model: *Actuators* on **sou14**determining the energy-flow, and on **tra6** determining its mass-flow; a *disturbant* determining the energy-flow into **sin17**, representing the load variation; *conservants* determining the energy-flow through **tra29** and **tra60**, representing the assumption of fixed energy-losses.

4.5 Coordination and Resource-Allocation

Power System operation depends on multiple actors with partially aligned and partially opposed interests. The coordination of inter-dependent actors is a central aspect differentiating power system control architecture from most other

complex plants[11]. Within the control system of a single power plant, or other complex plant, it is not be relevant to consider multiple actors' perspectives. Modeling for this domain thus requires the consideration of vertically as well as horizontally separated and interfacing spheres of responsibility. Since the market paradigm has been introduced to power system operation, this perspective has become all the more relevant.
As this work is aimed at developing relevant domain models for control architecture of power systems, domain models facilitating a multi-actor perspective should therefore also be considered.

This section is therefore aimed at outlining some central aspects constituting the relation between control, services and valuation processes. Interests, actors and agency are important notions in this construct and will therefore be discussed first. Here the role-concept is important, in relation to functions, but also in terms of inter-actor relations.
Actors' perspectives can be classified in relation to the means they employ and the roles they assume in interactions with other actors. An attempt to formalize this notion of perspective is presented. The resulting notion of interface will then be employed to suggest a formal perspective on control services.

Whether a service is fit for a given need is one kind of valuation problem. In a market paradigm, such service is further rewarded by monetary compensation, which constitutes another form of valuation (due to the mutual value-exchange). To model this form of valuation, a recent modeling framework for the modeling of actors and for value-exchange is suggested. Alignment of this framework with MFM will be discussed.

4.5.1 Actors, Perspectives and Agency

Requirements are first and foremost formulated in the point of view, the perspective, of the respective actor. The perspective of this actor is reflected both in the expression interests and the background knowledge (language) utilized in formulation of its position (the 'view' of a situation).

Actor- and Agent-Notions. Actors are actual or legal persons, who act according to their intentions. Actors, as well as agents have resources and

[11] An exception are holonic manufacturing systems (cf. Section) which also employ heterarchical organization structures and independent decision-making with respect to a shared process. However, as manufacturing processes are naturally sequential, there is a different modelling challenge.

responsibilities, interests and goals. They can perform actions and make choices according to their goals.

In the following discussion it is relevant to further distinguish two separate meanings of the notion “agent”. The first meaning derives from action semantics. In this context agent refers to the *performing*-role of an action - as opposed to, e.g. the object-role (ref. Fig. 4.11). The second meaning, which used for example for software-agents, refers to an entity situated in an environment that has goals and the ability to actively pursue them by interaction with that environment. Notions in MFM refer to types of roles.

An agent, in the second interpretation, is equipped with intentions (goals, objectives) and the capacity to act. For example, it can be a software-entity acting in representation of an actor, collaborating, acting and managing its resources toward fulfillment of an assigned objective. In the present context, we can therefore use the term *actor* and *intentional agent* interchangably.
This representation can be performed with respect formalized operations, both in the performance of control functions, and also by an engagement of economic exchange. In either case it is assuming the roles required toward fulfilment of its implanted goals. It is crucial to note here, that agents ultimately have limited valuation capacity: they act according to goals and rules of behaviour. For a computer agent, what is not represented does not exist.

Perspectives and Different Domains. Different perspectives are naturally associated with independent actors. When the coordination of several actors with respect to a common subject (e.g. a plan) is required, then it might be helpful to understand, formally, how their perspectives reflect different aspects of the subject.

As discussed in Section 2.1, not all requirements can directly be related to a given domain representation. For example, a one-line diagram, as a structural representation of connections and endpoints, would not include the geographic information necessary to identify whether private property or a nature reserve is affected. When electric energy from a power plant is bid into a market, the trader need not be concerned with emissions if they are not part of the market-evaluation. Such 'invisible' requirements may easily be ignored if architecture is only thought from the perspective of one given domain representation. Apart from these domain-specific notions and world-views, also actor-specific knowledge, roles and responsibilities have a share in forming an actor's the interests and thus its perspective.

Let the subject be the design of common system architecture. To achieve agree-

ment between actors, at least two negotiation steps are required:
1) agreement on some common basis for reflection (the common ground / common understanding / common language), including an understanding of the degree of freedom and a language to formulate interfaces;
2) identification of common and opposed interests and negotiation of interface requirements.

In the design of control architecture for power systems, requirements typically relate to the dynamic behaviour of entities, as well as to the modes of contracting of resources and services. In this domain even if the domain of formulating dynamic behaviour is agreed upon, perspectives may still differ as a result of different (opposed) interests (objectives).

Interest Alignment and Competition in the Electric Energy System. In a deregulated environment, energy producers (and partly also consumers), bid energy demand and supply offers in a marketplace. With interests opposed, the 'invisible hand' establishes an intersection of supply and demand, i.e. the market clearance reverses the opposed and selfish interests so that an equilibrium is achieved which is socioeconomically optimal (under certain conditions, e.g. [226]). In these situations where competing interests satisfy the assumptions that justified deregulation, selfish interest is aligned with best interest for society. However, in power systems, there is never pure competition, as all energy transactions require reliable operation of the power system. Due to this interdependency, it is so important that functional responsibility and market-related responsibility are well-aligned. Figure 4.19 illustrates the need-fulfillment (ends-means) organization of a power system where reliability is a common interest (end) of all actors, which cannot be provided on the basis of competition. System operators handle the complexities of secure power system operation and coordinate the complex functions required. If the functions required for system operation can be formulated as services ("ancillary services"), they may be contracted externally. If the service's properties satisfy the conditions for a market establishment, it can be reasonable to formulate respective markets for control resources ("ancillary service markets").

The formulation of more such markets is subject of current research and, peripherally, also subject of this work. For some concrete discussions on ancillary service formulation, see Section 6.1, for example.

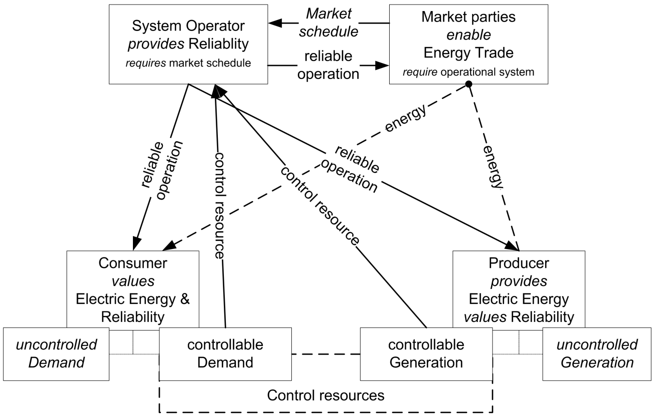

Figure 4.19: Needs (ends) and resources (means) in electric energy systems. The arrow-tips point toward the entity requiring the service specified by the arrow: Consumers value the availability of electric energy. Both consumers and producers value grid reliability - and both may offer “reliability-means” (controllable resources).

4.5.2 Formalization of Actor-Perspectives

The asserted formulation of actor-perspectives as a set (O, M) of interests O and domain-models M allows a further formalization of perspectives on the basis of our functional models. First, we present a preliminary formulation based solely on actions and action-roles in association with flow-structures, which was developed in [MFM-IIIa]. Next, we extend the MFM modeling domain by introducing a further encapsulation (whole-part relation) to the MFM models, in order provide a semi-formal notation for actor-related function-structures.

Action Perspectives. Assume an actor’s perspective can be fully represented by a mapping actor-to-function-role, either due to direct involvement of the actor as agent or indirectly due to ownership and responsibility relations. Fulfillment of functional requirements and achievement of an associated objective would fully model the interests of the respective actor. This means to formally ’lock down’ a perspective to specific roles in an action-system.

If multiple actors’ interests are thus formalized, the actors’ inter-relations are determined by their relative situation in this action-system. The semantics of MFM relations then provide a formalization of how shifts in perspective can be interpreted in context of roles and actions. For the sake of this analysis, assume that a combination of flow-structure and goal can be interpreted as a formalization of a (technical) perspective: A specific flow-structure is a domain

representation (the language e.g. mass flow functions and their causal relations), and the objective expresses an interest associated with it.
This formalization of the notion of perspective provides a classification of "shifts in perspective" that are modeled by MFM relations:

1. Object role → agent-role:: *mediate* relation
   In the mediate relation, the object of a flow-structure assumes an influencer-role at a flow function in another flow structure (e.g. water becomes heat-transport agent).

2. Action (function)→ agent-role:: *producer-product* relation
   The function(-state) at the means-side of the pp-relation becomes agent of the function at the ends-side flow-structure (e.g. energy-sink of a pumping process becomes transport agent).

3. Function&Intention1→Function&Intention2:: *Janus*-relation
   A Janus-relation means to keep the flow-context, while changing the associated flow-structure and respective intentions. The relation requires inverting state-change propositions: a sink becomes source and source becomes sink; the special character of the Janus relation is that it is a means-means relation (example in following paragraph).

4. instrument-role (of control function) → agent-role:: *actuate*
   An actuator entity that assumes the instrument role in a control function becomes an agent with respect to the flow-function the actuate relation points to.

5. intention → condition (i.e. enabler-role in act):: *enable*
   The information that describes an intention for one system becomes an enabling condition with respect to another system.

6. intention → function :: *Objective in Control structure*
   A process objective in a control structure undergoes a transition when it is considered part of a control structure: it moves from being an intention to being a function causally influencing its respective control function.

These shifts give an operational understanding of how status and role information associated with any function are mapped in an MFM model. Generalizing the result, one may say that awareness of these perspective-shifts could facilitate communication between actors/intentional agents that are inter-dependent due to their association with related functions. Full discussion of these relations and a formal notation for these perspective-shift are elaborated in [MFM-IIIa].

Different Interests – Common Domains. In order to identify which of the above relations could actually be relevant for cross-actor modeling, the actor responsibility should be visible. Power systems really are horizontally composed of interacting energy systems with a shared causal structure. To model the horizontally separate association of flow-functions with separate objectives in separate flow-structures, we introduce the "Janus-relation". The "Janus-relation" (-J-) establishes a connection between complementary functions in different flow structures. Two functions connected by a Janus-relation represent the same function-entity from different perspectives: an energy-sink is an energy source for another perspective – marking the shared system boundary.
Figure 4.20 shows a simple MFM model of energy exchange between "producer" and "consumer" over an "energy system". The three basic energy flow structures (source-transport-sink) are interconnected by the "Janus-relation", linking complementary sources and sinks.

The motivation for separating the flow-structure into three interconnected groups of functions is to emphasize the interests associated with different function-aspects of one action-system. The interests and roles associated with different actors can thus be modeled in parallel to the functional requirements. The functional requirements in the model are expressed by the shared system boundaries and associated causal roles: the satisfaction of the consumer's objective is dependent on its Janus-relation to the energy-system, and it is causally related to the energy producer by means of the electricity system. The means-ends structure of this process is fully horizontal, and also one-directional in some sense. Whereas it is the producer's operational objective to supply the demanded energy, it is its objective to gain a profit of providing this service.

The dashed line indicates three different spheres of responsibility that can be interpreted to belong to three respective actors. In addition to the flow-structures, we have also indicated the relation of these actors in a service-perspective: the energy service is provided by the producer and the energy need is on the side of the consumer. A market-process is introduced to facilitate the exchange. A market place provides support functions to ensure safety and simplicity of service contracts. We talk about "buyer" and "seller" because of the roles individual actors assumes in the market place. The economical relation of these actors can thus be modeled by three different roles with respect to the economic exchange-process.
In fact, the market-roles are defined by the market exchange process, not by the individuals taking part in this process. There seems a potential in formulating such economical relations in the same action and roles framework as the technical functions discussed so far.

From a perspective of the energy producer, the availability of a market-place is a necessary complement to satisfy its economic interest to recover the cost

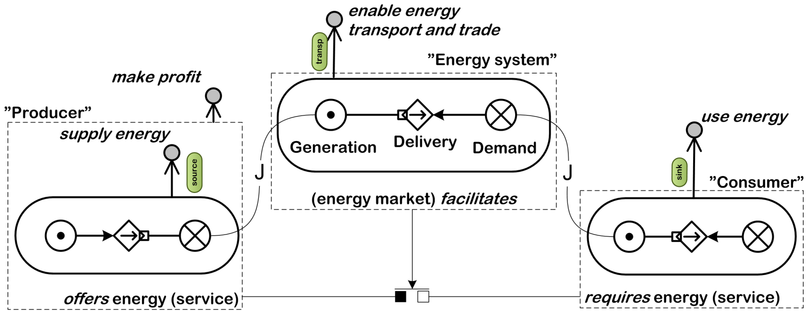

Figure 4.20: Sketch of the correspondence between MFM flow structures and market entities. The "Janus-relation" (-J-) establishes a connection between the Producer's sink and the *Generation* function, as well as between the Consumer's source and the *Demand* function. Producer and Consumer are further connected by assuming complementary roles in the respective market place.

of providing the energy-service to the consumer. Thereby, the means-ends directed flow-structure causality is complemented with an equally causal billing for energy services.
This counter-parallel between the functional (energy) connection of producer, consumer and energy system on one hand, and the their roles with respect to the market operation on the other, is illustrated in Figure 4.20. The introduction of an actor-level encapsulation of local (actor-specific) function-structures, while preserving the global interaction structure enables an analysis of cross-actor processes. At the same time, the cutset of functional relations crossing the actor-boundary defines a functional "interface" of the operational roles involved in a service-exchange.

4.5.3 Control as a Service

In the exchange of commodities, it is simple to account for the transition of ownership of a material something from one actor to another. For services, it is not quite the same. In the exchange of services the "product" is the performance of certain actions in a specified context – both the mode of delivery and performance criteria have to be agreed upon, and serve as a grounds of valuation. A service here is simply an action performed by one actor, servicing the need of another actor.

To understand valuation of control as a service, we must first recognize the two separate – and complementary – valuation processes that are required in this context. The first is valuation from a perspective of needs: Will the service satisfy the objectives I strive to achieve? This requires the ability to appraise the service, that is: to assess whether the action performed by the service-provider actually serves as a means to this actor's ends. This perspective implies appraisal, or valuation, in a means-ends perspective [57]. The understanding of functions as services modeled in a means-ends framework thus offers the interpretation of MFM as valuation framework. This perspective enables a judgement of fitness, and therefore to a measure of relative fitness to an actor's goals. The second valuation process is the process described as valuation by pricing of goods in a market-context. Here valuation is understood as the result of exchange-processes between actors, in which the compensation-value of a service is established in dependence of a larger context, on the basis of service availability (scarcity), and mutual needs of the actors.

First we define a mapping of services into the present modelling framework, using the above introduced notion of actor-responsibility. Next we interpret these service in context of control functions. The service notion then serves a discussion of the fitness valuation aspect in the MFM framework. The second valuation aspect is not central in this work, but the deep interactions between market design and the complexity of fitness requirements deserve some attention.

Service – Interface. To define service from a functional modeling perspective we employ the 'cutset' notion introduced in the previous section: the service is a *set of relations* crossing the dashed line (boundary of actor's responsibility).

The potential types of services that could be modeled in MFM are given by the MFM relations presented in Figure 4.21. A service is thus qualified by a relation, and the mutual roles are the ends of this relation. The mutual service interface is indicated by the small circle at either end of the relation. The types of interface requirements are specific to each relation, but will not be further detailed here. Note that four left-most relations, and the realize on the right, are explicitly means-ends relations. For these relations, the service roles are clearly defined from both the requirements- and the evaluation-perspectives. For the inter-flow-structure Janus-relation, the means-ends direction depends on the model-context.

To formulate the role of MFM in relation to coordination in one word: it allows the specifying the 'how' of system control: the modeling of purposeful, causally interrelated, actions. By providing a perspective of actors and services, this perspective enables us to analyze the relation between the 'who' and the 'how' of system operation, based on a decomposition of roles and functional requirements.

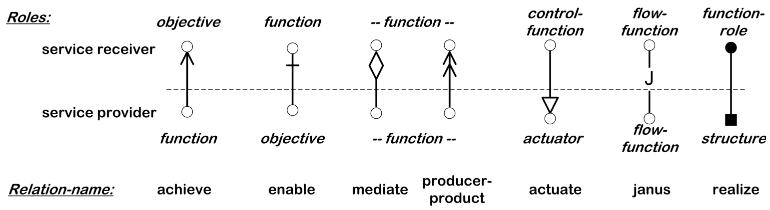

Figure 4.21: MFM relations and their interpretation as service. The mutual service interfaces are indicated by the small circles at either ends of the relations. The "achieve"-relation stands for all function/structure-to-objective relations. The "realize"-relation on the right, [150], has not been further discussed here but is also a meaningful means-ends service-relation.

This corresponds to the formulation of service agreements: buyer and seller need to agree on a definition of the service being provided. For example, "Energy" may be a well-defined unit, but its complexity comes with the specification of an energy carrier. For electricity, the functional requirements of the "exchange system" (as illustrated in Figure 4.20) are intricate: in order to establish a functioning system function that is necessary for the energy exchange, a partly cooperative approach and required; at the same time, degrees of freedom beyond these cooperation constraints can be subject to competition.

Valuation of Fitness. Valuation is a prerequisite for making choices. Valuation in the pragmatic sense is the task to find out *how fit* a given means is for a given purpose. In line with [57], the means-ends arrangement provided by MFM is the best way to model a system for valuation purposes. The means-ends interfaces identified by MFM provide a qualitative understanding of fitness. The models follow a logic of fit and misfit which is based on the definition of feasible model interfaces. Qualitatively, they define positively the requirements of a design. In relation to this positive frame of reference, an actual form, design or realization of these functions can be qualified by *how misfit* the design is in relation to the functional ideal. The goodness of fit can be viewed as absence, or degree of misfit [15].

Quantitative measures of fitness can be formulated on the basis of this framework, if clear valuation or performance criteria are established. A first, from a control perspective intuitively understood, criterion is related to the performance objective of a control structure: it qualifies the performance requirement on goal-achievement. A mathematical formulation of this requirement is discussed in Section 5.2.2.

The main pattern characterizing this ends-to means valuation is the aggregation of means toward a purpose. In a service-perspective, these functional requirements would be stated in relation to the service-interface: the set of means-ends relations that constitute one service. For example, a control service can be formulated by a set of two relations: an *actuate*- and a *janus*-relation. The service requirement from the perspective of service-need is the relation between actuation signal and response. The control-service interface requires these two relations, because it is otherwise not closed with respect to means-ends valuation: the valuation criterion must ultimately be related to an objective stating the overall requirement. The actuate and janus relations simply allow to 'cut open' the causal-chain that leads from intention to realization (an example of this service is discussed in relation to power system balancing in Section 6.1.2).

Control performance is always a means to other ends. so it requires a departure from control-internal perspective formulated in norms. This aggregation process can also be applied to other types of 'performance criteria', which can be aggregated toward overall valuation criteria. Such criteria could include: costs (as a sum of part costs), reliability (likelihood of successful performance); model precision, etc. These and potential further criteria could be evaluated on the basis of the means-ends structure provided by the functional model. Each of the criteria likely requires its own type of mapping to the process realization using different forms of mathematical models. For example, a reliability assessment would utilize a probabilistic modeling framework. Previous research, utilizing the "Energy Hub" conceptual model [79, 113, 110] suggests that such a mapping is realistic.

Economic Performance and Resource Allocation. The economic literature introduced the concept of socioeconomic welfare to evaluate the concepts of market functioning. Markets that maximize social welfare can be considered 'optimal' [226]. Central criteria for an effective market-based valuation are market liquidity and 'free competition' (the market equilibrium is not sensitive to the decissions of single actors). Whereas, it is not suggested here that MFM models support the evaluation of economic welfare, we note that the interactions between different services can be reflected such model.

In deregulated power systems, one of the central challenges for market design is that the energy delivery and the different services to be contracted for system operation are not independent. Energy and power markets, as well as ancillary service markets, can be improved by optimizing the timing and sequence of these markets [3, 203]. It can also be observed, that some power market designs do not treat services independently, but that they aggregate bids into so-called "complex bids", integrating several services into one bid [246][12]. This approach

[12]A complex bid can be 'plugged in' to a optimal power flow program to find the globally

is equivalent to a more detailed means-ends decomposition by the market maker, and, to a service-definition that would aggregate several relations into one service. This aggregation of bids enables a good technical optimization, but may limit liquidity as it requires a high level of organization on the side of bidding actors.
The trade-offs between these market concepts cannot be studied by means of MFM. However, it can provide a clear perspective on the system-decomposition and remaining interactions in different market models.

Agents, Roles and Resources. The modeling of functions as services can also be motivated by the potential use of functional modeling in coordination of service-exchange in a multi-agent based automated future power system. As suggested in [MFM-APP-CP], MFM models could be part of situation-specific "control plan", enabling the relation of control objectives to avaliable and required resources.

Effective allocation of resources, particularly in a computational context requires a) an effective coordination mechanism, facilitating exploration and matchmaking, and b) a common understanding of service descriptions, enabling the agreement on functions and interfaces. To identify the modeling need, let us look at how agents (in representation of resources) coordinate collaboration: The "Who-will-do-what?" problem statement.

One approach to modeling resource allocation in software agent coordination is the definition of roles specific to a plan. To assume a certain role, an agent has to fulfill the capabilities required for this role and it is the agent's role to bid a value (interpreted as price). This 'contract-network' [237] approach shows that an agent slips into two types of roles: when requiring services, an agent specifies the requirement and requests for bids, evaluates them and makes a choice depending on its judgment of another agents capability to perform a given role, in particular, if several agents fulfil the requirements.; the other role is that of a bidder, in which a (possibly strategic) bid is given that includes a price and a service description (e.g. suggested role and expected performance). In such a system, actors and software-agents representing them, make decisions about offering and contracting services. The means-ends and action-role oriented modeling appears to be providing clear interfaces of functional fitness for this coordination purpose.

In simple cases, roles and capabilities can be formulated ad hoc, but for the

optimal solution, satisfying all modeled constraints, including security constraints. The related Locational Marginal Pricing (LMP) concept is similar in the sense that a domain-model is part of the market clearance, however, it is a less complex optimization problem and therefore less sensitive to small changes in the bids.

sake of consistent methodology, it is desirable to have a more formal approach. A formalization of roles and capabilities can be formulated on the basis of functional models. This mechanism has been suggested in [MFM-APP-CP], where the means-ends modelling of control plans enables the valuation of fitness. The means-ends perspective of course could also be useful for organizing-forms other than the contract network, such as for example in a blackboard-architecture for control (e.g. [99, 237]).

4.5.4 Modeling Actors and Value-Exchange

Even though the present approach models all the means-ends relations, and therefore the *structure of valuation*, it does not represent the *processes of valuation*, that is the activities that lead to the choice of a specific resource allocation; it does not model the actors' interests, its material and monetary resources, and neither value-creation and -exchange. In the market paradigm, actors engage in service exchange if they can mutually see a benefit for their own objectives. The economic domain of choice, in one word, the "who" of system control, requires a different modeling perspective.

The goal orientation of actors determines their behaviour. Incentives can influence that goal-orientation, shaping the actor's behaviour and in particular, influence the allocation of resources. This aspect is relevant to consider in market environments where resource-scarcity influences prices. If a single actor can influence the availability of a certain resource in a market, it can artificially influence the pricing to maximise its returns. For example with respect to power system balancing, resource flexibility can be employed for several different purposes. Improper design of incentives and control structures then may artificially create scarcity – proper design can increase the market volume, reducing scarcity, lowering scarcity, and market power respectively (more in Section 6.1).

The association between actors, processes and resources, needs to be reflected to model this potential resource conflict or 'alignment problem'. The architecture of value-exchange processes can be modeled in the e3value modeling approach [92][13]. This modeling approach has been applied to the electricity sector for modeling value-exchange processes in distributed generation in several European research projects [95, 94, 116].

The purpose of the e3value model is the modeling and evaluation of value networks based on services. The methodology was developed with a particular

[13] The e3value graphical modeling software, a collection of related publications and project reports can be downloaded from `http://www.e3value.com/`. e^3*value* is a registered trademark.

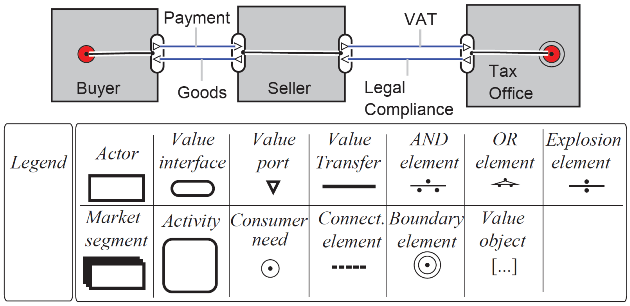

Figure 4.22: Educational e3value model, from [109].

focus on requirements engineering for e-commerce [93, 92]. It is an ontology, supported by graphical (diagrammatic) modeling concepts, which is also suited for reasoning techniques. In [92] the close relations between e3value to use case modeling are discussed. Central entities of the e3value modeling ontology are: *Actors*, *Market Segments* (multiple actors), and *Value Activities*. Value-exchange, as illustrated in Figure 4.22, is modeled between "stimulus-start" (e.g. consumer need) and "stimulus-End" as boundary element. Value Ports and Interfaces interconnect stimuli and value exchange between actors.

Value activities, are described in [92] as

> [...] *the physically and technologically distinct activities a firm performs. These are the building blocks by which a firm creates a product valuable to its buyers.*

In the perspective of Gordijn, the MFM modeling approach would be interpreted as a process model, such as IDEF0, Petri Nets or business process models, a model that describes *how* 'a process is put into operation'[14]. The value model, instead, models actors: *who* interacts with *whom*, and aims to resolve profitability, not functions. The different ways of decomposing activities are considered a core differentiation between methods. The decomposition of activities with respect to value modeling is aimed at separating profitable activities and modeling economic reciprocity in the context of service exchange.

However, as has been shown above, MFM offers very flexible ways of modeling and decomposing operational activities which are not available in other 'process models'. The decomposition of processes that can be modeled in MFM

[14]Note that MFM, of course, is not simply a process model in the sense of PetriNets or IDEF0.

can be seen as a means to conceptually decompose flow- and control processes into activities. With this decomposition, it is not just different from e3value modeling, but actually *complementary*. In particular, during the early requirements analysis phase, where e3value modeling applications have been suggested [94], also control structures and responsibilities need to be formally described. MFM is suitable for defining the actual control- and energy-related processes. Modeling control interactions, MFM models can be used to formalize processes and control interface requirements.

The so-called *e3alignment* framework, introduced in [191], integrates several such perspectives for studying organizational interactions for the purpose of evaluating organizational alignment. The interaction perspectives include a strategic, value, process and information systems perspectives [191]. However, the process modeling approach suggested in this framework, UML activity modeling is essentially a sequential modeling approach which is insufficient to model interacting physical processes and process control, as discussed above. Using this existing framework for the study of business alignment, MFM could be integrated to model and evaluate profitability and alignment of varying process- and actor-constellations. The decomposition of control functions into value activities associated with varying actors would then be formally constrained by MFM-based process requirements.

A value scenario is modeled in correspondence to an MFM example case in Section 6.1.2. Similar cases with a focus on distributed generation have been modeled in [191] or [95, 116]. For the remainder of this work, the association of processes (functions, objectives, flow-structures) with actors, if relevant, will continue to be indicated by a dashed line, as in Figure 4.20. Relations crossing a dashed line thus define interactions in the process domain, corresponding to the “value objects” exchanged.

4.6 Applications

The MFM extensions and the development of a representation for the power systems lead to a number of possible applications. Some are know and some additional have emerged. This section discusses existing and potential future applications.

4.6.1 Model Building

The models developed in this chapter are meant to present generic model cases. The goal was to establish a set of models that could serve as templates for model further concrete power system cases. Some generic modelling rules and some characteristic patterns for power systems could be identified. When a mapping from standard power system representations to these MFM patterns is identified, the model building can be automated. Further modeling rules can support human model makers, and, if formalized, could support modelling tools and reasoning applications.

Identified Domain Patterns. Patterns have a central role for harvesting design knowledge: instead of the focussing on detailed case solutions, the identification and sketching of solution-patterns guide the design thinking [17]. In this chapter we identified a number of patterns that should help us approaching more complex modeling problems. Figure 4.23 on page 129 gives an overview of the models developed in this chapter and their relation to another. When comparing the typical domain models (the one-line diagrams on the left) and the six different flow-structure models, some patterns seem obvious:

- the choice of model focus, respectively objectives, determines different characterizations of the domain components;
- there is an obvious parallel between the 'topological' MFM models and the one-line representation: distinct elements in the one-line view are often also a distinct patterns in the MFM models;
- control explicit (unfolded) and control-implicit (folded) models have overlapping model elements;
- aggregation of similar functions is a very common pattern;
- the model-hierarchy of different views, clearly highlights out some means-ends dependencies of views, but not all model transformations seem to require this hierarchical order.

The mappings can thus be identified by analogy, but they are not one-to-one mappings between structural and functional representations. To develop a new model on the basis of these templates, the model purpose and relevant objectives should be defined first, only then can the correct template be chosen.

Automatic Model Generation. Specific patterns of flow-functions are typical for a given application domain. This working hypothesis seems confirmed by the above models, and also seems applicable to other domains as for example in a recently developed model of a nuclear power plant [154]. The patterns allow the specification of partial MFM models (MFM patterns) as modular templates that represent standard components of the modeling domain. In power systems, such patterns can be identified for example in one-line diagrams or, correspondingly, in standard load-flow specifications. These domain-specifications then can be compiled into complete MFM models.

The basic procedure for automatic model generation is domain independent:

1. Define model purpose: What aspect of the system needs to be represented? (e.g. what is a 'fault'? active power flow? or reactive power and voltage?).
2. Define domain-specific patterns: Mapping from a given domain data-model to MFM patterns. MFM patterns need to be consistent, i.e. functions and causal roles should match the domain patterns also at interfaces. If causal roles change from case to case, consider additional, or larger, patterns.
3. Automatic model translation: Implement conversion of source file to MFM entities (formulated as Jess facts).

This idea has been taken up in a student-project, implemented, and proven for a 300-bus IEEE reference case [38].

Model Adaptation. A more advanced form of automatic model generation and modification could be based on transformation rules introduced in [67]. Using these rules, MFM models could be automatically adapted, detailed or simplified (aggregated), to a changing model focus.
On the basis of the abstraction levels with respect control developed in Section 4.4, additional rules for such model expansions could be defined for control-related model adaptation. However, automatic model adaptation remains a subject of future research. It could prove useful for automatic or computer-aided modeling and as support-function to other reasoning applications.

4.6.2 Utilization of Representations for Reasoning

Multilevel flow models are very well suited for several types of model based reasoning, as has been explained in Chapter 3. These applications all utilize the

causal- and means-ends relations of MFM to generate explanation- or planning-type of information. MFM models several types of relevant dependencies, which are used in different ways for reasoning purposes:
- explicit causal structure, expressed by causal roles;
- whole-part relations;
- normative model of flow directions;
- several types of means-ends relations.

These concepts have evolved over time and have been founded on firm logical principles. A system described by in this framework is very accessible to formal reasoning methodologies.

Diagnosis. The currently most developed application of MFM is fault diagnosis, and it has been shown in related work that -in principle- MFM-based diagnosis could be applied to power system use-cases [211].
For multi-level flow-structures, the diagnosis system is proven technology and with the systematic modeling approach developed in this work, consistent results can be expected also in the power system domain. A potential application could be in configuration management and restoration for the substation level and distribution systems.
The current workbench does not support diagnostic reasoning for control functions. The definition of control abstractions, as discussed in Section 4.4 should allow the development of new diagnosis rules on the basis of explicit and implicit control representations.

Planning MFM has been employed for planning of start-up processes [124, 55] , concerned with the establishment of functions; it has also been used in combination with numerical methods for counter-action planning as operator-support [90]. It has also been employed for planning purposes in relation to substation control and restoration [121]. Let us roughly outline the relevance of MFM-based information representation in such hypothetical planning system. Several methods can be combined utilizing common MFM, and MFM-related domain representations. MFM would serve as a configuration model, which could be adaptable to configuration changes. The role-oriented modeling of function-structure relations [148] would be important for the identification of meaningful or required plan adaptations. For planning in a dynamic environment, it is further desirable that plans are both made available as a result of prior planning or knowledge acquisition, say in a plan library, and that plans can be adapted and chosen in a given situation. With reference to the previous section on MFM as framework for valuation, one may conclude that a MFM-based representation could be a practical means of storing relational information of a plan, enabling plan-evaluation. For both method development and plan representation, the Action Phases (cf. Chapter 3) will provide a reference model for the decomposition of start-up phases.

As a central means of coordination in the automatic planning-system, a *control plan* suggested in [214, MFM-APP-CP], should then include:

- one or several *MFM models* specifying related control configurations
- a set of *function-structure* relations
- *pre-conditions* and *post-conditions*: statements specifying the situation before and after plan execution
- a *control sequence* specifying the control actions constituting the plan-execution

The need for the latter two parts of the plan is obvious, it corresponds to the plans developed in [124, 55] or the plans formulated in the Procedural Reasoning System (PRS) [257]. In contrast, the control plan envisioned here would have different levels of specification: from mere template to fully executable. The former parts of the plan enable coordination, plan development and ranking by the varied planning and valuation modules. As a unit, this control-plan maps well as information-vehicle into the generic practical reasoning framework proposed by Bratman et al. [32], and as information-model it should be suited for a distributed reasoning architecture.

In application to the recent standard on substation automation, IEC 61850 [1], the agent-based resource-allocation principles formulated in [214, MFM-APP-CP] have been further investigated by Saleem *et al.* [209]. There may be an opportunity for future applications by interpreting the structures, roles and functions defined in the standard in the sense of means-ends modeling to support automatic model generation and reasoning applications.

Control Structure Design. The introduction of agent-roles (Section 4.4.2) models the presence of external influences in flow-structures. The objective of control structure assignment is to associate control inputs and measurements with control objectives, and thereby configure the system to the desired encapsulation structure (Section 4.4.3).
A given external influence – disturbance or controlled actuation – may or may not influence a system objective, which is associated with the state of a certain function. Based on the flow-patterns introduced in Section 4.3.1, a reasoning application has been developed that analyzes whether a given system objective

can be influenced –mediated though the flow-model– by external agents. The causal-reasoning system aims at generating an influence-path from assigned external agent roles to an objective, that is, to the function associated with this objective's *mainfunction(s)*.

In context of the work on [MFM-IV], a system of production rules has been implemented in the MFM Workbench in the rule-based language *Jess*. The reasoning process can be divided into the following general steps:

1. *Analyze causal patterns* in all flow-structures of the MFM model: First transports are analyzed and categorized (according to the table in Figure 4.6), then the state-variables are assigned accordingly to sinks and sources; finally the patterns for flow-/potential balances are identified on the basis of foregoing analysis.
2. *Initiate*: Which control objective is to be traced?
   The control objective becomes root of the *influence-tree*.
3. *Generate influence-tree* for the selected control-objective. Propagation-rules utilizing the previously identified patterns, generate a tree-structure which notes all possible influences on the objective from the model. Potential loop structures can be accounted for at this stage.
4. *Trace causal paths* in influence tree: To generate a causal path from the available agent-roles to the objective, all tree-leafs including agent-roles are traced back to the root.

The result of this analysis is *a)* an influence-tree that contains a reference to all entities that whose state influences the fulfillment of the objective and *b)* a direct path of influence for each external-agent role with influence on the state of the mainfunction (*causal path*).
In comparison to the reasoning system for fault-diagnosis, the present influence-path only models one level of causal influence, and does not account for source-faults (missing energy) as the MFM root-cause analysis does. This conceptual difference is, again, grounded in the focus on modeling *action-performance* in this work. A further contrast is that the structure of the reasoning process is quite different due to the layered classification procedure.

As demonstrated in [MFM-IV], this information is relevant for control design and it is analog to the concept of input-output controllability. Moreover, the influence tree generated for the input-output mapping provides necessary structural information for the generation of an un-parameterized mathematical model (e.g. a transfer function or state-space model) for a given MFM model with objectives and the respective agent-roles. This information could be used for qualitatively predicting dynamical properties of the respective control configuration. In the sense of execution levels (cf. Section 4.4.3), the mitigation of a disturbance requires that a control agent can employ an actuator with sufficient resources to mitigate the influence of the disturbance with respect to the objective function. This behavioural and quantitative aspect is a subject of controller design.

This reasoning function may be employed in support of future MFM applications including: integrated process and control design; or online reconfiguration of power system control structures, such as multi-microgrids.

4.6.3 Information Modeling

Information modeling is a highly relevant challenge for information and communication technology (ICT), in particular with respect to the interoperability challenge (e.g. standardization of communication procedures and service descriptions). Information models are described by means of common modeling standards such as UML to establish a domain ontology (e.g. also MFM entities can be modeled UML entities).

In the power system domain, a very important development is the CIM, the Common Information Model for Power Systems [48]. It models components and interconnections on a technical level as well as services on an organizational level.
A case study on functional modeling and the CIM was performed in [MFM-APP-CIM]. It was found that entities on the organizational level are modeled with functional perspective, but that the current CIM has a weakness in bridging from the electric device-oriented modeling of the transmission structure to the more control oriented services. This weakness is partly due to the object-oriented modeling paradigm: from a technical point of view it inspires types of classifications based on common devices and a semi-structural hierarchy – functions are then subordinated to the device-level instead of the opposite. This makes it difficult to harmonize service specifications. This weakness could be overcome by introducing an intermediate layer for modeling control services in a function-oriented manner. Along the lines of [150], it is also recommendable to introduce explicit function-structure relations. Further, the teleology (goal orientation) of control functions and services is underrepresented. This aspect may be integrated in the semantics of the function-oriented layer, utilizing the concepts introduced in [148].

Also the IEC 61850 standard [1] defines information models, using the concepts of logical devices and logical nodes to model the information-aspects of control

functions of actual devices, and to map these to related communicatio-services. For substation-related equipment, this object-oriented, hierarchical classification of functions appears to be sufficient. As we have seen in the multiple modeling levels developed in this chapter, this purely hierarchical, component-oriented, partioning cannot be meaningful an overall system-level to model, for example, control services, which should in principle be implementation-independent.
As suggested in [235], the CIM is requires further extensions in particular with respect to automation. The organization of these extensions could be supported by a functional modeling perspective, possibly by introducing similar concepts as developed in this chapter. Infromation models that describe control services on a system level, certainly require a perspective that recognizes the need for a functional decomposition of control services, in addition to the present structural decomposition.
Whether MFM concepts are directly relevant for this modeling remains questionable: requirements for information concpets *within* automation systems differ from concepts *about* automation systems. As long as the latter type of information, the MFM-type of information, is not utilized industrial practice, it will hardly be relevant for the CIM ontology.

4.7 Chapter Conclusion

This chapter explored and extended the representation capacity of the multilevel flow modeling approach with respect to the new application domain of power systems.

In reflection about MFM modeling, it can be concluded that energy flow structures and in particular the causal roles proved to be valuable and versatile representations. Some in other domains commonly found multi-level patterns, however, are not present. There seems no use for mass-flow modeling which in other processes (for example in chemical engineering and power plants) are interleaved with energy flow structures.
AC power-systems are essentially electromechanical systems with strong and weak, mostly bi-directional interactions amongst electrical and mechanical variables. A multilevel structure is here established by means of control, isolating some and strengthening other interactions.
The models developed show that several levels can be modeled meaningfully by energy flow structures with careful attention to causal roles, control functions and the specific model purpose (what 'kind' of energy/interaction mechanism is considered?). The levels are formulated as different abstractions of the same process topology. Level-separation and interconnection is a formulated as dependencies: successful control on one level enables the conception of a flow-

structure at another level. The dependency is dynamic. Objectives can be met approximately, and such deviation from the “ideal” value is reflected in an inaccuracy of the functional representation at another level. Performance objectives associated with control functions express what deviation is “acceptable”.

To summarize contributions of this chapter:
- basic power system control cascades can be modeled in MFM symbols;
- the original modeling language was extended
- objectives and performance objectives can be specified and are meaningful w.r.t. the application domain;
- the newly introduced agent roles enable flexible approach to model the domain for control applications;
- abstraction levels map to disturbance encapsulation and execution levels;
- MFM has been formulated as a framework for the valuation of services;
- an important linkage to another modeling domain for valuation has been identified.

Further, the value of known applications of MFM models for power systems has been established and future applications have been identified.

In summa, a wide range of control aspects have been covered, and the means-ends and causality perspectives have been identified as vital for domain. What has been achieved is a strong foundation for conceptual modeling of control structures and for the particularly relevant challenge of multi-actor control in power systems. However, at this point it is unclear, how these models can support system architects in facing the challenges of designing for future power system operation.

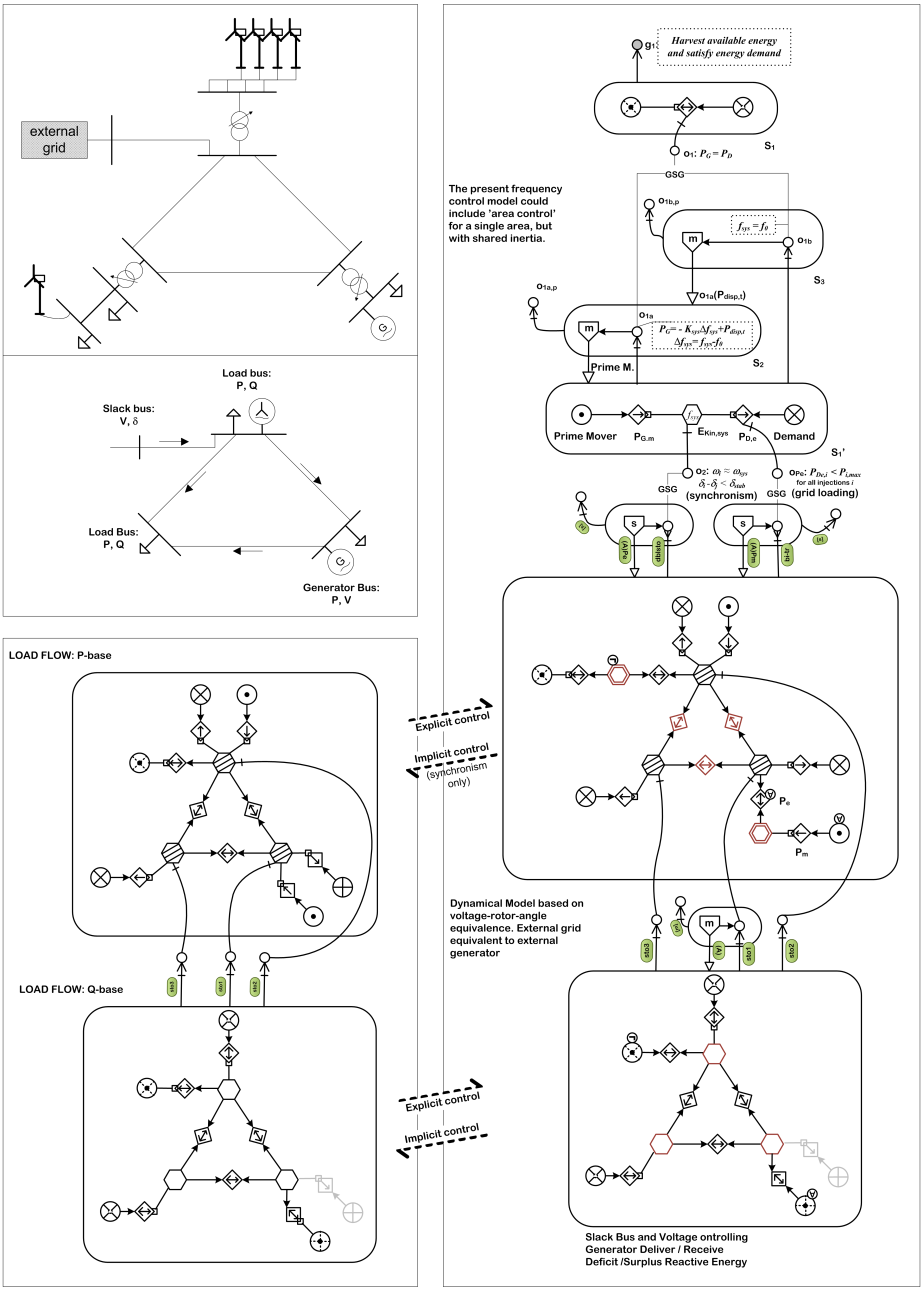

Figure 4.23: Overview and interconnection of the power system models. The upper left box illustrates a simple power grid using two common representation forms. The lower left box presents the active and reactive power models from Section 4.3.2. The right column displays a complete model hierarchy including 'dynamic' (explicit control) models.

Chapter 5

Operation-Planning and Supervisory Control

So far the modeling focus has been on exploring, interpreting and extending the representation capacity of Multilevel Flow Modeling with respect to the power system control structures. The models introduced so far describe control structures, but the fluctuations and uncertainty that will challenge system operation have not yet been reflected. What are the challenges for continuous power system operation and operation-planning? And how can these challenges be mapped to the relevant operation-functions?

Increasing (wind power) fluctuations affect in particular the need for flexible resources [39]. The mapping here, is a mapping of fluctuations to a control function at a given time scale. Uncertainty is associated with planning and scheduling of controllable resources. A formal representation of these concepts in the present conceptual framework would enable us to map the scheduling and planning challenges into the control structures, and thus enable a joint consideration of all these relevant and interdependent control challenges in a design problem.
From a control-room perspective, increased uncertainty and fluctuations make system supervision more challenging. Continuously changing grid situations require increased operator awareness of control needs and control options. Further uncertainty and complexity in system operation lead to a demand for appropri-

ate support functions to maintain safety and transparency for system operators [244].

First, a compact overview of central aspects of power system operation, planning and procurement is presented. Then we introduce a behavioural perspective on agent-roles, providing a mathematical formalization of fluctuation and deviations with respect to time-scales, control performance and planning stages. The application of this formalization to balancing ancillary services is discussed. Then the perspective is shifted to the requirements on the *practice* of system operation, as supervisory control.

5.1 Operation and Planning

The basic requirements of power system operation are the establishment and maintenance of a continuous power balance, as well as safe and reliable operation of the transmission, balancing and distribution of electricity. Power system operation and planning includes many time scales and several planning stages. The planning activities are required to establish an operating point for the system and to procure resources for the real-time operation. In operation-time, the system balance and other control requirements are maintained and supervised by operators and countless automatic control functions. Time-scales are an important criterion for distinction of control functions in real-time. Operation planning and market activities are better categorized in terms of the timing, or lead-time, with respect to real-time operation. The relations between the operation and planning functions in relation to both timing and time-scales is illustrated in Figure 5.1. A central theme is that secure real-time operation requires that all resource-allocation has to conclude before resources are activated. Further, operation-planning also anticipates disturbance situations and prepares suggestions for useful interventions (analog to the 'control plans' introduced above).

In the following, the relevant operation and planning functions are explained. This purpose of this section is to give a compact overview of these functions, conveying a sense of relative timing, performance criteria, and modeling needs.

Real-time Operation. In *real-time*, the power system's operation is aimed at maintaining a secure operating state. Operators supervise the system behaviour, supported by software visualizing the system state, offering decision support and providing access to controllable resources. Real-time operation is supported as

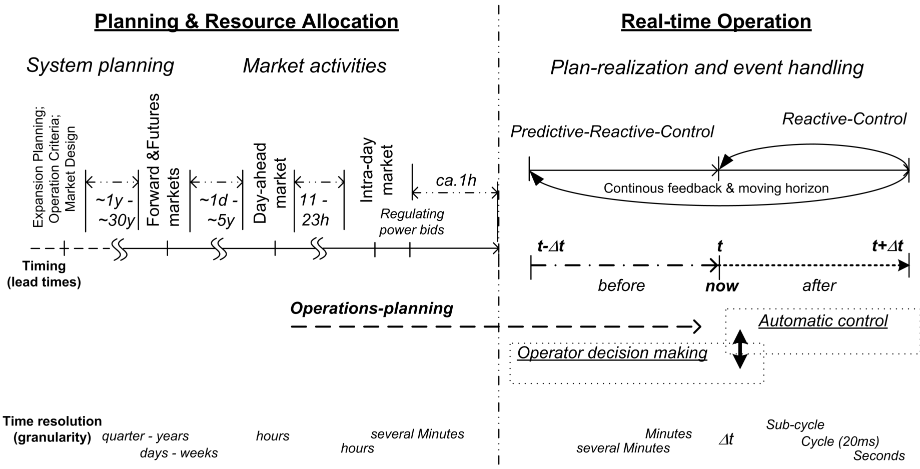

Figure 5.1: Overview of planning and operation functions: relative timing and time resolution. The market timing was inspired by the Nordic markets, however, the distribution of planning and operation functions on time scales is quite generic. Significant differences appear in the ancillary service markets [204, 24].

well by automatic control systems, which help stabilizing the system's dynamics and coping with consequences of disturbances.

Power systems are dynamical systems, engineered with a bounded 'acceptable' operating range for physical system parameters, and desirable equilibrium conditions. Operating conditions are unacceptable if they either threaten to destroy equipment or to interrupt system service. Extreme excursion of these parameters could harm the power system apparatus or threaten the power system's stability (its capacity to return to a stable operating domain after being subjected to disturbances).External disturbances causing such excursions cannot be entirely avoided (for example a tree touching a power line, causing a short circuit). Such faults have to be isolated quickly to avoid further damage to equipment: *Protection* systems identify the fault location and react quickly and disruptively to mitigate the imminent threat (e.g. within one cycle $\leq$ 20ms). The effective boundaries of operation are thus given by the settings of protection system and the stability boundaries of control systems.

Secure operation aims at minimizing the risk that any imminent disturbance (contingency) would threaten the overall operating state [119]. A common operation principle is the definition of an 'N-1' operation requirement. This requirement states that for any single contingency, the boundaries of acceptable operation will not be violated (the 'N-1'-criterion[1]). This criterion sounds

[1] It is contested whether 'N-1' is a sufficient criterion for security. Often, a selected number

relatively simple, but it requires a computationally expensive assessment. A complete assessment of all conceived contingencies cannot be carried out in real-time. Instead, a number of indices have been established that indicate the vicinity of the systems state to particular operation boundaries.

Preparing Secure Operation. As the operating equilibrium for power systems is continuously changing, the preparation and establishment of a secure operating state is an important planning task. Based on scheduling plans submitted by generators, as well as expected load and non-dispatchable generation, a system operator can plan a secure operating equilibrium. The static equilibrium, power flows in lines and operating voltages in the transmission system are computed. By simulation, via Optimal Power Flow (OPF) calculations, it is checked whether the state is 'N-1 secure', or decided which rescheduling-actions will render it secure.

In addition to the operating equilibrium, but as part of preparing a secure operating state, operating resources need to be to be made available for activation in real-time. These resources are referred to as ancillary services. The *procurement* of these ancillary services, may be performed by special bilateral contracts or through open markets. Their complexity and tight coupling with the physical system and its operation structure make ancillary service markets a complex design problem [203, 3]. In the larger scheme, the operation structure, timing and practice determine the amount and resources required and which ones would be available. Operation resources that have to be reserved for longer time-spans to be available for regulation purposes are naturally more expensive than resources that are offered whenever they become available. For example in system-balancing, operators can aim at prioritizing the use of the cheapest available resources as opposed to relying on reserves also for predictable variations[2].

The above pre-operation tasks comprise *operation-planning*, facilitating and establishing operation conditions and sufficient resources for secure real-time operation. The time horizons for these routine activities are coordinated with the energy markets, typically separated into intra-day (until shortly before real-time) and day-ahead. If maintenance and energy availability from natural resources (e.g. Hydro reservoirs) are also taken into account, this time horizon may extend up to one season ahead of the respective operation time.

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of combined contingencies is tested in addition ('N-2'). Also the boundaries of its assessment in an interconnected system are critical. Academically, probabilistic approaches have been suggested [245], however, it remains a very operational criterion and is most commonly applied in practice.

[2] This difference can be obeserved between the operation practice in several continental European countries as opposed to the practice in the Nordic system operation [24].

Coordinated Resource Allocation: Power Markets. Another aspect of planning is the commitment and dispatch of power generation. In vertically integrated power system environments, optimal dispatch of power generation could be performed centrally, including also the cost of transmission losses. *Unit commitment* and *dispatch* are two entangled but often separated problems: Commitment defines the time spans for which a unit should be online whereas the operating points of online units are decided in the dispatch.

In today's market based environment [226, 24], the power generation schedules are an outcome of energy markets where plant owners bid their generation capacity with respective prices. Whereas, in principle, this change should only imply a change to the mode of allocation of energy resources, also the unit commitment and dispatch principles and decision criteria have been adapted. The timing of markets determines the timing of planning functions, and the separation of grid operation and power generation has changed the optimization criteria (e.g. grid losses are no longer included in the optimization).

By the principles of competition the energy prices were expected to be reduced. These principles also meant that future generation capacity needs would be anticipated by the "intelligence of markets". Here it is important to acknowledge that electricity markets did not 'emerge' naturally, rather they are 'designed' by institutions. There are several different market designs, and not all designs perform as intended [51, 19].

Organizationally, energy markets introduce a higher complexity to the coordination of power systems; also the independence of resource allocation (dispatch of generation) and operation is not entirely a given. Experience and modelling of real-time-markets (markets with a very short time between final market schedule and actual operation) has shown that interactions between pricing-behaviour and the dynamics of generating plants are plausible [18].

Power System Reliability and Operating Reserves. Formulated as a question, the criterion of reliability is: How likely will a given operation setup succeed in providing the service it is intended to provide? Power system reliability is formulated in terms of the probability, with which the service of an intact power system is provided [119].

In a vertically organized, conventional power system, reliability is provided to customers. The requirement can be formulated from a customer perspective, e.g. in terms of the maximum hours without electricity per year. Customer service may be interrupted locally, due to outages on a distribution level, or as a consequence of contingent situations at a transmission level, caused by congestion or major imbalances causing emergency load shedding. For bulk power systems it remains common practice to define such a level of reliability as standard requirement. In principle, it would also be possible to define a costs of unreliability, and correspondingly to trade off outage-costs with costs of reliability provision. Reliability is also required horizontally, e.g. as reliability of partners: In a coordinated multi-area system, a reliability requirement is evaluated as the probability with which a subsystem will satisfy its commitment to balance internal disturbances[3].

As a performance criterion for power systems, reliability requirements affect several aspects of system operation and planning. As performance measure of continuous operation, the reliability-requirement is associated with *power system security.* For this purpose, reliability methods model the factors that cause disruption and imbalances as well as the system operation practice. System reliability modeling therefore also depends on statistical information about the disruption causes and the likelihood of failure of apparatus, which have to be accumulated based on statistical evidence [26]. The definition of *operating reserve* requirements for control structures are then derived from a reliability requirement. Reliability is also a measure used for long-term planning of power systems, then termed *system adequacy.* Systemic and long-term aspects of reliability are associated with the design and built of the power system, providing a ground for policy and investment decisions.

5.2 Models for Control and Operation Planning

Control resources and fluctuations are associated with specific time scales; uncertainty scales with planning stage and horizon, due to the dependence of forecasts on the lead-time. Both fluctuations and uncertainty, and controllability are also a function of the granulation of resources, the finer the granulation, the more flexible and robust are control resources, and the wider the distribution of fluctuating resources, the more likely is a cancellation of uncorrellated fluctuations.

A resource which may seem heavily fluctuating in one time scale, may appear fairly constant in another time scale. Accordingly, the agent roles which model the characteristic behaviour of a resource with respect to a function-perspective, may be interpreted differently at different time scales. As the functional organi-

[3] This is the case for area-control (secondary frequency control) in the continental European synchronous network. Failure to balance a local mismatch in production and consumption by secondary reserves will not lead to outage, but to a frequency deviation, reflecting the balancing contribution from other areas.

zation of a system can be arranged differently at different time scales of operation (take for example the primary and secondary controls), a mapping between those fluctuations and appropriate objectives and control resources also requires a notion of time-scales in the modeling paradigm. It should thus be appropriate to associate different functional models with separate time scales. In addition to the classification by time scales, we recognize that the certainty about a resource's expected behaviour changes over time and thus the planning-process is also employed to re-allocate behaviours to different functions.

From an energy resource perspective, behavioural characterisitics can be qualified by different time scales. Fluctuating and partly predictable resources, or dispatchable but inflexible resources play different roles depending on the time scales considered as well as on the stage of a planning process. However, the distinction between fluctuation and uncertainty is "artificial": it requires the definition of a reference frame. Due to the context of power and energy markets which employ a fixed time-frame, a discretization of times-scales on the basis of fixed time-slots is suggested.
This logical framework serves the coordination in a planning process, because it provides a qualitative discrimination between resources and their potential function.

5.2.1 Time Scales and Fluctuation

When modeling control functions with respect to a process, the time scale associated with the model determines whether a process is considered fluctuating or constant, whether a faster process is considered dynamic or quasi-static. These time scales are also reflected in modeling control functions with MFM and the agent-roles introduced in Section 4.4.2. In power systems, slower time scales are coordinated by means of discrete schedules. The agent roles also characterize certain types of behaviour in relation to the flow-structure.

Focusing on these behavioural aspects, we introduce a mathematical formalization that enables us to define the notions of time-scale, fluctuation and deviation with respect to a process.

Mathematical Formulation of Roles. As expressed in Section 4.4, we can assume a mapping from a functional model to a behavioural model. In this model, each function is associated with a state $s \in S_f$ and causal- or external agent roles influence or determine that state. The agent-roles characterize the behaviour of an external process with respect to the modelling assumptions.

A functional/behavioural interpretation of the roles is illustrated in Figure 4.12: The disturbant ξ can be described as a stochastic process $\Xi_t = \xi(t) \in S_f \subset \mathbb{R}$ in continuous time t. Whereas the possible range of its state S_f is quantified by its associated function f, an active range $S_{\xi,p} = [a; b] \subset S_f$ can be qualified with a limited certainty $p = P(a \leq \xi \leq b) = \int_a^b P(\xi) d\xi$, where $P(x)$ is its probability density function. This general description can be adapted to more specific ones for a given process.
The control range $S_{\forall} \subseteq S_f$ of an actuator $\forall$ is typically programmable and often corresponds to the technical range of the respective controlled variable, $u \in S_f \subset \mathbb{R}$. Further parameters could characterize its dynamic range or ramping limitations.
The conservant $\neg$ indicates the assumption of a stationary value $u_s \in S_f$. This could correspond to a setpoint of a controller, a fixed value of an adjustable parameter, or a stationary process (which may be dynamic in a slower time-scale), for example.

Role-Translations by Time Scale. In time-scale decoupling, a conservant $\neg$ also corresponds to a seemingly constant value of a dynamic variable at a slower time-scale:

$$\text{In Fast Time Scale } \mapsto \text{In Slower Time Scale}$$

$$\neg \mapsto \forall$$

$$\neg \mapsto \xi$$

As the interpretation of "fixed" and "dynamic" provided by the roles is understood in relative terms, the notation may be employed to model behaviour in continuous time, discrete time-steps and multiple time-scales in relation to one another.

Discretization. There is a variety of ways in which a continuous-time signal may be discretized and how the discrete time signals can be related to their continuous-time counterparts. Interpolation theory and lifting techniques have been applied to this problem in the past and shall only be mentioned for the inclined reader [46].

For the practical purpose of this work, we consider only one type of discretization that is "energy preserving". For a given step-size $\Delta t^{(k)} > 0$, and the respective discretization steps $t_{k+1} = t_k + \Delta t^{(k)}$ with $k \in \mathbb{N}$, let $\tau_k = [t_k; t_{k+1}] \subset \mathbb{R}_+$. A

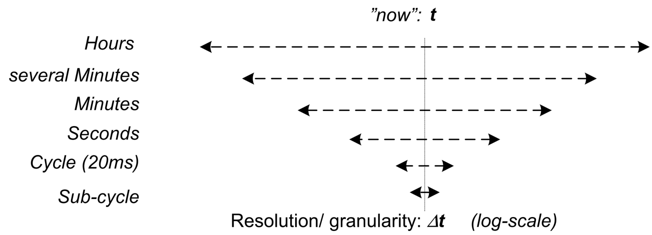

Figure 5.2: Time Scales in Power System Control.

given signal $\xi(t)$ is then discretized as its mean value over τ_k:

$$\xi_k = \bar{\xi}(\tau_k) = \frac{1}{\Delta t^{(k)}} \int_{t_k}^{t_{k+1}} \xi(t)dt \ . \tag{5.1}$$

Discretizations with different step-lengths are common in power systems, such as the different sampling times of controllers or market-oriented program time units (PTU). Let $\Delta t^{(k)} < \Delta t^{(l)} < \Delta t^{(m)}$ denote the interval-lengths of a multi-rate discretization with corresponding time steps denoted as t_k, t_l and t_m, respectively[4].

Schedules. In a time scale larger than that of a respective model context, the constant value of a conservant $\ominus$ may be interpreted as piecewise constant process, constant for each time step $\Delta t^{(k)}$, called a schedule. A schedule is a vector tuple

$$\mathcal{S} \in \mathbb{R}^{N_s \times 2}, \text{ with } \mathcal{S}(k) = S_k = [\tau_k, s_k])$$

denoting power values for each time slice, characterized by a time step $\Delta t^{(k)}$ and a number of steps N_s. In a market-context a time-slice τ_k is referred to as Program Time Unit (PTU).

Fluctuation vs. Deviation. Fluctuating and uncertain processes are modeled by the role ξ. To characterize the process with respect to control objectives and schedules at a given time scale, we distinguish between *fluctuation* and *schedule-deviation*.
Power fluctuations are deviations of the real-time power value from some mean

[4] For example, interval lengths of 30 sec., 15 min., and 1 h would correspond to a discretization classifying secondary control, regulating power and market schedule, respectively.

value. Here, we define the *fluctuation* $\delta_l \xi_k$ as the deviation of a shorter time-scale signal from the mean given by a longer time-scale:

$$\delta_l \xi_k = \xi_k - \xi_l = \bar{\xi}(\tau_k) - \bar{\xi}(\tau_l) \text{ for all } \tau_k \subset \tau_l \ .$$

For continuous time fluctuations we may analogously define $\delta_k \xi(t) = \xi(t) - \bar{\xi}(\tau_k)$ for all $t \in \tau_k$.

Here we define a *schedule-deviation* as a deviation of the mean of an actual process from a scheduled value in the same time-scale:

$$\bar{\xi}(\tau_k) - s_k \quad .$$

In market-terms this (integral) schedule deviation is referred to as imbalance. Note that *schedule deviation* and the *fluctuation* are complementary notions in modeling process behaviour with respect to plans and control objectives.
During operation, the deviation can be modeled by computing a rolling average with a window-size of the respective time-scale $\Delta t^{(k)}$, which will match the actual deviation whenever $t = t_k$. Tracking control for the rolling average can eliminate schedule deviations, but may introduce additional fluctuations.

5.2.2 Control Structure Performance

Performance is first and foremost defined by the choice of evaluation criteria. In mathematical control theory, norms are employed to measure the distance between desired and actual system state.

The design of control structure determines the mapping between disturbances, performance criteria and the required control efforts.
The control effort can be formulated as a valuation of the activations of an actuator $J(\textcircled{\triangledown}) \geq 0$. For a given overall disturbance behaviour and performance requirement, a "good" control structure minimizes these activation costs, avoiding unnecessary activations. The activations of an actuator $\textcircled{\triangledown}$ depend on the controller that actuates it and on the disturbance $\textcircled{\xi}$ it is counteracting. A controller is designed to fulfill a given performance requirement, and the control objective determines which disturbances are to be counteracted.
Thus, implicitly, performance requirements and control objective are the fundamental design criteria.

Performance Measure and Requirement. The performance of control systems can be specified and examined by a variety of criteria [223]. In general the specification of a performance requirement depends on a performance measure, which is a function

$$J_P(\Sigma, \textcircled{\triangledown}, \textcircled{\xi}, \textcircled{\neg}, r) \geq 0 \quad ,$$

where Σ denotes the system (here: function model) and r the control reference. In the given framing of balancing services, there is no dynamic reference tracking. Thus a static reference setup ($r \cong \textcircled{\neg}$) is considered and the focus is on the 'disturbance rejection' performance, removing all $\textcircled{\neg}$ offsets.

For the present purpose, we define a general *performance measure* as

$$J_P = \|h(\Sigma, \textcircled{\triangledown}, \textcircled{\xi})\|_p \tag{5.2}$$

with $h \in L^p(\tau_k, t)$, $1 \leq p \leq \infty$, with h being the system output (deviation from objective), such that $J_P = 0$ implies perfect control[5]. In case of static active power balancing this corresponds to $J_P = \|\textcircled{\triangledown} + \textcircled{\xi}\|_p$.

Based on this measure, a *performance requirement* can be stated for example as $J_P < k$. A more general formulation of performance includes a dynamic weighting of the output: $J_P = \|h * w\|_p < k$, where $*$ is the convolution operation which corresponds to multiplication in the frequency domain.

Typically, power constraints imply a performance measure $\|h(\cdot)\|_\infty$ and energy-schedule imbalance is evaluated by a measure $\|h(\cdot)\|_1$.

Aggregation of Stochastic Processes. For any two signals (functions of time) f and g in $L^p(\tau_k, t)$ (i.e. finitely integrable over the considered time-span) the triangle inequality

$$\|f + g\|_p \leq \|f\|_p + \|g\|_p \tag{5.3}$$

holds for all $1 \leq p \leq \infty$. Equality holds for $f = \lambda g$ (linear dependency).

Assume that for any two disturbances

$$\|\textcircled{\xi}_1\|_p < \|\textcircled{\xi}_2\|_p \text{ holds } \|h(\cdot, \textcircled{\xi}_1)\|_p < \|h(\cdot, \textcircled{\xi}_2)\|_p \ .$$

[5] $L^p(S, \mu)$ is the vector space of all measurable functions that satisfy $\|f\|_p := \left(\int_S |f|^p d\mu\right)^{1/p} < \infty$. This condition is satisfied for all practically possible behaviours, where S is characterized by a time-slice.

This assumption certainly holds for the present power-balancing cases. Then it follows from (5.3) that any aggregation of disturbants $[\textcircled{\xi}_1 + \textcircled{\xi}_2]$ is beneficial to the performance measure.

5.2.3 Planning, Prediction, Procurement

Scheduling and prediction facilitate coordinated planning for the establishment of the system operating points (schedules), and the allocation of control ranges (reserves) to balance fluctuations and schedule-deviations. This planning process, coordinated through power markets, is the central resource allocation mechanism for power systems. The means of hedging uncertainty in a fluctuating process is to forecast its behaviour. In general, at any point in time, given the present state of a system, models of a process can provide information about possible and likely futures.

Resource allocation means to map between available and required resources. Resources, here viewed in the functional sense, are energy sources or sinks, characterized by control ranges, setpoints (schedules). Requirements are, complementarily, characterized by forecasts (schedules) and residual uncertainty (fluctuation and deviation). The mapping of functions to physical resources, that is, components performing those functions, is a further mapping, which is only implicitly relevant here. These mappings are many-to-many mappings. Any function can be performed by a number of components, and one component may actually perform several functions at a time. Also the mapping between functional resources and requirements discussed here goes beyond one-to-one mappings. These types of mapping are categorized in the following.

Forecasting and Uncertainty. A simple forecast is a schedule $\mathcal{S}_{t_\mathrm{pre}}$, characterized by the prediction time stamp t_pre and prediction uncertainty. The prediction error $X_{k,t_\mathrm{pre}} = \bar{\xi}(\tau_k) - s_k^\mathrm{pre}$ is the deviation of the actual process from the forecasted power schedule. It can be modelled as a vector-valued stochastic variable $\mathbf{X}_{t_\mathrm{pre}} \in \mathbb{R}^{N_s}$ denoting a separate error variable for each timestep.
Assuming a Gaussian behaviour of the forecast error, that is $\mathbf{X}_{t_\mathrm{pre}}$ independent and identically distributed (i.i.d.) as $N(0, \underline{\underline{\sigma}}^2)$, denoting a normal distribution with zero mean (no systematic error), and (co-)variance matrix

$$\underline{\underline{\sigma}} =< \sigma_{ij} >= \begin{cases} \sigma(t_k - t_\mathrm{pre}) & \text{for } i = j; \\ \sigma_{i,j} \geq 0 & \text{for others.} \end{cases}$$

Here, variance can be described as an increasing function of the forecasting time[6]: $\sigma(t_k - t_{\mathrm{pre}}) < \sigma(t_{k+1} - t_{\mathrm{pre}})$. In case of wind power, the covariances cannot be ignored either, as the wind speed develops in macroscopic timescales.

The generation of a wind power forecast often entails the generation of several (n_s) 'scenarios' (forecast ensemble) as a set of schedules $\mathcal{S}_{t_{\mathrm{pre},i}}$ with $i = 1 \ldots n_s$. From this set of scenarios, the forecast may be computed as a mean. However, the optimal dispatch with respect to an uncertain process should not be based deterministically on the mean or median value of the scenario, but rather should the dispatch be computed on the basis of individual scenarios, which then each have a likelihood based on the scenario input [63, 195, 248].

Timing for Planning Coordination. Planning stages are characterized by lead times with which resources are allocated. Such lead times are, for example, motivated by resource-related minimum activation times related to internal planning and startup procedures. More importantly, centrally and decentrally coordinated resource-allocation, for example on energy markets, requires the definition of a common framework for the timing of decisions. The synchronism of decision making is essential for effective coordination.

Figure 5.3 presents different timing frameworks for coordination of planning procedures. The differences between the three processes are the relative proportions of decision-, implementation- and lead times. It can be noted that the timing and sequence of such planning frameworks with respect to energy and ancillary service markets influence the availability of resources from a market point of view [3].

Planning stages are indirectly also associated with time scales, or here better: time-resolution, which characterizes the level of detail in a time-perspective. A very long-term plan usually need not be concerned with very detailed problem aspects, however, for fixed-horizon planning, also detailed time-resolutions are feasible. For the other two timing frameworks, there is a fixed relation between implementation time-step and planning (decision) step.

A direct relation between planning stages and time-scales appears in model predictive control (MPC). In MPC, the planning issue is build into a control and optimization framework, which optimizes over a discretized planning horizon, but only implements the first step.
This control technology is suitable to continually control the portfolio of a single

[6] The literature on wind power forecasting describes a mean absolute error and a root mean square error. According to the discretization scheme employed, here only the mean absolute error is considered. However, qualitatively this relation holds for either case.

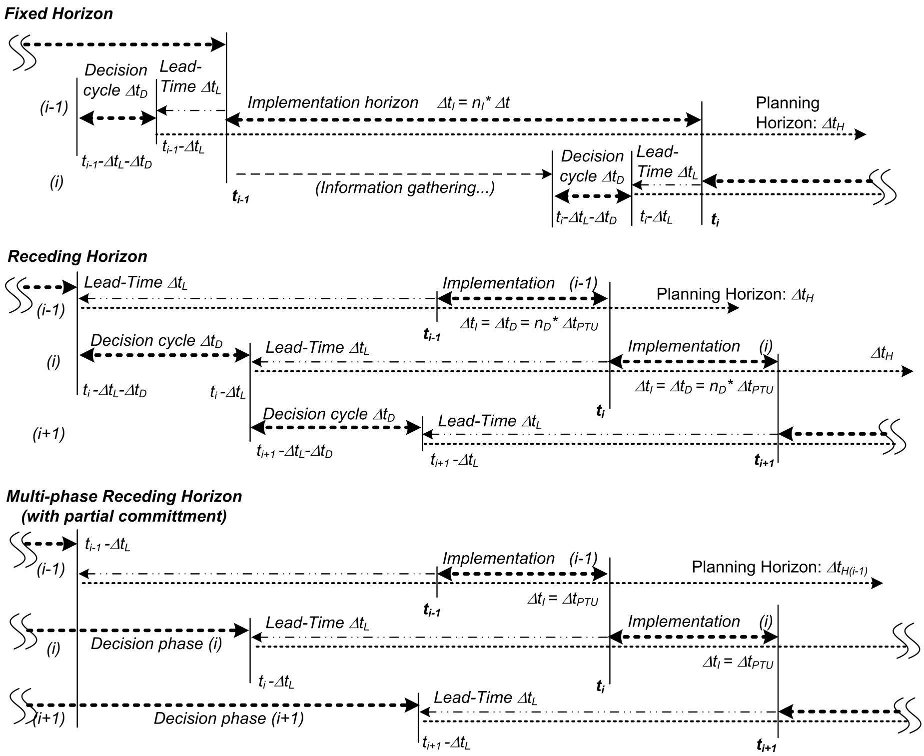

Figure 5.3: Relative timing of planning and execution aspects under different planning paradigms. They correspond to optimization and market techniques: Day-ahead market, Model-predictive control, Intra-day market.

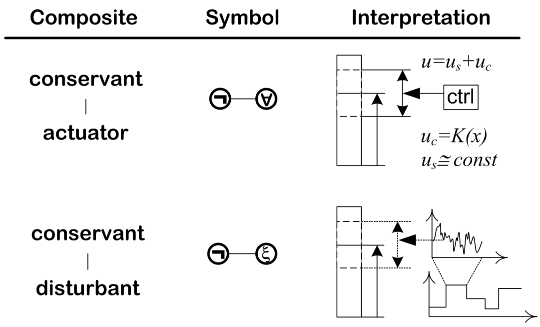

Figure 5.4: Composite Roles as a combination of schedule with a fluctuation or control reserve.

market actor and to optimize it for profit; it is also particularly suited as a control methodology for integrating energy-constrained resources.
A hierarchical cascade of planning levels with increasing time-resolution toward lower levels can be implemented on the basis of this methodology [231]. From an implementation-perspective, the relation between hierarchy-level and resolution is strongly related to the computational effort, but it can also be generalized by an entropy-based argument [215].

Composite Roles for Planning. Consider the operation of a generator in a market environment. Maximizing its expected profit, it will bid part of its generation capability onto an hourly market, and dedicate another share as control band to a reserve market. Complementarily, demand and wind generation will also be allocated on the basis of forecasts. This (partial) allocation and mapping corresponds to the reformulation, splitting of a function to be associated with several different roles, as illustrated in Figure 5.4. Realistic units may therefore be modeled by composite roles: *a)* $\xi \mapsto [\ominus - \xi]$
For uncontrolled units, such as load and wind power, the original uncertainty is decomposed into a forecast schedule, constant for each PTU of the market $\ominus$, and a remaining uncertainty ξ. In real time, this uncertainty includes both, prediction errors for the respective PTU and fluctuations as deviations from the average production.

b) $\forall \mapsto [\ominus - \forall]$
For controllable units, the market results in a schedule which is a series of constant setpoints for a generator for each PTU. For some generators also market outcome also includes a commitment to reserve part of their adjustable range for balancing control, made to cover the remaining uncertainty caused by short-term fluctuations, prediction errors and unforeseen outages (contingencies). The

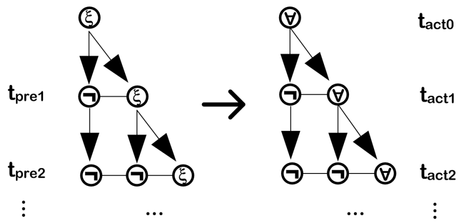

Figure 5.5: Hedging operation. More uncertainty may be hedged with decreasing lead-time.

control band $\forall$ is associated with the respective balancing control and the constant setpoints $\neg$ are the generators liability to the market.

c) $\forall \mapsto [\forall — \forall]$
Accounting a control range for several different control structures can be employed, if control ranges are separated by time scale. For example a power plant can provide both primary and secondary reserve (if time-scales and are not separated for the control actions, then the alignment of control objectives is essential). This composition is relevant for planning with regard to control reserve procurement.

One important benefit of the functional model is the abstraction from the physical devices it represents. The split of roles thus can also be interpreted as a split of a device's functions. This splitting then allows the aggregation of functions with common properties, e.g. for control purposes. Here it is important to take care of mutual dependencies and associated constraints.

Planning and Commitment. Operation planning can be described as an activity aimed at incrementally hedging the uncertainty of uncontrolled generation and demand processes (illustrated in Figure 5.5). For controllable (dispatchable) units, this entails the incremental reservation of their controllable range, and for uncertain processes the uncertainty is more and more confined.

Gate closure signifies the end of the hedging process in the perspective of market participants ($t^{(m)}_{\text{pre}}$). The reduction of prediction uncertainty is thus a main driver for reducing market lead-times. In operation-time, however, further predictions with shorter lead time $t^{(l)}_{\text{pre}} > t^{(m)}_{\text{pre}}$ and higher time-resolution $\Delta t^{(l)} < \Delta t^{(m)}$ are possible, which allows for a continued hedging on the operator side.

The composite behavioural roles express a conceptual decomposition of a process which can also be mapped to MFM functions. The splitting of the original process into separate functions is established by planning and control functions.

5.2.4 Control Functions and Balancing Services

At the end of this planning process, there remains an uncertainty which cannot be planned in form of a schedule but requires the provision and real-time activation of operational reserves, i.e. balancing services. Nevertheless, also operation planning for this type of uncertainty is a hedging operation as it is aimed at minimizing the risk of insufficient reserves. On the side of plant owners and operators, the end of the hedging process does not necessarily imply that all available capacity is committed to a market. The off-market reserve is usually invisible to the operator. Market rules may require plant owners to provide information about spinning and standing reserves [24].

Steering and Reactive Control. It is the role of the system operator to *establish* and *maintain* the system balance after gate closure. Intuitively there is a difference in the type of control that is applied when an operator requests an output increase of a power plant or when an automatic control maintains a e.g. a certain exchange schedule by continuously tracking the current measurement and adjusting its output. There are fundamentally two ways of providing balancing power: By ordering balancing power through a markets, or by activation of previously allocated reserve, associated with closed loop balancing controllers (e.g. primary and secondary frequency control). These correspond to the difference between the *steering* ([p]–produce) and *regulation* ([m]–maintain) control functions. The four types of control functions, introduced in [143], *steering*, *regulation*, *tripping* and *interlock*, have been discussed above (Section 4.4.3).

Here, the control functions [p] and [m] can be employed to describe normal operation:

- [p]: In order to first establish the balance, the higher-resolution ($\Delta t^{(l)}$) prediction established by the operator[7] enables the anticipation of larger imbalances that can be curbed in anticipation through predictive control actions (calling for regulating power). The anticipation and counteraction of network congestion typically is also a predictive/steering control action.

- [m]: The continuous system balance is maintained by reactive control measures.Reactive control reserves are dimensioned on the basis of power system

[7] this prediction may be established separately for uncertain processes with different character, such a as load and wind.

events which cannot be curbed by prediction. In the continental European power system, “secondary” control reserve is also utilized to counteracts deviations from scheduled exchanges.

- [p]: Regulating power is requested to relieve the reactive control reserves. The amount of reactive reserve in utilization thus also depends on the reaction speed of operators with which the relieving power is requested and activated.

- [m]–[p]: Apart from the operator, so called “Balancing Responsible” market participants (BRPs) aim at keeping their commitment to the market, which is to serve the energy requested for each PTU (this composition is discussed in Section 6.1).

The distinction between foresight and hindsight becomes intricate when several control levels are interacting, and therefore it more accurate to categorize control functions by their basic action character as either *produce*- or *maintain* functions.

Control Resource Procurement. Resources for power system balancing can be acquired in fundamentally two ways, roughly associated with the two types of control mentioned above: short-term regulating power markets and reserve markets. The former can be associated with a [p]-function and the latter with [m].

In the ad-hoc or short-term regulating power market, the traded good are ‘last-minute’ adjustments of the power dispatch. A regulating power market is thus a special kind of power market in which market bids are distinctly separated in time from market clearance which happens in real (operation-) time. Whether a bid will be activated then depends on a) the need for regulation (determined by the operator), and b) the relative bid-price of the regulating power offered. Reserve markets are quite different in market terms: Similar to 'normal' power markets bidding and market clearance may happen well ahead of operation-time, but the product traded is not energy but the reservation, which is the potential of activation. Activation is then performed reactively, in hindsight.

Reserve power is more comforting and deterministic than regulating power, as it corresponds to continuously available capacity.

The total price of regulating power tends to be significantly lower than that of reserves, mostly due to the increased opportunity cost of reserves, but also due to the faster response required of such units. It is thus not surprising that regulating power markets have received increasing attention in areas with relatively high shares of fluctuating renewable power generation; on the other hand, it may be surprising that in most continental European power systems, most regulation is performed by reactive reserves [24].

Reserve Needs Estimation. Conventional reserves are necessary for unpredictable plant failures. Fluctuations of uncertain power generation are partly predictable, and therefore should not be accounted for with the same regulation resources. When fluctuating generation becomes more relevant for system operation, it becomes essential to revise operation practices with respect to both the activation of other control resources and the estimation and procurement of reserves.

As introduced in Section 5.1, control reserves are procured on the basis on an estimate of the required reserve. The required reserve can be determined from a probabilistic analysis with respect to power system reliability/security specification (or was specified according to the 'trumpet curve' [230]).
If the reserve need is specified by probabilistic analysis, both the causes of disruptions and the utilization of the respective control resource in the control sequence of real-time operation needs to be accounted for [50, 216]. The more pro-active control or regulating power can be employed to balance deviations, the less reserve may be needed.

Reserve need due to power plant failures models several failure and operation-modes. Any transition stage comes with a certain success probability. Both plant failures and failed startup procedures are modeled, in relation to their impact on the system balance. Due to the different impact and behaviour of fluctuating renewable energy, its impact on reserve need has a different character that is very much time-dependent.

In increasingly more complex power systems, this technology-specific modeling may not be sufficiently generic. Supported by a functional decomposition of the system, as introduced here, probabilistic information about plant failure rates could be coupled together with stochastic inputs from fluctuating generation, as well as with control structures and their associated performance. In this vision, the functional model provides the necessary information for structuring a Monte Carlo-based approach for assessing the activation of reserves in a control scenario. The complexity of such an approach, however, seems prohibitive at this time, and the benefit of accounting for re-configurable control structures would hardly be relevant for present power system operation concepts.

Incentive-Based and Indirect Regulation Motivated by an economic paradigm in which all relations between stimulus and response are necessarily only approximate, 'control' mechanisms have been suggested that are based on a loose coupling between actuation 'stimulus' and actuation performance 'response'. Effectively, an implementation of such control mechanisms would require a departure from deterministic thinking in control structures, more toward a generic flexibility approach [130].

The control approach has been suggested to provide balancing power [178] by incentivizing a deviation in power consumpition, which corresponds to the [p]-character of regulating power, but without the certainty that a requested power deviation is delivered. Instead of demanding a certain power Y value and tracking in real-time, whether the demanded output is delivered, a signal X, the incentive, is provided. An 'internal' model of the controller would estimate the incentive X to be send for the desired output Y. The certainty with which the actual response Y' is close or equal to Y depends on the quality of the model, and is always uncertain.

The convergence of model and control response is to be achieved by means of estimating the actual response from several data sources, and improving the correlation of incentive signal and response in over time. Obviously this approach requires the assumption that the response behaviour is sufficiently stable and uncorrelated.

From a control perspective, it is in-essential whether the signal X is a price or another type of signal. The central challenge from a control perspective is the lack of a deterministic relation between signal and response, and thus the need for probabilistic modelling within the control. Another type of indirect control has been suggested by [42], where the focus is on probabilistic modeling of the internal state of thermal appliances.

It is clear that indirect control cannot directly deliver the control performance of a deterministic control. However, in many control scenarios, direct control is not feasible – then the scalability of indirect control opens up possibilities for additional control resources, such as distributed loads [42, 41]. The potential of indirect control is in reducing the need for reserve capacity. Its utility can only be evaluated on an overall level, where it is evaluated is by economic measures, balanced against the reliability contribution (reduction of reserve need) it provides.

On Balancing Service Formulation. A number of recent publications have been concerned with exploring and describing the design space of balancing an-

cillary service markets (e.g. [3, 180, 29, 204]). As a result, there is a relatively good natural language understanding of the different dimensions of market design for ancillary services [3]. The design of balancing markets is often taken from a market/economic perspective and has arrived at a good formalization on the economic framework perspective. In this perspective, market liquidity, market timing and allocative efficiency are important requirements. A good market design should be able to allocate the cheapest resources to the most appropriate services (control functions).
When these specifications are to be evaluated with respect to a future market design, particularly when looking toward a future power generation mix, it may be misleading to evaluate market design parameters on the basis of simulation models of present-day technology and control structures.

The conception of technical design parameters is usually derived from a combination of natural language descriptions and (engineering textbook-) mathematical models. Natural language is imprecise and can be misleading under changing operational contexts. Mathematical models, on the other hand, are precise, often too precise when considered in comparison with other modeling assumptions.
The modeling framework introduced in this chapter is aimed at a modeling tool for the specification of services and associated requirements, providing the basis for formalization of the technical design parameters.

5.3 Operation and Coping with Uncertainty

> *"Well, you know, can't promise you what Mother Nature will deal us, but right now the system appears stable and strong, there's adequate reserves, and we're monitoring it by the minute."* J. Norris, FERC Commissioner (July 2010)

Most of the above work focused on these challenges from a perspective of modeling of control and planning, also in a market context. However, supervisory control of power systems is performed by human operators. Power System operation is coping with uncertainty, about the actual state of the system and about imminent state changes. In terms of the changes anticipated for future power system operation, both, the increased complexity and the common uncertainty will challenge system operation in particular. With certainty, the above quoted Mother Nature will become even more present in the operation of future power systems envisioned in 100% renewable energy scenarios. Whether the response will be as confident, largely depends on the availability of appropriate support systems. Correspondingly, the modeling concepts are required to understand, describe and support operator decision-making.

The challenges an operator deals with in real-time and the corresponding priorities are quite different from those perceived from and engineering perspective; operators therefore would value *safety* over *efficiency*, stability, transparency, veracity and robustness over speed, accuracy and controllability [244].

This section introduces some central concepts of power system operation and then discusses the relevance of a conceptual understanding of control structures for system operation. Here, MFM is not directly relevant. However, it stands in a tradition of cognitive system engineering and, as discussed in Section 3.1.4, much MFM-related research is closely related to operator support systems.

5.3.1 Secure Operation

During operation, the complexity of the overall system security is reduced to three main concerns dealt with by operators [253]:

1. Stability issue: Stable operation following disturbances or major changes in the network, including the maintenance of reserve margins for (N-1) contingencies.
2. Thermal overload issue: Electrical network capacity and losses limit electric power transmission. Capacity considerations may include real-time weather conditions as well as congestion management.
3. Operating Voltage Issue: Sufficient reactive power support must to maintain the transfer capacity.

These issues are dealt with by human system operators who are facing challenges in realtime operation [244]:

1. external influences: 'disturbances'
2. clustering of events: disturbance-sequence and clustering, stress
3. uncertainties in real-time system status: what is actually going on?

A secure operation architecture must support system supervision at time scales and at a level of complexity accessible to human reasoning. Data and processed information should be presented to support *situation awareness*, and interactive functions should support safe operatot decision making.

Stability and Control The behaviour of power systems is therefore engineered to reduce its *apparent* complexity, by structuring its behaviour into separate control problems. Control systems stabilize the fundamental system variables: Maintain synchronism between the synchronous machines, e.g. by damping oscillations; maintaining stable voltages at reference points in the transmission system; and finally, frequency control to govern the continuous balance between production and consumption.
In contrast to these system-oriented controls, which aim to maintain intended system state, protection systems are build to "destroy" a situation (state) which may be physically harmful for power system components.
The conditions under which system stability can be maintained, and under which it is lost, are the fundamental concerns of system operation. Any new challenge and any improvement in this domain either affects the observability and situation awareness, the capability to react and plan effective countermeasures or the domain in which operation is considered secure.

Operating Modes and Operating Region The operating condition of the power system can be visualized as a point in the parameter space of a power system, illustrated in Figure 5.6, on the right.
The acceptable operating region Ω_a is bounded by stability and equipment protection requirements: $\Omega_a \subseteq \Omega_P \cap \Omega_S$. Some control structures are directly aimed at protecting the power system from instability, providing countermeasures for mitigating the specific threats of instability (thus expanding Ω_a). However, control is also aimed at directing the system toward specific operation goals, such as nominal voltages or the nominal frequency, thus moving X toward a specific location in Ω_a.

In support of the operation-challenges noted above, power system operators distinguish separate operating modes during real-time operation. Operating modes classify the global operating 'situation' in terms of the severeness of the current operating state. Each state requires prioritization of different specific issues and is correspondingly associated with different classes of available control actions. Even though these operating modes are operation guidelines, they could well be formulated as a discrete event system (cf. Section 3.1.2). A depiction of these operating modes is provided in Figure 5.6, which has been synthesized from [177] and [120].

The operating states are not exactly the same for all operation paradigms, but

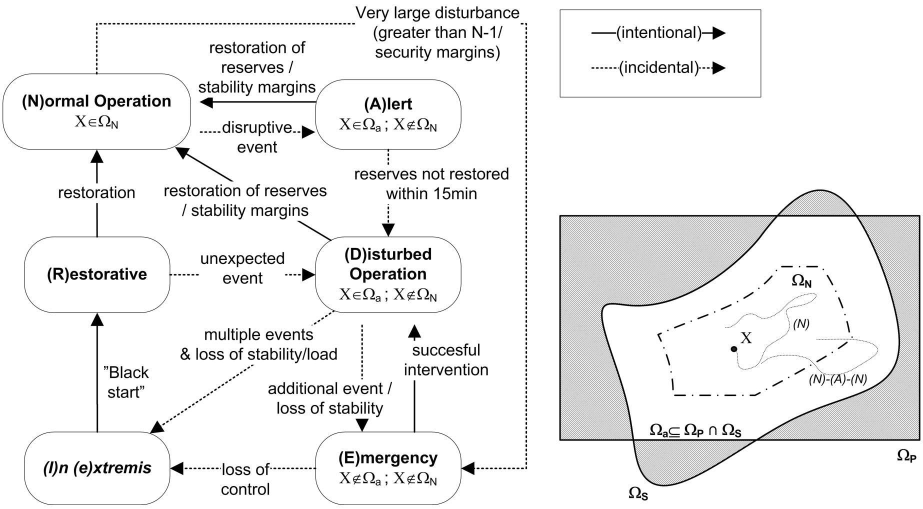

Figure 5.6: Operating modes and transitions, synthesized from [177] and [120]. Intentional and unintentional transitions are marked to differentiate disturbances from operator interventions. The corresponding operating domains are illustrated on the right. Two exemplary trajectories of the system state are shown, and their relation to the operating states is indicated.

they can usually be related to the following states [120]:

- *Normal*: All operating ranges in normal range; (N-1) security is given and maintained; sufficient operating margins available. Continuous activation of normal operating reserves in anticipation of deviations of scheduled and actual power balance.

- *Alert*: Due to a larger non-anticipated contingency, operating reserves have been activated. The system state is acceptable, but there are insufficient reserves for an additional event. The operator attempts to restore reserve margins.
  Disturbed Operation is considered if the restoration of reserves did not occur within 15 minutes. This, in comparison to [120], additional boundary provides an improved organizational awareness of the operating situation in the time domain, and is aligned with the Nordic definition of regulating reserves.

- *Emergency*: An additional event or an unforeseen large disturbance causes extreme excursions of the system parameters. Normal operating reserves are insufficient and emergency measures, such as load shedding, need to be taken to restore system stability.

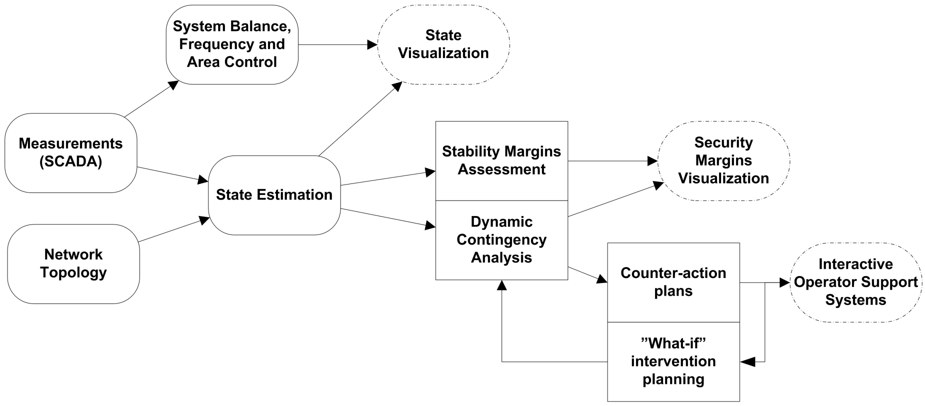

Figure 5.7: Online Security Assessment Functions.

- *In Extremis*: The system condition is out of control. Cascading outage, uncontrolled loss of generation and load shedding occurs. A partial or complete system collapse is the result.
- *Restorative*: The steady-state condition after a collapse is reached. Incremental and planned restoration of connectivity. In case of a complete Blackout, i.e. specific units with Blackstart capability are started.

The figure relates these operating states to the location of the system state within respective operating regions. It can be seen that the boundaries of the normal operating region Ω_N do not coincide with critical operating boundaries. This region is purely organizationally motivated: it expresses the transition from normal to alert mode, which corresponds to the observation that some predefined security margins are exceeded. In alert mode, counter-actions need to be initiated to restore these security margins.

In the operation rules of the former NORDEL synchronous network [177], an additional 'disturbed' operating mode is introduced, which is automatically transited into if the disturbance is not mitigated after a given time period (here: 15 min). This additional state addresses the situation from the perspective of an operator, for whom the 'clustering of events' and related stress also impacts the operating situation.

Security Assessment. Security is the technical robustness of the system with which it may be able to survive imminent disturbances. The system security can be described by operational margins to stability limits, and some operator support tools are available to assess the system state and to support counter-action planning, mostly based on the N-1 security criteria [171]. Further assessment methodologies are possible, for example on the basis of synchro-phasor measurement, demonstrated e.g. in [108]. The 'organizational' security margins are both part of operation planning and reference during operation. In real-time operation, the system security is fomulated in similar terms as noted above, as N-1 security, but with knowledge of the actual system state, including current reserve utilization and dynamic stability margins. In *dynamic security assessment* (DSA) the objective is to support power system operator with situational awareness by assessing the distance of the current operating state X to the boundary of acceptable operation $\partial\Omega_a$. Figure 5.7 depects the different functions of security assessment, including the various interfaces. Some of the corresponding interfaces are actually visible in Figure 5.8, where the main screens display the system state and side-screens inform about various margins. Whether a counter-action planning function is available to the operators in the picture is unknown to the author.

5.3.2 Situation Awareness

As the system operator oversees the system behaviour to identify critical aspects of any given operating situation, it is crucial that he is aware of the need for control, but also of her available control resources. Software and display panels support system operators to make informed decisions. Displayed information supports assessing the overall situation as well as focus on details. This hybrid requirement is achieved by the use of large displays, offering literal "overview" and sufficient resolution to focus on detail aspects and organizing information by context. We also see in Figure 5.8 that measured and expected values or ranges are overlaid. On the other hand, clearly, too detailed information means information overflow.

Filtering and organizing process data toward creating contextually relevant information is fundamental to successful supervision. However, what is contextually relevant information? The question really is what kind of information needs to be communicated to facilitate the operator's situation awareness. So, we need to understand, on the one hand, what constitutes operator situation awareness, and what constitutes a control situation.

Situation Awareness as Continuous Problem Solving. Supervisory control is about managing lower-level control functions toward higher-level and overall operation goals. Maintaining system security is an overall goal for power system operators. Understanding the problem-solving process that occurs during operation is fundamental to providing effective operator support functions.

Figure 5.8: Snapshot from Red Electrica (Spanish TSO) control room. Source: Red Electrica, http://www.ree.es/sala_prensa/web/fototeca_categorias.aspx?id=10 (Nov. 2010).

Research in the domain of cognitive work analysis has established that operator situation awareness can be modeled in several levels of process abstraction, present in all decision processes [201]. The decision ladder, as illustrated in Figure 5.9, stratifies these levels of abstraction both for state-analysis and planning of control actions. (Figure 5.9)

The decision ladder indicates that e.g. a power system operator, upon observing certain data, must relate it to a (mental) model of the power system in order to identify the system state. To interpret this state as the operating situation, the state is related to an intended goal-state. It is thus apparent that information about the process state needs to be relevant with respect to the operational objective, for example a desired process state. Information about objectives is just as important for a situation-awareness model as data from the process.
Both in the *interpretation* of signals and in the *generation* of control inputs, the abstraction levels can be distinguished between "raw" signals from and to instrumentation, variables interpreted as representations of a physical process state, process states and behaviours interpreted in relation to operating situations, and situations related to operation goals.

In the left leg, each level converts data from the process to higher level contextual information by relating it to a normative model (the expectations). In the right leg, the concretization of goals toward procedures and executable ac-

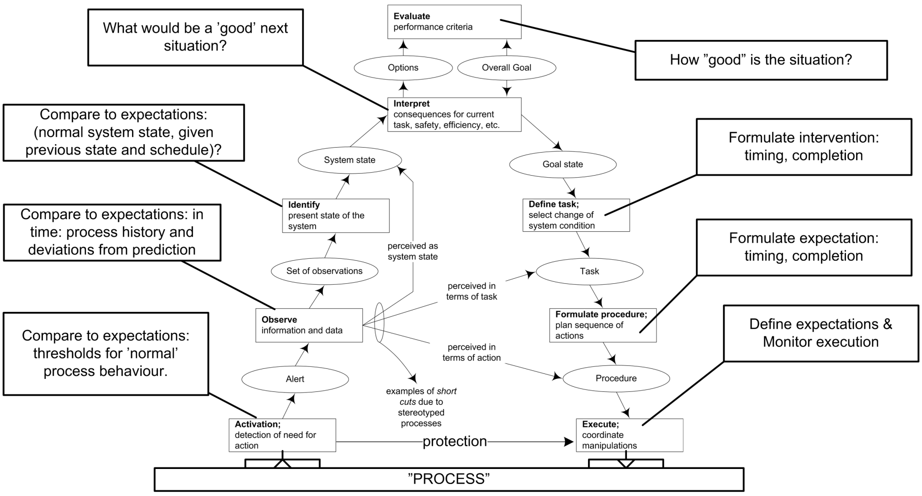

Figure 5.9: Rasmussen's Decision Ladder, adapted by from [201] (original graphic with permission from M. Lind.). The boxes represent information-processing activities, while the ellipses represent intermediate states of knowledge. The figure indicates the types of expectations associated with each level. Predictions and plans would be reflected, as expectations of uncontrollable and controllable resources, respectively.

tions and actuation signals. The role of representations in supervisory control can be read from this model as well. All intermediate states of knowledge -if to be made explicit- require an appropriate knowledge representation, so that the information processing-activity may utilize it. Therefore, different types of representations would be relevant at each respective level.

Seeing that an operator has a functional understanding (and intuition) about the system, a software agent, designed to support and partly replace human operator reasoning, requires comparable representation capabilities. Control systems without representation (i.e. models), can be utilized for firm control objectives: here the state interpretation with respect to the system objective is stable, so that a "short cut" can be taken from observation to execution of existing control procedures.
A system-state should be interpreted both with respect to control objectives and available resources. Reasoning and deliberation over alternative control objectives, tasks and procedures, choice of resources all remain basic requirements for operator intelligence.

Control Situations. A control situation is embedded in a work domain, here the power system, fundamentally as a specific set of control requirements (needs/goals) and control possibilities (control actions/means). The work domain is organized by mean and ends and by internal and external constraints [188].

Control needs are an interpretation of to the current state of the power system in relation to operation goals. For example: after a power plant failure, the system frequency dropped, the power exchange with neighbouring control areas is deviated, some security and reserve margins are low and tie-lines are stressed. The system appears stable right now, and the operating mode is “Alert”. According to Fig. 5.6 this mode demands that reserve levels are to be restored to return the to normal. However, a the tie-line overload cannot be sustained, because its breakers will disconnect it within a few minutes. Priority is to relieve the stressed tie-line first.

To return the control situation to normal, the operator is required to intervene: to choose from a range of possible control actions and to initiate the control actions that will bring about the desired goal state. This choice entails that the operator can anticipate the effect of his intervantions. A critical aspect is thus the operator’s understanding of cause and effect: which intervention will bring about which state change? Intuition and experience guide the operator here, but she can also draw on support functions that can simulate the interaction of system components (e.g. diagnosis, power flows and optimization).

Operator interventions can be distinguished from the continuous control loops that are an embedded and part of the system which is supervised. Feedback control is designed to continuously resolve a specific predefined control issue, such as stabilizing sudden voltage deviations. In contrast, operator interventions are targeted at resolving broadly varying control situations, by selecting from a wider range of available control means. Here, both the situational understanding is much broader than can be defined in a purely mathematical control framework and the range of control options also varies widely.

In a power system, these control actions require the activation of control resources partly provided by external entities. Control resources need to be procured prior to the operation in order to be available as a control possibilities.

5.3.3 Uncertainty Concepts and System Operation.

The acceptance that concepts of uncertainty should be a means of system operation is naturally difficult. Uncertainty, at first sight, is the ’enemy’, the source of complexity which must be overcome by means of insight and deterministic control actions. Control is a means of defying uncertainty, for example by encapsulating it with deterministic control objectives (cf. Section 4.4.3). Whereas this deterministic view of the world seems comforting, it is in fact an illusion.

Uncertainty as a Means of Operation. In the vertically integrated power system, control was naturally central, hierarchical. In this framework, a schedule X would be the same as the actual dispatch X'. Deviations and fluctuations necessarily could only be explained by load behaviour, or be attributed a character of disturbances. Uncertainty in a hierarchical control perspective is therefore merely a question of qualifying disturbances.

The benefit of probabilistic modeling of fluctuating resources is of course not that it introduces uncertainty to system operation: instead, it can *reduce* uncertainty by means of quantifying existing uncertainties in a structured manner. In that way, the deterministic character of probabilistic modeling is in giving structure and meaning to a complex environment. Good probabilistic tools should enable more effective decision-making, or in other words, enable a translation of the probabilistic information back into 'deteministic' categories.

This decision-making takes a clear understanding of objectives and performance criteria, as well as a classification of resources. Functional models could provide transparency to this problem by using functional information to structure and classify large sets of process information and re-organizing them to match a given operation-perspective.

Markets and Uncertainty. Whereas deterministic thinking prevails in system operation, thinking in markets and incentives also requires a probabilistic perspective. In the market paradigm, an additional uncertainty has been introduced: whether a party will honour its commitment to deliver according to plan or schedule X, that is: Will X approximate X'? In a market-place, this is a question of aligning interests between market parties and the system. The control means become incentives and disincentives, market rules, rewards and penalties.

In a deterministic perspective, operation and control would minimize potential deviations by defining restrictions and strict performance objectives. Possibly motivated by this deterministic perspective, also short-term imbalances of balancing responsible market parties are also penalized, which may induce counter-productive regulation system (further discussed in Section 6.1.2).

Another line of thought acknowledges the relation between incentives and resource availability. Motivated by the economic paradigm in which relations between stimulus and response are necessarily only approximate, ‘control’ mechanisms can be conceived that are based on a loose coupling between actuation ‘stimulus’ and actuation performance ‘response’ (discussed as ‘indirect control’ in Section 5.2.4). Effectively, an implementation of such control mechanisms would mark a departure from deterministic thinking in control structures. However, it is not going to be easy to convince an operator to think in terms of probability. This type of service can only be meaningful in context of another ‘safe’ control reserve which with a deterministic response characteristic. In a valuation-perspective, the benefit of this additional service would be measured in terms of the consistent and predictable reduction of safe reserve margins it enables reliably.

5.4 Chapter Conclusion

A meaningful representation is achieved, when:
a) central functions and objectives of today’s system operation are included,
b) the challenges formulated above, can be reflected as challenges to these operation functions, and
c) the modifications by which the challenges can be mitigated or overcome are reflected as well.

The discussions above have shown that a) and b) have been achieved with respect to the basic concepts. To reflect on c) some modeling attempts will be presented in the following chapter, presenting some of those modifications.

The discussion of system operation from a perspective of the control room emphasized some of the basic challenges that will remain important also in a more automated power system. Both, and understanding of operating modes and the interaction with human operators are essential aspects that should not be forgotten in automation design for future power systems. Further, it should be noted that many proposed ‘novel’ control structures strongly interfere with present operation practices. A formal understanding of the relation between operation requirements and the potential impact of new control solutions will allow for a better design. An application of this perspective to the design of multi-agent based control structures has been discussed in [MFM-APP-CP]. Experience with software systems, including multi-agent system, discussed in Chapter 2 suggests that the availability of related conceptual models will enable the development of control software that respects the requirements of human supervisory control and partly mimics related decision processes.

Chapter 6

Modeling Example Cases

The means-ends modeling approach has been further developed and adapted to represent some of the central challenges in the design of operation strategies for future power systems with 100% renewable energy, including vast amounts of wind power. The challenges are related to the coordinated design of control structures as services as well as to the increasing fluctuation and uncertainty which will demand significantly more flexibility from controllable power system resources. Figure 6.1 gives an overview of the various concepts that have been introduced to the modeling of power systems. Each 'dimension' supports an understanding of a different aspect of the overall system architecture. The graphical MFM concepts and relations are centered on functions and means-ends relations, respectively. Due to underlying action- and role-oriented modeling concepts, it can also be related to actor-specific objectives, function-structure relations and conditions for the establishment of function-performance. In application to power system control, we have identified the means-ends organization of the control and process functions (considering coservation principles and execution-levels), and discussed time-scales and planning stages in relation to system operation in general. Further, the potential in modeling separate actors was discovered and its relation to modeling value-activities was discussed. The need for consideration of the modal aspects of system operations (e.g. using action-phases)in particular in relation to modeling the transitions between operating modes was recognized, but not treated further. Finally, also need for a system-operator perspective was stressed and related challenges and modeling conepts were outlined.

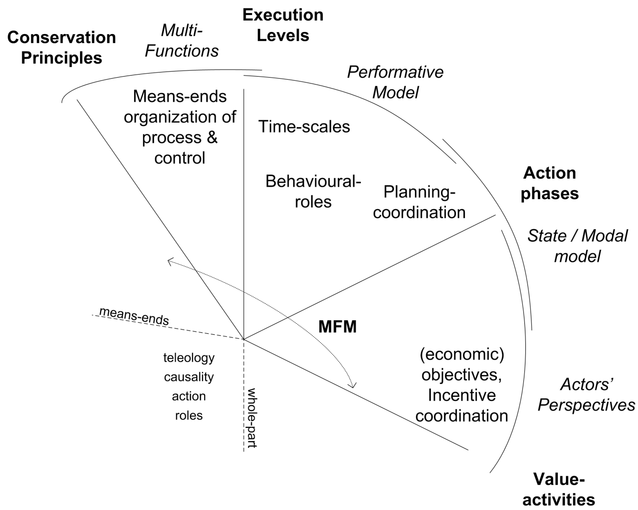

Figure 6.1: Semantic dimensions related to control structures. Each dimension is associated with its own group of (core) concepts. The central concepts and relations enabling all other relations are stated in the lower left corner, they form a conceptual basis.

This chapter is to apply the modling methodology to a few of case studies in context of the control and coordination challenges anticipated for the operation of future power systems. First, based on present operation concepts, two 'solutions' in relation to the challenge of increasing wind fluctuation for system balancing will be introduced. Here, the motivation of the particular solution is also discussed in relation incentive structures and resource scarcity and their mapping to control requirements and resource needs. Next, model application the to 'future', proposed, control structures is explained; and finally, a distribution-level case study is presented to illustrate the method in context of a conceptual design.

6.1 System Balancing

The balance between load and generation in a power system requires a reponsible entity that can manage its resources to establish that balance. With power system interconnection, the exchange between systems became a matter of mutual responsibility, so that disturbances from one part would eventually be balanced in their region of origin. This grid-topology based reponsibility is still in place today with respect to area-control (time-scale: seconds to minutes).

A model of system balancing and area control was introduced in Section 4.2, Figures 4.3 and 4.4 in particular. Only the central functions and conventional grid control were modeled.

System balancing shall now be studied in light of the challenges posed by large-scale integration of wind power. It was observed that large scale wind power implies that the fluctuating part of the energy is not 'hidden' in the load any more, demand and generation are no longer equivalent to fluctuating vs. controllable. Consistent with the conventional language, we are speaking of wind power as 'negative load', so that the total load may be negative. On the other hand, controllable demand is introduced, which, consistent with the conventional paradigm, must be 'negative generation'. As already illustrated in Figure 4.5, these altered functions are simply modelled by a controllable source-sink $\bigcirc\!\!\!\!\!\nabla$–**sousi** and a fluctuating sink-source $\bigcirc\!\!\!\!\!\xi$–**sisou**, maintaining the causal structure. Note that, considering the decompositions introduced in Section 5.2.3, that this model is equally valid for only considering the imbalance-aspect of the system: Market clearing means that all planned or forecasted demand and generation, import and exports are mapped to a balanced schedule, $\bigcirc\!\!\!\!\!\neg$–**sou** - $\bigcirc\!\!\!\!\!\neg$–**si** $= 0$.

All planning and forecasts are subject to change: outages, deviations and fluctuations that cannot be anticipated. They are be accounted for by control reserves and short-term regulating power, capacity that is withheld from the scheduling of controllable resources. Control reserves are costly and reducing the need for reserve is desirable. However, to guarantee system security with present operation strategies, the need for reserves would rather increase with the anticipated volume of wind power.
There are thus two sides to the improvement of the control design with respect of system balancing:

- reduce balancing need

- reduce balancing costs

In a system-perspective, any control structure that can reduce need for balancing by design is thus beneficial (Section 6.1.1). On the contrary, control structures that demand unneccesary balancing are just wasteful (Section 6.1.2). The reserve needs are estimated by probabilistic methods based on the control structure, disturbance properties and reliability requirements e.g. [50].

6.1.1 Inter-Area Balance-Netting

Fluctuations of independent random processes partly cancel each other. As demonstrated mathematically in Section 5.2.2, combining two random processes under the same performance criterion improves is always beneficial. The less correllated the processes are, the stronger the effect. In relation to wind power, the effect of uncorrelated power-fluctuation is called "Geo-diversity" [39]. The correllation of wind power fluctuations decreases by distance – the faster the time scale, the shorter the distance per decrease. Highly correllated fluctuations need to be balanced by controllable generation, but uncorrelated fluctuations will cancel each other. The quantitative analysis by Ernst [64] suggests that for regulating power with a relevant time scale of 15 min., the correlation of power fluctuations is nearly zero for turbine distances beyond 50-100km. A similar analysis is also reported in [39].

This cancellation effect could be utilized by combining control areas under a central authority, so that opposing fluctuations are exchanged instead of counterbalanced by e.g. secondary regulation. The required centralized control authority, however, may be difficult to establish organizationally [60].
The same practical effect can also be achieved by overriding the area-control requirement when power-imbalances cancel each other. This approach was proposed and implemented as a control method called Area Diversity Interchange (ADI) in the US [179]. The method has recently been improved by Makarov *et al.* [265, 65], who included methods to integrate transmission congestion and a range of 'fairness' criteria. The method has also been implemented as "Grid Control Cooperation" (GCC) in Germany, where it has been combined with a collaborative approach to secondary control dispatch and reserve procurement [266].

The mechanism can be modeled in MFM with respect to models for area-control (cf. Section 75). Figure 6.2 presents two MFM models of this control feature. On the left, the causal model (i.e. implicit control), models the algorithm from a logical perspective; the controllable generators $G_{sec,A*}$ on either side act as slack whenever imbalccnes occur. The imbalance is reduced by the conditional activation of the ADI-related transport functions, overriding the exchange schedules. On the right, the relation of the ADI control function to the existing secondary control structures is provided.

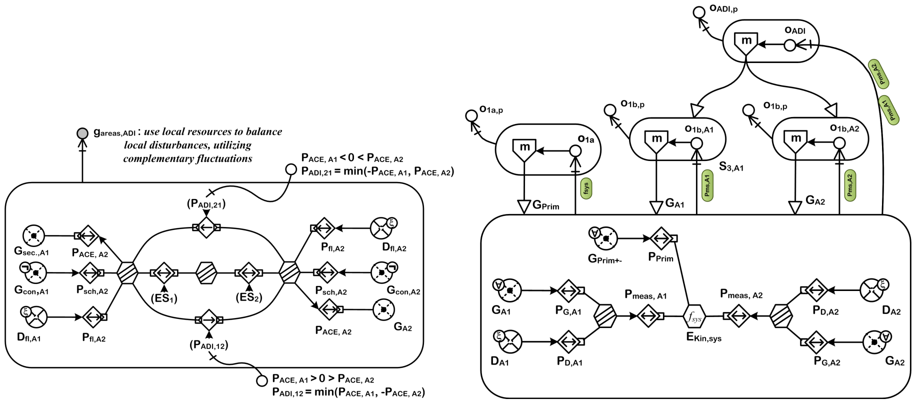

Figure 6.2: The purpose (left) and realization (right) of "Area Diversity Interchange" (ADI) illustrated on a two-area system. The ADI control structure modifies the reference ACE of the area control structures, and thus requires a central coordination.

6.1.2 Portfolio Balancing

By the introduction of markets, the concept of balance responsibility has also been applied to market-parties. Balance responsible parties (BRPs) are responsible for their portfolio to adhere to their respective market schedule. Schedule deviations are penalized by the regulating power price (plus a premium)[1]. BRPs are therefore inclined to elminate their schedule deviation, which is also called "imbalance". As schedule deviation (cf. Section 5.2.1), the imbalance is formulated in terms of energy over one PTU. (e.g. calculated as 15min. integral of the instantaneous difference scheduled and delivered power).
The benefit of intra-portfolio-balancing from a system perspective is that uncertainty of load behaviour is partly encapsulated by making balancing a responsibility of market parties. It would be assumed that the BRPs have a better knowledge about the demand in their portfolio and thus the ability to predict, observe and counteract deviations more accurately. In Figure 6.3, this setup is modeled in MFM. The system, a single area sharing frequency droop control with other areas (CS_{PR}), and one actor (BRP) is modeled. The time-scale for the model was chosen as intra-PTU, such that regulating power (dispatched by $CS_{Operator}$) is modeled as a conservant ⊖ and secondary control as actuator ∇. The BRP aggregates generation and demand, provides to control services and is connected to the system by three Janus relations. Two Janus relations are associated with secondary and tertiary control and the third corresponds to its instantaneous portfolio-imbalance. Internally, the BRP is modeled by two

[1] This basic concept holds for most European markets, however there are significant variations in the details [24].

control structures CS_{BRP} and $CS_{BRP,LF}$. The former directly controls all controllable assets available to the BRP, providing the control services. The latter is aimed at eliminating the imbalance (integral), and is decomposed into two control functions: one [p]- actuates the its own control resources on a schedule basis (the same 15 min time resolution as the tertiary control); the other [m]- actuates the same BRP-internal control function as the system services, as on the same time-scale as the secondary control.

Secondary frequency control and portfolio balancing are thus separate control functions that draw on the same type of controllable resources. Whether the counteraction actually contributes to the system balance, however, cannot be known at BRP level. The control objectives of BRP balancing and system-balancig are not aligned: frequency/area control is aimed at maintaining a continuous power balance, whereas the BRP load-following controller aims to eliminate portfolio-internal energy-imbalances with respect to market-time-slices. For two reasons, there may be (technically speaking) unnecessary control actions caused by the BRP's [m]-portfolio-balancing:
a) similar to the ADI across regions, also the imbalances of market parties (BRPs) may cancel out;
b) control actions targeted at the energy integral[2] may not be aligned with the area-power imbalance, and thus may cause additional counteraction by the secondary control.

A conflict of controllable resources exists between the system-level and the portfolio-control. In Figure 6.3 this is illustrated: intra-time-scale controllable resources associated with a BRP are reserved for two purposes: system-balancing and internal portfolio-balancing. Whereas it is beneficial for the system that market parties make good schedules to achieve effective market clearance, it is desirable that all remaining controllable resources be made available for the system balancing functions (reflecting actual balancing needs).

One method of resolving this balancing responsibility issue could be to functionally separate uncontrollable generation from balancing portfolios.[3]
In a perspective of incentives and and resource allocation, it is, however, desirable that uncontrollable generation is part of the market dispatch. This inclusion causes imbalance penalties to creat e an incentive for the best possible prediction and scheduling, as well as an socio-economically more optimal dispatch solution [61].
In summa, the socio-economically better situation on a larger time-scale appears

[2]Portfolio-imbalances are counted with respect to 'program time units' (PTU; energy-slices, in Europe typically on a 15min basis), so an imbalance need not be balaced immediately, but only over time, so control actions do not necessarily contribute to the system balance, or can even be countering it.
[3]As practiced e.g. in Germany under the Renewable Energy Act.

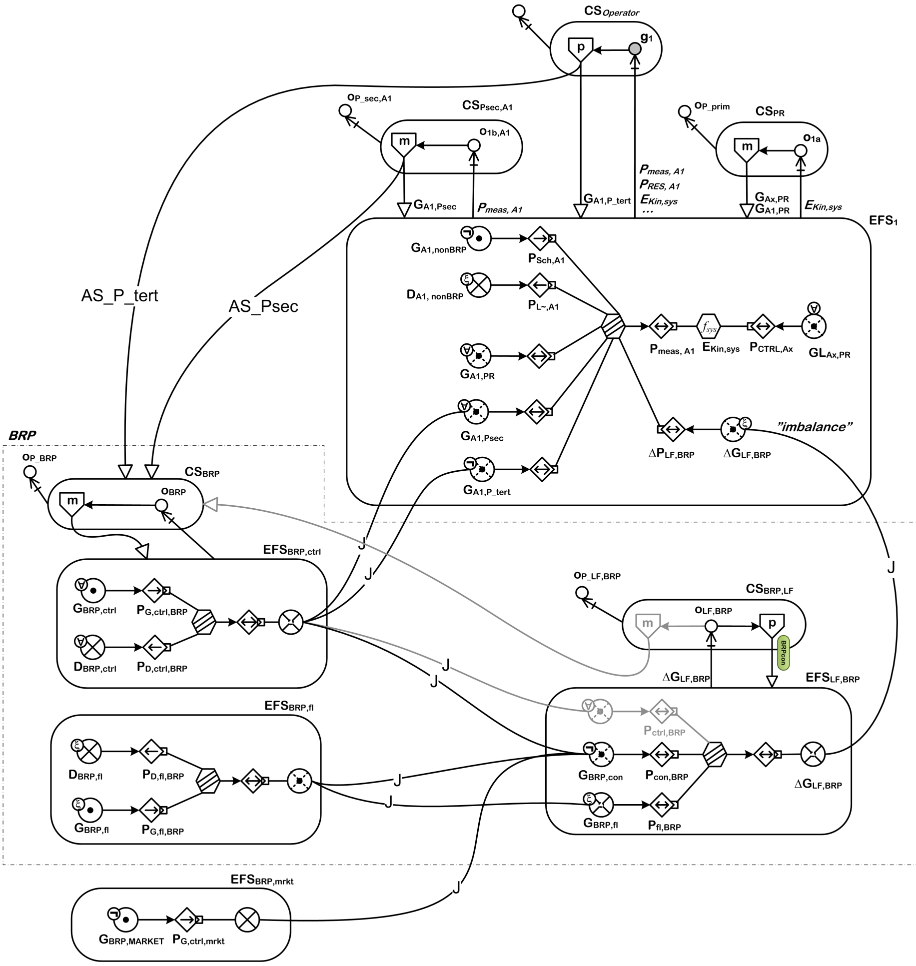

Figure 6.3: One control area and one balance responsible party with associated resource portfolio. The reactive [m] control functions draw similar controllable resources ("reserve capacity" as in reserved control ranges) from the market. The [p] control functions do not react 'in closed loop', and are here employed to model scheduling functions, acting on $\neg$-flow functions. The differentiation between scheduling actuation as $\neg$ and reactive control actuation as $\forall$ is motivated by the considered time scale of $\leq 15min$.

to be creating mis-aligned incentives on a shorter time-scale. The incentive to achive a perfect internal portfolio balance draws balancing resources from the 'public' balancing market for portfolio-internal balancing. This setup thus creates an unnecessary scarcity of controllable resources, which should be avoided in high wind power scenarios.

Finally, we can identify one possible solution to resolve this dilemma: Balancing of portfolios based on online measurement at the intra-PTU time-scale should be prohibited, and only be allowed on a schedule-basis. This, of course, would at first increase the cost for BRPs with controllable resources, because intra-PTU imbalances can no longer be counter-actedd. This natural opposition from a BRP perspective should be balanced on a system-scale, however, where the total balancing cost would be reduced because unneccesary control actions are avoided and previously unavailable control bands would become available.
This solution was identified in the MFM model: In Figure 6.3, the grey functions and control relations should therefore be inactivated.

The resource conflict related to the balancing resources could also be illustrated in an e3value model, as a 'flexibility' service on a given time scale, would have to be offered by the same resources to these two competing bidders (i.e. TSO and BRP). We omit presenting this value-model here to avoid further symbolic confusion. For reference, a multi-perspective case study on a "distributed balancing service" was presented in [116]. Here, a "flexibility service" offered by flexible consumers and distributed power producers to a 'supplier' (BRP) to perform portfolio-balancing. Interestingly, in their value model, the overall system balance does not appear, and so the resource conflict is not identified. We can conclude that the explicit formulation of the system's causal paths and control functions by the functional model effectively serves as a complement to such other conceptual representations (called 'perspectives' in [191]).

6.2 Future Control Structures and Aggregation

A central feature of several proposed "future" control structures are aggregation concepts, which simplify the coordination of the diverse energy resources with the control functions required for power system operation [33]. Here we shall demonstrate that 'functional aggegation', which is natural in MFM, can be employed to explain and analyze the various functionalities the can be meaningfully associated with such control structures. To divide the discussion, we first discuss grid-topology oriented control structures and then topology-independent functional aggregation. However, it can be stated upfront: 1) the distinction between aggregation concepts as 'commercial' and 'technical' is imprecise and misleading.

This distinction is associated with the primary driver motivating the aggregation concept; 2) the concepts are not mutually exclusive as often suggested by other modeling approaches – only their respective structural (topological) and mathematical representations are.

6.2.1 Topology Oriented Control Structures

Area control and voltage control are control structures directly oriented on the grid topology. That does not mean, that they form the same types of part-systems. With respect to the grid-topology, voltage control forms an aspect-system, whereas area-control is formulated as structural subsystem (which is aligned with the responsibility of the respective system operator). In Chapter 4, the common control functions for power systems have been introduced, using the most aggregated representations suitable to explain the respective control functions. The larger scale integration of distributed generation and controllable demand technologies enables – and requires – control also structures that actively integrate these units in the monitoring and control of lower voltage grid structures.

Active Distribution Networks have been introduced as a general category summarizing new control structures at a medium or low-voltage level. A definition of active distribution networks has been elaborated by the CIGRE Working group C6.11 [40]:

> Active distribution networks (ADNs) have systems in place to control a combination of distributed energy resources (DERs), defined as generators, loads and storage. Distribution system operators (DSOs) have the possibility of managing the electricity flows using a flexible network topology. DERs take some degree of responsibility for system support, which will depend on a suitable regulatory environment and connection agreement.

As a generic category, we view active distribution networks (ADN) as substransmission and distribution networks that have added on control capabilites beyond the passive role today. One challenge for distribution systems Active control of distribution systems is oriented on two control needs relevant for future grid operation:

- *external*: "responsible" control capabilities of reactive and reactive power exchange with respect to transmission system;

- *internal*: management of voltage, and grid constraints, network configuration and active power balance.

The adaptation or reconfiguration of protection settings in presence of distributed generation, [229, 181], would also be considered internal. Both aspects relate to control requirements for those active control structures that are required to actively integrate further distributed generation and controllable demand.

Let us review the control functionality of some of those control structures suggested for this purpose:

- **Microgrids** are explicitly low-voltage subgrids, that is their interface is defined by the physical link between local and external grid [129]. Microgrids consider two possible operation modes: a *connected* mode, and an *islanded* mode [242]. Here the "point of common coupling" (PCC) is also formulated as reference for grid services, so that in connected mode a MicroGrid could be operated as one power plant (often without synchronous generator, tough). Most Microgrid scenarios focus on the islanding capability and consider a central coordination/optimization of all microgrid resources.
- **Cells** are control structures exclusively devised to enable island operation of a ditribution system [160]. The voltage level considered is 60kV and thus the PCC for a cell is toward the transmission system.
- **TVPPs**, technical virtual power plants, introduced in [199], have been motivated as control structures with active subsystem/distribution system voltage control as a complement to commercial VPPs. Here, the central feature is that a distribution system could deliver voltage-control related services (e.g. reactive power injection), at a PCC, providing a service similar to that of a power plant. A related control methodology is associated with controlling clusters of wind farms [207].

Other control strategies have been proposed, aiming for example at congestion management. What all these approaches have in common, is their motivation out of technical feasibility considerations, a value driver that is hardly motivated in present power system operation concepts and market structures.

So, in Microgrids, the research focus is on internal operation capabilities on the low voltage level in islanded operation. Cells' research focus is on internal operation, but the value driver, the motivation, is a relibility service, also to the transmission system. And TVPPs stand for aggregated voltage control. It

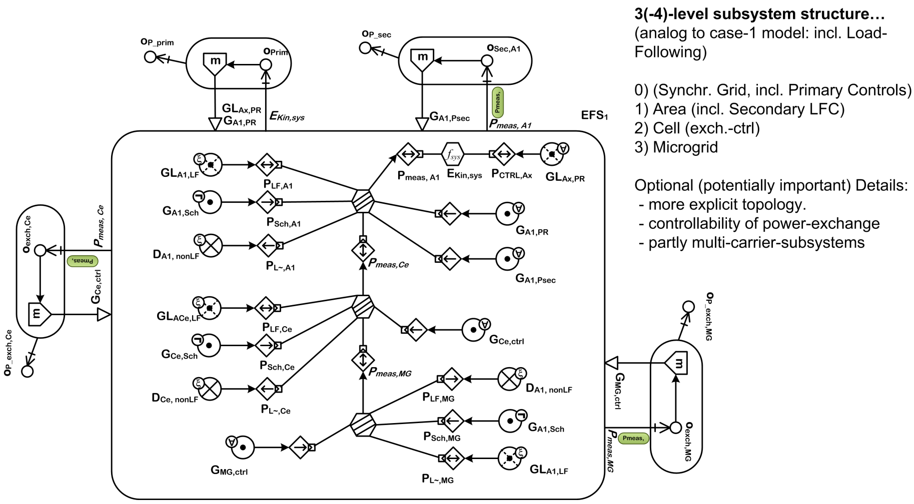

Figure 6.4: "Vertical", topology-oriented composition of transmission, sub-transmission and distributions networks, associated with control levels of microgrids and cells.

should be noted that special control stratgies have been developed for frequency and voltage control in Microgrids, which overcome the challenge of the relatively small X/R ratio on low-voltage levels (a high X/R-ratio is necessary to motivate the decompositon into separate active power and voltage-control by reactive power levels, cf. Section 4.3.2).

The central question for the evaluation of "future control structures" is: Can these concepts be scaled to provide a vision for future grid operation?

Micrograms are meaningful, and already applied, mostly for private networks with high reliability requirements, such as airports or server farms. Despite the suggestion that Micrograms could be coordinated (e.g. MoreMicrogrids.eu), the concept's purely topological control inclusion does not offer a perspective for markets which require rather less sectioning than more, let alone frequency control. The full alignment of ownership and control is also problematic. A future power system architecture composed of multiple LoCALGrids, which are comparable to Micrograms, is proposed in [101]. Such architectures are, however, focused very much on deep changes to the power system structure, and requiring a complete redesign rather than an incremental adaptation of present system structures.

The Cell concept is more functionally motivated, suggesting an additional control function to the present operation. Conceptually, this is easier to integrate with todays control architecture. A caveat should be observed in relation to the 'autonomy' of such control structures: switching between interconnected and disconnected operating modes requires a local operation intelligence that is also aligned with overall systems operation [210, MFM-APP-CP].

Active distribution system control is also reasonable for less critical situations, in which benefits both internally for the distribution level and externally for the transmission level are possible. The overlap of authority and control requirements between local and global system operation makes this case conceptually more challenging. In [199] and [207] that problem is solved by suggesting a power plant analogy.
The functional representation intoduced here provides a convenient means of considering this design challenge more flexibly. By offering the possibility of considering alternate configurations, separately for each control context, it provides the option of considering different forms of aggregation with respect to separate control functions.

6.2.2 Virtual Power Plants and Indirect Control

A virtual power plant (VPP), taken literally, is a functional entity providing services comparable to those of a power plant. It is 'virtual', because its functional unity does not coincide with physical unity. Its parts could be almost anywhere. Its unity is generated by shared control structure and the coordinated operation toward joint control objectives. What characterizes a virtual power plant further is the typically dispersed ownership structure and correspondingly, the need and ability to coordinate operation of physical resources toward independent, potentially conflicting objectives. A local CHP unit, satisfying a local heat demand while producing electricity at best market prices exemplifies this conflict.

Two different aspects combined in a virtual power plant have troubled previous definitions of virtual power plants: a) the commercial benefit of an aggregation of units can be independent of the location of its parts; b) some ancillary services provided by conventional power plants are bound to a grid location (e.g. Voltage control), but still may be provided by an aggregate of units.

The real clash between these two perceptions of virtual power plant is that one perspective is easily (entirely) conceived from a market-economic perspective. Its purpose is to form a business unit. Whereas, in the other requires the considerations of internal multi-functionality and heterogeneity are relevant. And, if several services are provided, also external heterogenity. In addition, the consideration of the technical infrastructure matters, which, in case of relevant

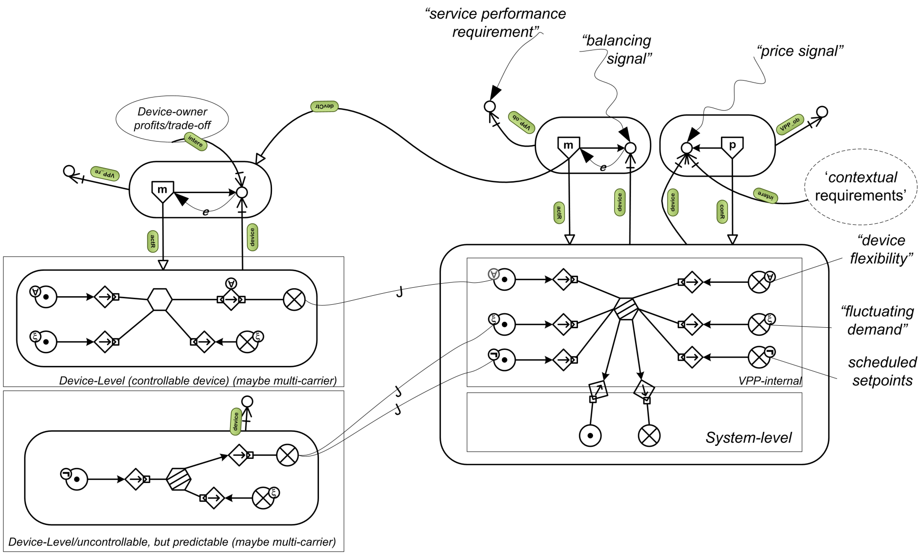

Figure 6.5: A sketch of different ownership levels of a VPP.

grid constraints, an "external" constraint, which affects the internal configuration/structure of a virtual power plant perspective, at most could be considered an external constraint.

If a virtual power plant that is entirely motivated and conceived as an economical entitity such as the commercial VPP, CVPP, in [199], such topological (i.e. also functional) constraints cannot be conceived of.

The control modeling challenge in a virtual power plant is to understand how the integration of a diverse unit portfolio can be build to perform as a single controlled unit, with respect to control services (i.e. ancillary services). The involved control problems, need to be dissected if market thinking ought to be applied. The solution offered here is a formalization of the control services, i.e. a also a standardization of control functions and their performance.

6.3 Distribution System Control and EV integration

A case illustrating a how the functional mdoeling approach supports the development of new control structures. The case is a hypothetical distribution-level

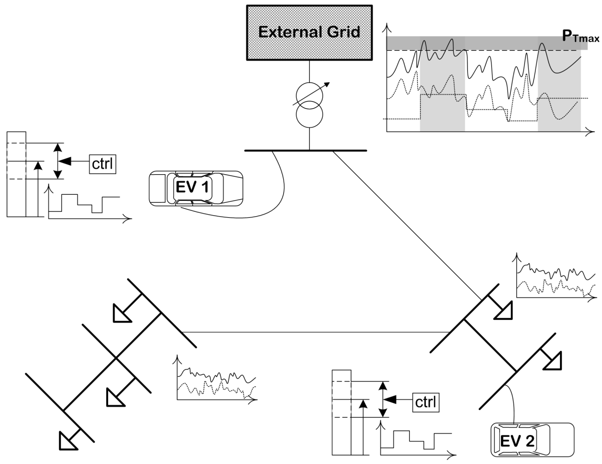

Figure 6.6: Distribution feeder with several loads. Transfer capacity of the transformer is constrained but the cables have sufficient capacity. For illustration purposes, phase-imbalance, voltage and reactive power are not considered.

ancillary service that is aimed at safely maximizing the utilization of existing network capacity.

Suppose a future distribution feeder scenario as illustrated in Figure 6.6. Both classical uncontrolled loads and electric vehicles (EVs) are connected to the feeder. The electric vehicles are 'smart charging' enabled, thus can control their charging power and may communicate to a service provider and the local substation through their respective charging stations. Due to classic household load patterns, the transformer is dimensioned to $P_{T,max} \approx \frac{1}{5} \sum P_{i,max}$ where $P_{i,max}$ is the individual household connection capacity (the $\frac{1}{5}$ is an estimate resulting from discussions with experts). Uncontrolled EV-charging might thus threaten network assets.

Households remain classical in that they are uncontrolled and that their consumption levels are estimated for the market in the $\bigcirc\!\!\!\!\neg$–$\bigcirc\!\!\!\!\xi$ fashion introduced above. Suppose further a market and ancillary service environment where electric vehicles may bid aggregated schedules (schedule step-size: $\Delta t^{(l)}$) into the market (PTU length: $\Delta t^{(m)}$) and also balancing ancillary services may be offered by such EV aggregators (with sampling rate $\Delta t^{(k)} \ll \Delta t^{(l)}$). Both EV 1 and EV 2 participate in the coordinated scheduled charging and both accept a minor uncertainty in their final level of charge. Considering the lowest sampling-rate $\Delta t^{(k)}$, they may thus be modelled as $\bigcirc\!\!\!\!\neg$–$\bigcirc\!\!\!\!\forall$. EV 2 thus additionally participates in an ancillary service on grid level (e.g. a secondary control service), a control loop which is out of the scope of the distribution level constraints. EV

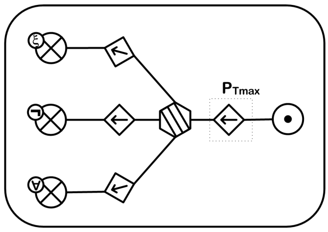

Figure 6.7: Function model of the distribution feeder controlled loading problem.

2 thus is locally also $\neg$–ξ. EV 1, still $\neg$–$\forall$, offers its control range a local control service. As the only topology-constraint in consideration is the distribution transformer, we may aggregate the loads into three categories: $\forall$-, $\neg$- and ξ-sinks (Figure 6.7).

The local market has been incentivized by the particular design of a "smart" safety function: In addition to the conventional protection setting, the controllable loads, here EVs, are obliged to participate in the additional safety system. Curbing the risk of transformer overloading, and resulting loss of load, the advanced protection system disconnects the *largest* EV-load in the instant of any transformer overload. By implementing this safety, the risk of overcharging the transformer has been turned into an incentive for the electric vehicles to cooperate with respect to this overloading problem.

The distribution system operator now enables a service, providing information of the transformer loading condition. The service is to balance out any spikes in the fluctuating demand that may exceed the transformer capacity. By means of this control service, the effective transfer capacity of the grid is increased, which allows the charging schedules to charge at a higher rate than otherwise (Change: grey area in Figure 6.8), and therefore to also participate in a regulation service that requires deterministic control bands.

EV's control curbs the risk of overloading and thereby can somewhat shift the safety margin upward. The control objective of this service is $h(\neg, \xi, \forall) = P_T(\neg, \xi, \forall) - P_{T,max} \leq 0$ formulated as a $[m]$ or with inverted sign as $[s]$-control function. Here, $P_{T,max}$ may be induced by the protection setting or a thermal loading limitation. A performance requirement would specify the maximum reaction-time required of EV 1, based on the cut-off time induced by the protection setting and/or thermal loading limitation.

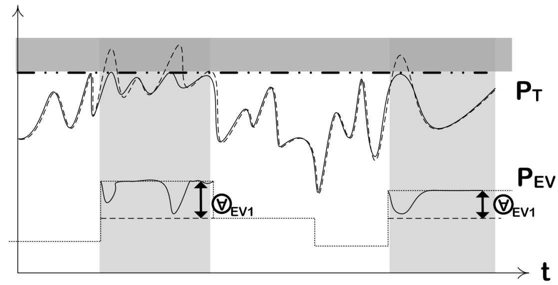

Figure 6.8: Plot-illustration indicating the effect of the overcharging avoidance control by EV 1. The solid lines indicate the behaviour with control and the dotted lines that if the EV would not intervene. The dark grey area illustrates the capacity that is made available by this service.

6.4 Chapter Conclusion

The presented cases demonstrate a flexible and generic modeling approach capturing the control relevant coordination aspects for balancing-oriented ancillary services. Both, process management aspects (controllability, predictability) and topology aspects (network constraints, dynamics) are represented and can be adapted to a variety of different settings.

MFM is particularly suited for modeling and understanding the potential roles of controllable HVDC lines in the mixed environment of AC and HVDC transmisssion. Here the control modes and the failure modes of HVDC lines are both features that can easily be modeled by MFM control functions and causal roles.

Part II

Operation Design and Scenario Analysis

Chapter 7

Toward Coherent Operation Design and Scenario Analysis

Plans are worthless. Planning is essential.
Dwight D. Eisenhower

The best way to predict the future is to invent it.
Immanuel Kant

To plan is to familiarize oneself with the future, and the future is always uncertain. In everyday life, we are comforted by the the expectation that things will be 'as usual', normal. Uncertainty about the future situations is thus mediated by *certainty of process* that enbables us to plan. In case of future energy systems, however, it has been widely understood that a continuation of a "business as usual" will not be possible. This situation is discomforting, as now we are even more uncertain, both about the future situation and about our methods to deal with it. Instead, we shall now seek a method of dealing with this doubly uncertain situation. This is the subject of the present chapter.

Anticipating the future is a complex task in itself – to deal with an uncertain future means facing a 'stunning' complexity[1]: we are unable to take a decision,

[1] Here 'stunning' describes, psychologically, the state of mind which is the natural response to being exposed to a highly uncertain and unfamiliar situation [190].

to choose any action, simply because there is no reference to decide upon. To give ourselves the opportunity to reason about this complexity, we require an object of reflection, to assume some things to be true in the future. Engineering models can help identifying opportunities, but ultimately, societal needs are not identified within the engineering method. Energy system models can be utilized to create scenarios open to reflection and goal analysis with a broad range of approaches and expertises.

On the one hand, we have models of present and near future operation concepts and control structures, which form the basis for redesign of power systems. On the other hand, we have scenario models facilitating the identification of a feasible resource mix that will challenge all present operation concepts. Both model types serve a common goal: the incremental transition of the present energy system to some future energy system, somehow guided by top-down and driven by bottom-up processes of design and experimentation. But how does this general process work? And how can information generated with one type of model be integrated with information from another type of model?

This chapter discusses the methodology of energy scenario development in context of modeling needs for integrating scenario design with the re-design of strategies for system operation and control. The relevance of an integrated approach to scenario development is emphasized, and in particular the role of conceptual and "intermediate" models is discussed in context of design and evaluation of future operation concepts.

7.1 Energy Scenario Modeling

The development of "scenarios" is a methodology to create a shared meaning and understanding of potential futures. The scenario is a set of assumptions defining the state of the world with a certain domain focus, spatial scope and resolution with respect to some specific time or time range in the future. In contrast to a 'vision', which implies a sense of shared purpose, the scenario is a coordination tool that creates a point of reference for reflection of different perspectives. Scenarios are thus also a means of providing a broader context for an interdisciplinary discussion of alternative futures. The formulation of such 'alternatives' also requires a the formulation of a reference, typically referred to as Business as Usual (BAU) scenario. The creation of scenarios is supported by scenario models mapping economic and environmental resources to socio-technical energy needs. The models support policy development by quantifying effects. Scenario models implicitly also assume given engineering requirements or lead to the formulation of new engineering requirements.

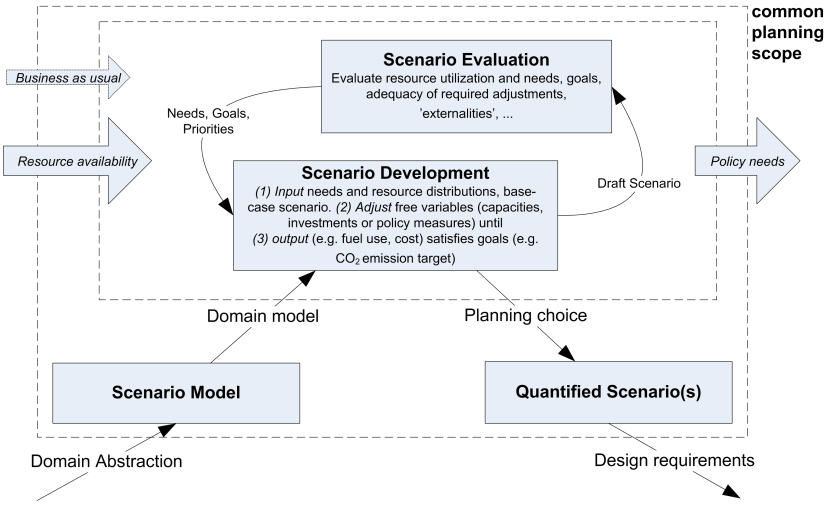

Figure 7.1: A block diagram illustrating the scenario development process. Energy scenarios are created by an iterative process in which the consistent quantification of a scenario serves as a ground of reflection. The quantification is facilitated by energy scenario models that enable a quantitative assessment of interdependent variables. Planning- and model-specific expertise is required for the scenario development, but reflection of the scenario impact and prioritization can be considered can be considered interdisciplinary and involve other fields of expertise (or non-expertise, for that matter). A common scope is understood as common time-span, spatial extent and domain (e.g. energy sector, electricity only, ...).

7.1.1 Energy Scenarios and Models

Energy scenarios are created for the planning of energy systems. Quantitative specification of a scenario requires the formulation of a scenario model, which models the internal composition of an energy system by specifying pathways, controllability constraints and operation (optimization) strategies. A scenario model is used to constrain the design space of a scenario, enabling a consistent quantification, and to operationalize the scenario development process into external requirements, assumptions and decision variables. The scenario model is thus meant to ensure that a scenario created on its basis can be considered 'realistic' – that is, to ensure that a reasonable quantification is formulated for which an implementation can be conceived.

Broad energy scenarios are typically created as a means to support political goal setting and appropriate policy development with a medium to long-term scope of five years to several decades. With a developing focus on climate change

mitigation and renewable energy sources, the development of energy scenarios has become an import means of coordinating political vision. Thereby, the methodologies that support the development of energy scenarios have received increased attention. In the scenario development process, which is illustrated in Figure 7.1, scenario models provide consistent relations for a quantitative formulation of the scenario, by defining input, output and optimization criteria/rules. Thereby they have a fundamental role in determining what is to be considered 'realistic' and contribute significantly to what is perceived as 'optimal' [225, 156] in the scenario development process.
A comprehensive review of energy planning tools to 'integrate' renewable energy is provided in [49]. From this review, it can be observed here, that:

- 'Conventional' planning tools tend to be designed for institutional environments such as governments or intergovernmental organizations, are complex and have a small number of expert users; alternatively, they tend to be sector-specific optimization tools used for utilities.
- A number of more recently developed tools tend to be relatively simple and integrate different energy domains, with a specific focus on integrating renewable energy sources; in that they differ from traditional sector-oriented and complex economic planning models.
- There is no 'general purpose' planning tool: *planning purposes* include (macro-)economic projections, optimal investment and operation planning, design of economic policies for the energy-sector, or creating cost-oriented alternative energy supply scenarios for small or larger areas.
- Planning tools require preconceptions: both model simplification and optimization criteria are part of any planning tool and can lead to different results of with respect to what is optimal [225].

The varying planning purposes each require different trade-offs between representation capability (domain model), handling (interface and data requirements) and computational complexity (e.g. optimization algorithms).
The planning tool developer decides which aspects are to be considered primary and which secondary and to develop simplifying assumptions accordingly. For example, the model-simplifications acceptable for renewable energy system planning are different from those for conventional energy systems: planning simplifications that remove time-sequence from the planning procedure, such as the traditional 'duration curve' oriented planning methods, cannot simulate realistic effects of operation strategies on interactions between energy storage and fluctuating renewable energy sources.

Apart from the specific planning tool, other relevant scenario studies focus on the assessment of large scale resource availability. For example in [103, 28], a resource assessment on a European level investigated how an optimal mix of wind power and PV could supply 100% of Europe's electricity demand. Such resource assessment provides information on relevant design parameters, as it characterizes renewable energy resources temporally and spatially. It supports scenario development, but is not a scenario model in the sense considered here.

The EnergyPLAN Model in MFM. The energy scenarios developed in the CEESA project were modeled with help of the scenario tool EnergyPLAN[2]. EnergyPLAN implements a model of an energy system composed of energy production, conversion, storage and consumption functions. The modeled energy domains include electricity, transportation, heat, "fuels" and hydrogen. Inputs to the model are formulated as specific technologies, but grouped by characteristic functions. Domain-internal transmission constraints are not included. Its inputs are hourly profiles of supply and demand (scaled by annual energy), conversion and storage capacities, as well as efficiencies, and its outputs are the utilization of dispatchable resources of different kinds and electricity imports [159].

The MFM model presented in Figure 7.2 demonstrates the conceptual structure of EnergyPLAN's domain model. Observe that the causal structure of the model shows two residuals: Electricity imbalance (**sosi**, at the top right) and fuel/biomass (**source**, bottom left). For matching demand and supply, controllable functions can be adjusted (marked by $\bigtriangledown$). Flexibility in production and consumption is offered by fuel-based technologies, demand flexibility (not illustrated), and by energy storage serving as a buffer in various locations in the topology.

The built-in scheduling mechanism in EnergyPLAN is rule-based and offers several strategies for optimization, such as technical and cost-oriented decision-criteria. An overview of the effects of scenario optimization criteria is provided in [225]. For example, hourly export-import can be eliminated by eliminating the electricity imbalance. In this mode, the residual planning variable remains the biomass (fuel) consumption. In economic optimization modes, for example marginal fuel costs are traded off against electricity costs.
Whereas the optimization can consider different decision criteria, it does not simulate actual decision making in the time-sequence, and it does not model forecast uncertainty. Clearly, the trade-off for this model is toward simplicity of computation rather than accuracy of system behaviour – how could this be a reasonable trade-off when computation time and power seems abundant?

[2] The EnergyPLAN software is freely available at http://energy.plan.aau.dk/.

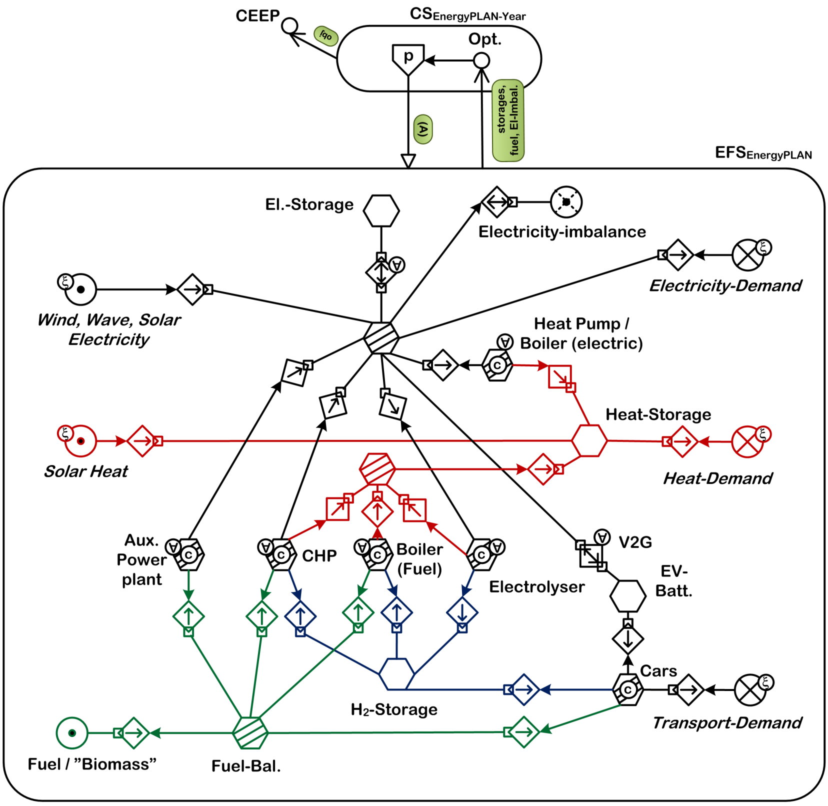

Figure 7.2: MFM conceptual model of EnergyPLAN (adapted from EnergyPLAN schematic [159]). Supply and demand distributions are modeled as ⓧ attached to a source or sink, respectively. A few pathways and differentiations included in EnergyPLAN have not been modeled to avoid an overly complex diagram.

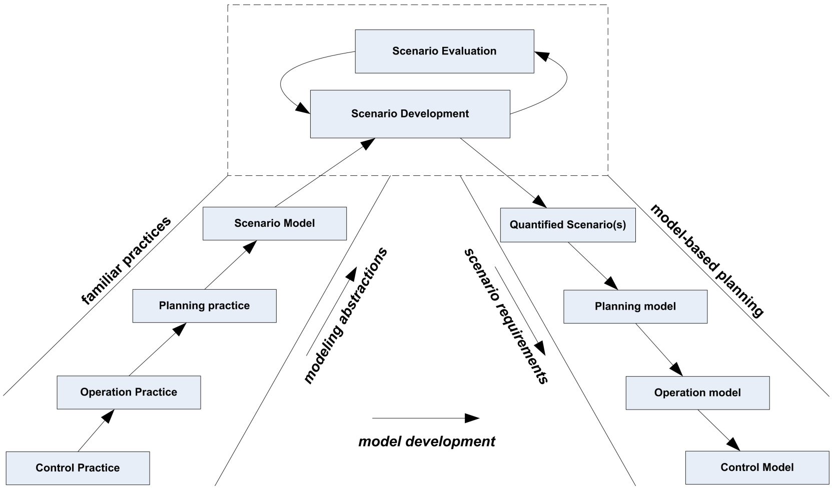

Figure 7.3: Scenario models are developed as simplified planning models, using abstractions of familiar operation and planning practice. A given scenario poses design requirements for policy development, but also for the planning of future system operation in case of qualitatively different requirements.

7.1.2 Scenario Feasibility vs. Feasible Scenarios

While a scenario model is considered a simplification of the 'real world', its purpose is to capture major quantitative interactions in energy systems. In analogy to model-simplifications that are employed for the technical reasoning, these simplifications are aimed at providing insight for quantitative decision-making. The difference is thus that scenario models are built to approximate the quantitative outcome, but not to simulate the actual process. The abstraction level is chosen as high as possible to allow for simple computations whilst providing quantitative results as accurate as necessary (illustrated in Figure 7.3).

Highly Feasible Models. A highly complex scenario model for which current and proven operation concepts as well as existing power plant data are mapped into the model constraints can provide exact estimates of cost and resource utilization. A quantified scenario based on such calculations is very likely to be technically and economically feasible. On the other hand, consider that operation strategies are likely subject to change. Also current and proven technology is not a good reference for future energy scenarios which will be based on new and future energy technologies. For example, some of the models presented in [49] would not be employed to model 100% RES scenarios, because the often

detailed models require data that is still highly uncertain, or build for example on market rules that may not support energy systems with largely fluctuating electricity generation. Detailed and complex models may require more input data and skill in utilization, which may make it harder to iterate over the decision variables and in the general scenario development and evaluation process illustrated above. This iteration is important because it enables experts from other domains to identify opportunities and barriers in a scenario that are invisible from a model-internal perspective.
Model complexity also translates to opaqueness: if other experts gain insight into the modeling assumptions, the scenario consistency cannot be verified[3]. The complexity of highly accurate models thus may induce a number of external risks to the planning.

Simple Approximate Models. The simpler a scenario model, on the other hand, the more uncertain it is, whether a scenario created on its account is realizable/feasible. A higher certainty of feasibility can be achieved by employing conservative simplifications based on current conventional operation concepts (speaking of "base load power plant", for example). To gain a comparable level of certain feasibility as a complex conventional model, such a model necessarily would have to be significantly more conservative. A simple model is more accessible for discussion of quantitative alternatives and therefore more accessible to evaluation and feedback (Fig. 7.1). This feedback is valuable for identifying opportunities and mitigating systemic risks in general. Here expertise from different backgrounds can be gathered to discuss rather than to identify pathways and barriers, rather than to calculate the 'optimal' system.

The purpose of long-term energy planning is not the evaluation of alternative system designs, but to assess feasible alternative resource allocations, using a good approximate system. For a system that is feasible in terms of resources and technology, control interactions and further details can then be further designed. A suitable model for long-range energy scenario planning has risk-minimizing properties: deliver the best trade-off between uncertainty of technical implementation and the uncertainty of systemic barriers that cannot be modeled within the optimization.
EnergyPLAN is a scenario model of this latter category: It is relatively simple and very fast and serves facilitation of multi-expert discussion [158][4], it is well-documented, though, as a rule-based model, possibly difficult to assess.

[3] One should note here, that simple computation does not guarantee transparency: a rule-based model is harder to analyze than an optimization-model, which more compactly formulates its objective and constraints.

[4] Also the STREAM model (`http://www.streammodel.org/`) and to a more radical extent, the physical model underlying the edacational planning-simulation "Changing the Game" (`http://www.changing-the-game.org/`), are designed to this purpose.

7.1.3 From Scenario to Design Requirements

An energy scenario created on the basis of such a "good" energy scenario model, thus necessarily is highly uncertain in terms of technical feasibility. It is thus important to recognize this *design problem* embedded in the scenario analysis. An energy *scenario* developed in this way provides a *reference* for identifying specific challenges to be met by further scenario detailing and engineering design. A *frame of reference* for the challenges to be anticipated can be identified from the assumptions built into the underlying *scenario model*. Some specific simplifications utilized in EnergyPLAN include:

- Hourly resolution instead of continuous time; no ramping limitations
- Lack of internal transmission limitations & spatial distribution of resources
- Deterministic hourly distributions (i.e. no probabilistic information)
- 'Benefit-of-hindsight', rule-based, heuristic operation modeling

Each of these inspires the need for more accurate models and deeper analysis. For example, many scenario tools are based on mathematical optimization, where the choice of objective functions yields a more transparent dispatch behaviour, or they include a time-forward perspective that includes uncertainty of future developments (as in e.g. the WILMAR model [248]).
However, each further specification also implies further design steps: What objective is the system optimized toward? What are actual costs? How are operation and investment decisions influenced by the policy framework? Furthermore, there are concrete questions regarding the operation design: How is the system balanced on a continuous basis, how responsive would the available technology be? How accurate are prediction models and how can system operation be organized to provide sufficient affordable resources for balancing the system in the short-term? How should transmission lines be distributed – and how does the cost of power transmission compare to the cost of energy storage?

These questions require technological and policy developments on many different levels. For example, if technical feasibility is to be studied, models are required[5] that are oriented toward the domain of the technical design. In the engineering

[5]The purpose of a scenario is creating a common understanding of goals and options. For requirements analysis in complex (software) engineering projects, the "use cases" methodology serves for a similar purpose, but it presumes a given context and goals. In the strict sense, the control cases discussed in the previous chapter are embedded – as 'control use cases' – in future energy scenarios which provide the context for future power systems. In contrast to a scenario, use cases model specific activities in relation to actors' interests and capabilities – their purpose is formalization of knowledge toward engineering requirements.

approach, design choices are made incrementally, usually on the basis of existing and acquired engineering knowledge and procedures. In case of major steps in the scenario requirements, an incremental development may not be feasible on the basis of existing domain knowledge. As energy systems are complex, the design space to be explored is vast and the complexity of models may make it hard to evaluate alternatives.

Each design advancement can have implications for other scenario aspects. For example, to decide whether electric vehicles should be prioritized in the transport sector, has been found to be dependent on the prioritization of wind power – however, to what extend this dependency can be quantified is partly a question of system operation and control design. Such implications are not easily mapped from one domain to another. For a coherent advancement of energy scenarios, technology and policy design, it is essential to recognize this interdependency and to look for ways of integrating the different forms of advancement.

7.2 Formation of Future System Operation

Control architecture of power systems is not just re-invented and changes are not implemented ad-hoc – it transitions by different forms of advancement. Both technology-oriented and overall 'systemic' conceptions of control are adapted with time. Different levels of advancement coexist.
As complexity of power systems is increasing, also the respective design problem is getting more complex: new resources with varying characteristics are to be integrated in a way that complies with more varied perspectives. The increasing complexity becomes a problem also for communication, human reasoning and collaboration which require a common frame of reference, a shared understanding of the subject matter [190]. Change also means that common conceptions loose validity. New conceptions of system operation have to be developed, partly in a top-down fashion by research, and largely also by technology-driven and social experimentation.

Top-down design requires representations for planning, more or less abstract models which can be employed to relate design objectives and challenges to process and control functions. Also for the bottom-up approach, it is important to relate results to requirements and expectations for future control scenarios. Either way, generic models and formal frameworks can provide the context for fruitful experimentation and meaningful research. Qualitative modeling supports facing the challenges of complexity in designing and planning for future power systems.

7.2.1 Integrating Design and Experimentation

Clearly, there is a very practical challenge of transforming present practices and conceptions of power system resource allocation, operation and control. The future practices would be coherent with quite different operation concepts that are practical and appropriate for those challenges posed by sustainable energy scenarios. But is 'trans-formation' the right concept to start with? The 'trans' implies the existence, at least conceptually, of another side. But that other side is yet to be defined. The consistent re-development of energy scenarios is an important (societally mediated) process. But a scenario is not a 'plan'. An energy scenario with 40 years horizon is not defined today and 'implemented' tomorrow. It is part of a process of integrated planning and experimentation. This process corresponds to the development of that 'other side'.

The challenge of transforming a running machine in operation, as the electric power system, requires at least two separate planning/design steps: *formation* and *transitioning*:
Formation means an approach of integrated design and experimentation that is facilitated by simulation of technical and policy alternatives. Its inherent goal is the breaking up of present operation concepts and development of new operation concepts which can be manifested by integrated modeling and simulation at several levels of modeling abstraction. The outcome of such a process is a clear conceptual understanding of that 'other side' of the transformation. In context of the scenario development, this process is illustrated in Figure 7.4.
The second step would then be *transitioning*. Its objective is the actual adaption of present operation (control, coordination and market) principles toward the concepts developed in the scenario-oriented formation process. Present operation concepts don't change abruptly, but adaptation is always possible. Consistent long-term adaptation would be supported by the identification of transitioning strategies, which can be seen as a 'deployment' strategy for a new understanding and practices. Effective transitioning requires a common conceptual understanding and decomposition for both present and future (formed) operation principles.
For the remainder of this dissertation, the focus remains on the formation problem. It is obvious, however, that in practice, such as in large-scale 'demonstration'-projects, both formation and transitioning must be integrated. If the formation-aspect is disregarded, the 'demonstration' degenerates to a large-scale, thus expensive, experiment, which is not bad or a failure in itself, but has a different value proposition (i.e. innovation vs. deployment).

The idea that concept development and experimentation form an integrated process for adaptation to uncertain, complex and changing physical and social environments is not new in other domains. In the military domain, the work

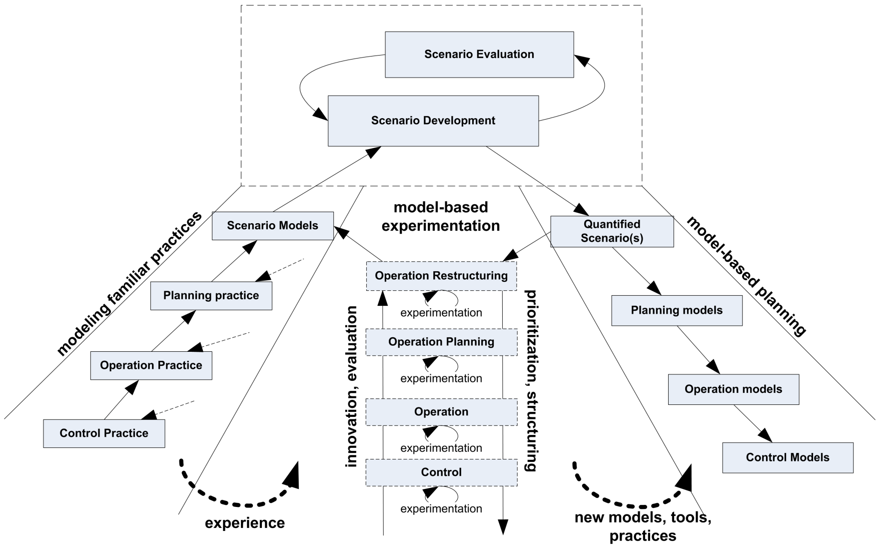

Figure 7.4: In addition to modeling as simple abstractions from current operation and control practices, new models and simulation environments are required. These environments serve as a means of experimentation and, supported by formal methods, evaluation of alternatives.

of Albert and Hayes [8, 7] sets a focus on frameworks and methods for experimentation and emphasizes the need for a deep conceptual understanding, in particular of non-software and control concepts [9], for the 'harvesting' of solutions to retain new solutions and to avoid re-development of known solutions. With a very different background (sociology) and application domain (carbon taxes or trading), also Callon [43] advocates an experimental, and thus also learning-oriented, approach to the development and deployment of policies and infrastructures for carbon trading. The idea of experimentation with infrastructures and concepts of dependability and resilience engineering in the software domain are related (e.g. [224, 98]), but at present there is no support for the conceptual development and adaptation outside the information and communication domain.

Here, the focus is not only more specific on the energy and power systems domain. We also emphasize the utility of combining control-oriented (means-ends) formal models for problem formulation with simulation approaches for experimentation. This is to support an integrated approach to problem identification, formulation, modeling and solution development. The scenario-oriented development of operation concepts requires 'top-down' evaluation and adaptation of models, as well as 'bottom-up' experimentation for actual problem solving.

7.2.2 "Top-down": Problem Formation and Evaluation

The means-ends modeling approach used and extended in Part I of this work is also a tool for incrementally structuring the design space in a top-down (ends-to-means) fashion. By providing concepts of control and energy flows, MFM offers building blocks for a systematic representation of the processes that form energy systems. Systematic model simplification (abstraction) and concretization facilitate the design process by incrementally *structuring the design space*. In a structured design space, requirements can be mapped to respective model abstractions, which then can be adressed for design and problem-solving.

The model abstractions can be developed systematically on the basis of MFM. On the one hand, transformation rules can be applied to to flow-structures which correspond to detailing and simplification of the domain models. Implicit and explicit formulation of control structures provides a conceptual means of clarifying acceptable design abstractions for planning models (the folding-unfolding of control structures was presented in Chapter 4, Section 4.4, and is illustrated in Figure4.23). Further, the means-ends composition of these models provides a hierarchy of impact: the performance of design-oriented models justifies the feasibility of modeling simplifications. Internal constraints can be mapped to performance characteristics at higher levels of abstraction (e.g. distribution-level constraints cannot be always be modeled at higher level models, but they influence the availability of power reserves at these levels.)

In a very concrete way, the "approximate design" of the energy system present in the scenario model, the domain model in Fig. 7.2, can be adapted to focus on the requirements of the electricity infrastructure: the system topology can be adapted incrementally, first by reducing the flow-structure to model functions that interface with the electricity domain, by moving the system-boundary, or by aggregating non-electric functions. Here it becomes apparent that, depending on the problem formulation, the integration with other domains influence the degrees of freedom available for operation in the electricity domain. In this case it could be crucial to identify interfaces between different modeling domains. Eventually a detailed model such as that in Figure 8.4 on page 205 can be derived.
New operation objectives would have to be defined, corresponding to the model-aspects in consideration. Control functions can be added, depending on the scope of the design. For example other optimization approaches can be formulated. If the modeling scope is on understanding system operation, actual control structures can be included, such as those from Section 6.1. Detailing performance requirements for control structures requires also further study of the fluctuating process behaviours and component dynamics. In a top-down fashion, this model adaptation formalizes the studies to be performed for eval-

uating the feasibility of energy scenarios.
In another perspective, the models also formulate a framework for evaluation of experimental results in relation to the feasibility of alternative scenarios.

7.2.3 "Bottom-Up": Experimentation

Experimentation can be understood in the widest sense: "to try something and to observe what happens". As a methodology, experimentation is a mode of (possibly systematic) hypothesis-testing. Experimental set-ups, as well as modeling tools, provide an environment where cause and effect, hypothesis-formulation and -testing are integrated. The direct feedback of success and failure enables an explorative approach to hypothesis generation and testing. Innovative solutions tend to spring form explorative approaches, and thus experimentation is an essential ingredient to any venture into unknown spaces.

We don't need to further explain the value of experiments here. The key point in relation to the conceptual and architectural approaches discussed so far is the need for some form of "experimental setup". Every experiment is characterized by a certain confinement that, at least conceptually, isolates the experimental domain from its environment, such that experiment and result can form a coherent unit. Further, the construction of a experimental setup requires an understanding of expectations and valuation: In what framework can the experimental results provide relevant information can be gained from the experiment (i.e. what kind of information?). Problem formation, also supported by conceptual models, helps specifying such requirements for experimental environments – and they provide the grounds of integrating experimental results into related studies.

7.3 Chapter Conclusion

In the search for new ways of ensuring energy supply for society, energy scenario models are not merely planning models, but rather a communication and coordination tool in the search of a feasible and sustainable energy supply. This different role of a scenario model induces different criteria on the scenario model than on a planning model. A planning model is aimed at reflecting actual operation procedures which enables more concrete decision-making in a planning context (for example to investigate timing and sequence of market gate closures [164]). Planning models should therefore also be adaptatable for design of operation procedures.

The concepts and results presented in this chapter suggest a synthesis of scenario development and simulation-based operation design. It was clear beforehand that future operation concepts cannot be designed and applied ad-hoc, simply because power system are too complex and the changes required are too deep. The introduction of the formation and transitioning concepts enabled an understanding of the central role that a conceptual understanding of "what system we're coming from" and "where we're going to" has in the transformation toward future power systems. The representations developed in the previous chapters can hereby facilitate the incremental problem formulation and analysis of operation concepts.

The proposed use of MFM-based conceptual models for integrated scenario analysis and operation design can be viewed in line with the vision of MFM as a means for sustainability-evaluation of energy and evironmental systems, which was proposed by Yoshikawa *et al.* [261].

Chapter 8

Extension of Conventional Power System Models

A central feature of the scenario models discussed above was their integration between the different energy sectors. For studies of power system operation or power markets, those sectors are typically not included, which is meaningful when sufficient adjustable resources are available to compensate uncontrolled fluctuations of the power demand and renewable power generation. The conceptual boundary of power system operation, and its respective models would end at the meter, or even before the distribution level.
In energy scenarios with, say, 50 % wind energy, the activation of today still uncontrolled resources becomes a necessity. For example thermal energy storage, which may already be in place physically, could act as a buffer between supply and demand. Whereas the physical storage may be in place, its function as a buffer for the power system usually is not. And if a storage is already in place, it likely is already a meaningful resource for a different purpose.
The question for operation design for such future power systems is, whether and how controllability of storage or other 'external' resources should be considered.

This chapter discusses the role of energy storage in power system operation with very high amounts of fluctuating renewable energy. Then a new modeling and simulation framework for power system operation studies is introduced, which has been presented in [PN-I, PN-II]. In context of planning and scenario modeling, the application of conceptual models to the domain is illustrated.

8.1 Operation with Energy Storage

It has been widely accepted that energy storage has an increasing relevance for power systems, and the integration of energy systems in general. For example, it has a role in integrating wind power beyond about 20% of the electric energy supply in present power systems [233]. It is considered relevant for high-level modeling approaches, including the scenario models given above and th study of other concrete financial or reliability oriented planning approaches [79, 112, 110]. It is also envisioned for the concrete provision of concrete technical services at all levels of system decomposition (e.g. [72] provides an overview).

8.1.1 The Energy Storage Challenge

In general, energy constraints are hardly considered in present power system operation concepts[1]. For the longer term and a system composition of the kind anticipated in the CEESA scenarios, energy storage aspects and limitations (beyond electric vehicles) will become more and more important for power system operation. Energy constraints, that is constraints to the *duration* of power delivery, can become a security critical factor in future system operation. In the present operation paradigm, energy storage can only be 'hidden' within the portfolio of a balancing responsible market party. In particuar if energy storage should be included as a reserve, the constraints of this resource need to be transparent to power system operator(s). Another important study aspect is the evaluation of energy storage against transmission investments, which can also be viewed from a security/reliability perspective.

Energy storage is not 'naturally' part of power system studies, because it is always at the periphery: from an electrical perspective, it is not to be distinguished from other demand and supply units. It can be distinguished in dispatch problems where also rate-constraints of generating units need to be considered. However, demand and supply have already ceased to support the clear-cut conventional categories that used to define generation (supply) as controllable and demand as fluctuating (as discussed in Section 4.2). Electrically, we distinguish controllable from uncontrollable units separately with respect to

[1] One could argue that the "frequency containment" measures (incl. primary frequency control) combined with secondary frequency control actually control the energy level of the buffer provided by the inertia of synchronous machines.

active power and reactive power (Section 4.3), which qualifies as a simplified but accurate assumption for higher voltage levels. The controllability of active power, consumption or generation, also characterizes energy storage of different types.

8.1.2 Simulation Experiments with Energy Storage and Wind Power

As part of the collaboration work on the CEESA project, simulations of grid control and electric vehicles have been performed. Some of those results are reported in [193, 194] and more are found in [192]. Some main outcomes are:

- electric vehicles have – in principle – a very significant potential in providing fast grid support for frequency balancing in disturbance situations, in particular if enabled to discharge electricity to the grid ("V2G mode");
- the energy limitation of electric vehicles renders them unfit to provide continuous support for conventional control services, because a bias in the control signals is not uncommon; this leads to battery storage under- or over-flow.

The latter issue can technically be resolved by applying a high-pass filter to the control signals (as demonstrated in [131]), or by dynamic co-optimization with other units as demonstrated in [76]. However, institutionally, this option needs to first be enabled, for example by providing regulations to enable aggregate responses to grid signals (discussed in [77]).

8.2 Power Nodes Modeling Framework

As suggested above, frameworks for experimentation have to be developed to study in combination the feasibility of scenarios and the need for new technical solutions. This section presents a modeling framework and simulation environment that follows the idea of integrated experimentation and scenario-oriented evaluation of operation strategies.

We propose the following "Power Nodes" concept as a framework for the study of power system operation on the basis of energy storage. The main results of this work have been published in [PN-I] and [PN-II]. Here only a summary is provided and a connection to the MFM conceptual models is established.

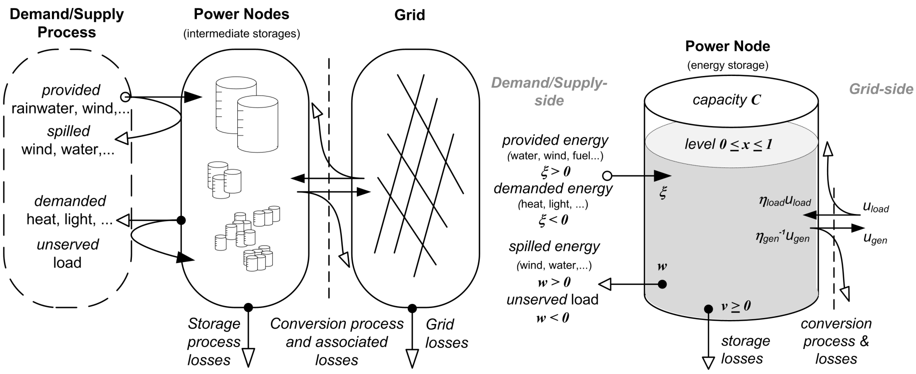

Figure 8.1: The Power Node Domains concept and notation for a single Power Node.

8.2.1 The Idea

The basic premise of the Power Nodes approach is that any power source or sink connected to the electric power system requires the conversion of some form of energy into electric power, or vice versa. These forms may be termed "supply"- or "use-forms" of energy, respectively. The degrees of freedom available for fulfilling the power balance in the electric grid arise from the freedom that the supply- and use-forms of energy provide, either by being controllable or by offering inherent storage capacity. Abstracting from the physical unit and the internal composition of a supply- or use-process including the associated energy conversion, we represent it from a grid-perspective as a single lumped unit with characteristic parameters, a "power node". The introduction of a generic energy storage perspective adds a modeling layer to the classical modeling of power systems, illustrated in Fig. 8.1, to the left. All supply and demand processes are connected through a power node to the electricity grid. In other words, the modeling of an electric energy system is not extended to a multi-carrier system, as in the EnergyPLAN scenario model above or in the Energy Hub concept [79], but to a *buffered electrical energy system*. If a demand or supply unit is considered not to include relevant storage of sorts, the storage capacity is simply set to zero.

8.2.2 Model of a Single Power Node

Consider the structure of a single power node consisting of the elements illustrated in Fig. 8.1, on the right. In comparison with the three-domains-model on the right, the provided and demanded energies are lumped into an external process termed ξ, with $\xi < 0$ denoting use and $\xi > 0$ supply. The term $u_{\text{gen}} \geq 0$ describes a conversion corresponding to a power generation with efficiency η_{gen}, while $u_{\text{load}} \geq 0$ describes a conversion corresponding to a consumption with efficiency η_{load}. The energy storage level is normalized to $0 \leq x \leq 1$ with energy storage capacity $C \geq 0$. Fig. 8.1 illustrates how the storage serves as a buffer between the external process ξ and the two grid-related exchanges u_{gen} and u_{load}. Internal energy losses associated with energy storage, e.g. physical, state-dependent losses, are modeled by the term $v \geq 0$, while enforced energy losses, e.g. curtailment/shedding of a supply/demand process, are denoted by the waste term w, where $w > 0$ denotes a loss of provided energy and $w < 0$ an unserved demand process.

This labelling for the power node equation provides a generic embedding of energy conversion and storage processes. The dynamics of an arbitrary power node is described by the energy balance:

$$
\begin{aligned}
C_i\,\dot{x}_i \quad &= \quad \eta_{\text{load},i}\,u_{\text{load},i} - \eta_{\text{gen},i}^{-1}\,u_{\text{gen},i} + \xi_i - w_i - v_i, \qquad (8.1)\\
\text{s.t.} \quad &(\text{a}) \quad 0 \leq x_i \leq 1 \quad ,\\
&(\text{b}) \quad 0 \leq u_{\text{gen},i}^{\min} \leq u_{\text{gen},i} \leq u_{\text{gen},i}^{\max} \quad ,\\
&(\text{c}) \quad 0 \leq u_{\text{load},i}^{\min} \leq u_{\text{load},i} \leq u_{\text{load},i}^{\max} \quad ,\\
&(\text{d}) \quad 0 \leq \xi_i \cdot w_i \quad ,\\
&(\text{e}) \quad 0 \leq |\xi_i| - |w_i| \quad ,\\
&(\text{f}) \quad 0 \leq v_i \quad \forall\, i = 1, \ldots, N \quad .
\end{aligned}
$$

Depending on the specific process represented by a power node and the investigated application, each term in the power node equation may in general be controllable or not, observable or not, and driven by an external process or not. Internal dependencies, such as a state-dependent physical loss term $v_i(x_i)$, are feasible. The constraints (a) – (f) denote a generic set of requirements on the variables. They are to express that (a) the state of charge is normalized, (b, c) the grid variables are non-negative and bounded, (d) the supply/demand and the curtailment need to have the same sign, (e) the supply/demand curtailment cannot exceed the supply/demand itself, and (f) the storage losses are non-negative. Ramp-rate constraints, especially constraints on the derivatives $\dot{u}_{\text{gen},i}$ and $\dot{u}_{\text{load},i}$, can be included for power system studies under dynamic operating conditions with a simplified representation of the local dynamics.

A Power Node without Storage Power nodes are also useful to represent processes independent of energy storage, such as intermittent renewable generation or conventional generation and load. A process without storage ($C = 0$), implies an algebraic coupling between the instantaneous quantities ξ_i, w_i, $u_{\text{gen},i}$,

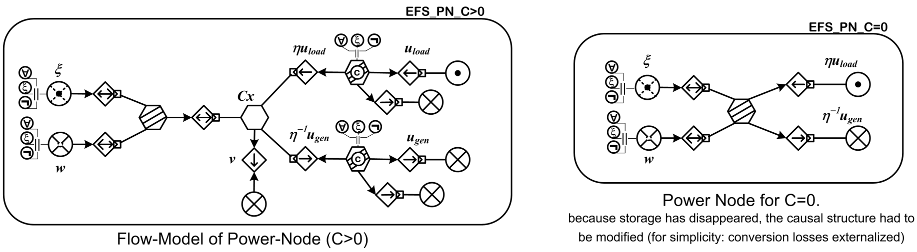

Figure 8.2: MFM model of Power Nodes. The process agent roles indicate which flows are determined by external constraints as controllable ∇, fluctuating ξ or constant $\ominus$. The roles are connected to indicate alternative options, only one role can be active in one model.

and $u_{\text{load},i}$; storage-dependent loss does not exist ($v_i = 0$). Equation (8.1) degenerates to

$$\xi_i - w_i = \eta_{\text{gen},i}^{-1} \, u_{\text{gen},i} - \eta_{\text{load},i} \, u_{\text{load},i} \quad . \tag{8.2}$$

This model is particularly relevant for external supply and demand processes, which are not directly controllable, while there may be a choice to curtail the process. Examples are intermittent power generation ($\xi_{\text{drv},i}(t) \geq 0$) and classical load ($\xi_{\text{drv},i}(t) \leq 0$).
In the case of a fully controllable supply process such as a conventional generator, either the grid-related variables $u_{\text{gen},i}$, $u_{\text{load},i}$, or the power exchange with the environment through ξ_i can be considered as the controlled variables. ξ_i then accounts for example for primary energy usage.

For further details on the interpretation and application-oriented interpretation of the concept, please refer to the papers [PN-I] and [PN-II].

8.2.3 Power Nodes as MFM patterns

The Power Node concept has been conceived as a generic functional pattern of grid-connected units with inherent energy storage, such as a reversible storage unit or a buffer between conversion to/from electricity and demand/supply process. Even though a mathematical formulation of this process has been presented first, it is motivated as a functional pattern. The two basic patterns are presented in Figure 8.2. Special cases of this model typically mean that one or another of the functions is disabled (examples in Figure 8.4). Note in particular how controllability aspects are transparently modeled as external agent roles. The reduced controllability in the no-storage case also follows the logic of MFM patterns. The three options for external influence are indicated by the three attached roles. Only one role can be valid at a time, but as suggested by the discussion in Chapter 5, Section 5.2, a decomposition of functions by time-scales and planning stages can be considered, which will be discussed in the following Section.

8.2.4 Multi-Stage Formulation of a Power Node for Operation Planning

As discussed in Chapter 2, planning and resource allocation are an integral part of power system operation. Resources are allocated in different planning stages and are allocated to control functions that operate at different time scales. One physical resource can thus serve different control functions at different time scales. By planning, a share of its behavioural range would be reserved for the respective function and time scale. It has been observed that the consideration of time scales is reflected by behavioural roles in Chapter 5), by choosing what is considered controllable, constant, or fluctuating. Also the representation of energy storage is affected by time scale and planning considerations. Consider the following three cases:

a) Energy storage 'disappears': it is *too small* for the considered time scale.

b) Energy storage 'disappears': it is *too big* for the considered time scale.

c) Energy storage is split up.

Cases a) and b) reflect a common understanding in time-scale separation (decoupling) of a dynamical system into fast and slow dynamics.
In case a), a storage that is relatively small in proportion to its respective time scale, $\Delta t \gg \frac{\text{allocated energy capacity}}{\text{allocated power range}}$, is modeled as a balance ($C \approx 0$). A degree of freedom is thus removed from the system, and consequently also one external influence must disappear: either process fluctuations or controllability 'disappear' together with the storage. For example the thermal capacity of a conventional power plant process would not be modeled explicitly as storage for the planning stage of unit-commitment.
For an energy storage that is relatively large with respect to the considered time-scale, $\Delta t \ll \frac{\text{allocated energy capacity}}{\text{allocated power range}}$, inflow and outflow from the energy storage are decoupled: the storage state is quasi-stationary ($C \to \infty$). Here the two flow-processes connected through the storage (e.g. primary energy supply and electricity generation) are decoupled, therefore one of the processes would disappear. To offer regulating power, one would not not need to model the energy storage embedded in the fuel supply (e.g. the coal storage). As a result, the

system boundary is moved and the respective process would also be modeled by a balance, corresponding to the power node model for $C = 0$. By convention, both cases are thus modeled as non-buffered Power Nodes.

For case c) there are two possible interpretations: a common perspective is that the actual system is composed of several storages and flows that correspond to separable time scales (e.g. in a cooling system: the compressor level vs. the actual cold storage).
Another interpretation is particularly relevant for the consideration of one unit in separate planning stages that have approximately the same time scale of execution: As previously observed, controllable ranges are "hedged" so that different fractions of a controllable range are allocated to different (control) functions. This separation is essential for the allocation of resources for system operation to different functions. The storage should thus be divided much in the same fashion as a controllable range of a power plant, for example. Portions of the energy storage capacity and storage state would be allocated separately, to different functions, stages, and possibly time scales. Mathematically this is possible by the principle of superposition. However, this principle is only valid for linear systems. In [PN-II] it is shown that the decomposition can also be applied to an affine model of power nodes which applies for a wide range of component classes including thermal storage systems [111].

The multi-stage formulation of the Power Node model also is a good demonstration of the importance of differentiating between the physical component and its functional role in system operation.

8.2.5 Modeling Examples for Power Nodes

Modeling in the power nodes framework offers the benefit of clear energy balancing, and it is thus easy to apply. It differs from other multi-domain models in that not the interconnection of energy systems is modelled, but only the degree of freedom made available. As a result,power system operation can remain to be viewed as an isolated problem.

Let us discuss an example case, as presented in Figure 8.3. The system would likely be modeled differently in a dispatch and in dynamical operation view, depending on whether the respective component would be participating in the respective control context. In Figure 8.4, the grid is modeled in the dispatch perspective as transmission constrained. Other model perspectives can be associated with different control levels – in analogy to the grid operation models presented in Chapter 4 Figures 4.8, 4.9 and 4.23.

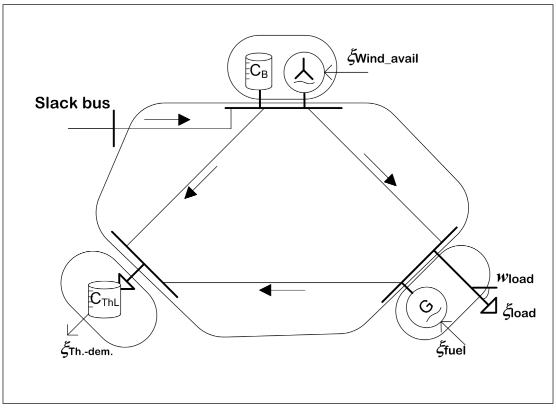

Figure 8.3: Example power grid with controllable and fluctuating generation, buffered and curtailable load, and a reversible storage system. The domain modeling is illustrated by bubbles encircling the grid as a whole and the power node domains at the interface.

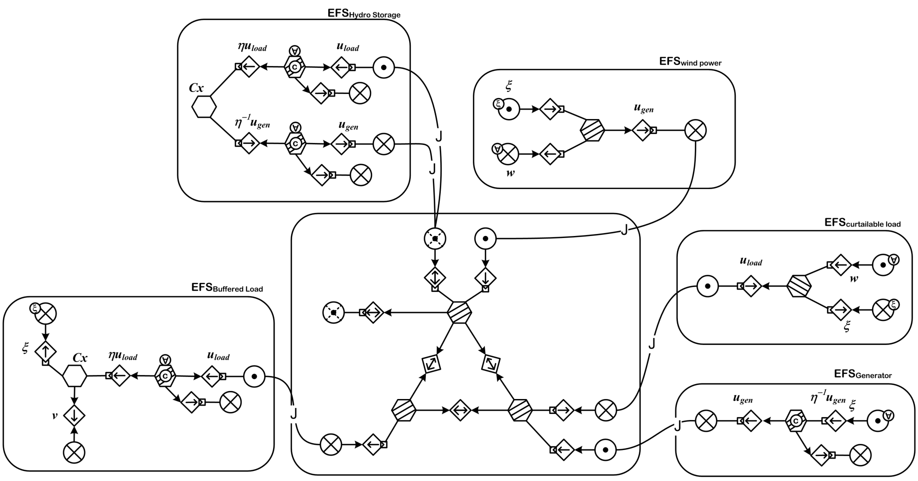

Figure 8.4: Example power nodes domain model in MFM notation. The view presented shows the domain model in view of a transmission-constrained dispatch problem. The power nodes domain is separated from the electric grid perspective by Janus relations. The generic power node cases of Fig. 8.2 have been adapted to the given special cases.

8.3 Simulation Framework

The simulation model is aimed at an integrated simulation of system operation within a scenario-oriented environment. Operation simulation on the basis of a scenario requires a relatively simple and easily configurable system description. To simulate system operation, both short-term planning under uncertain forecasts and actual execution on the basis of scheduled and fluctuating generation need to be included. The planning stage aims at establishing an optimal schedule based on uncertain system knowledge, which implicitly models the market outcome based on marginal operating costs. This objective can be formulated as minimizing the cost of system operation while maintaining power system security constraints. In real-time operation, the schedules define the expectation for an operating point, to be disturbed by the actual events. The power system dispatch schedule is generated in a two-stage planning process:

- *Day-ahead dispatch*: daily multi-period optimization for a complete day, with optimization horizon of several days; generates baseline operating point schedule for the controllable variables and storage states, utilizing predictions of the uncertain variables with a time-lag of half a day; the optimization result can be interpreted to reflect a market outcome.
- *Intra-day rescheduling*: receding horizon optimization, executed e.g. hourly, utilizing predictions with a short time-lag as well as the day-ahead baseline controllable variables and storage levels; results in new operating point schedule for controllable variables; the result can be interpreted to reflect the intra-day market outcome.

Here, the formal structure of the power nodes framework enables a simple reconfiguration of the scenario data. The dispatch is solved as global optimum for the planning horizon and on the basis of uncertain forecasts. The dispatch is then utilized for the 'real-time' execution of power system operation on the basis of dispatched and 'actual' generation:

- *Real-time operation*: simulation of continuous system behaviour with high time-resolution; utilizes the operating point schedule for the controllable variables and actual values of uncertain variables, enhanced by characteristic power fluctuations; here, power system operation structures are modeled.

An implementation of this simulation framework has been developed and presented in [PN-II]. It consists of two main parts: a) The "planning-simulation"

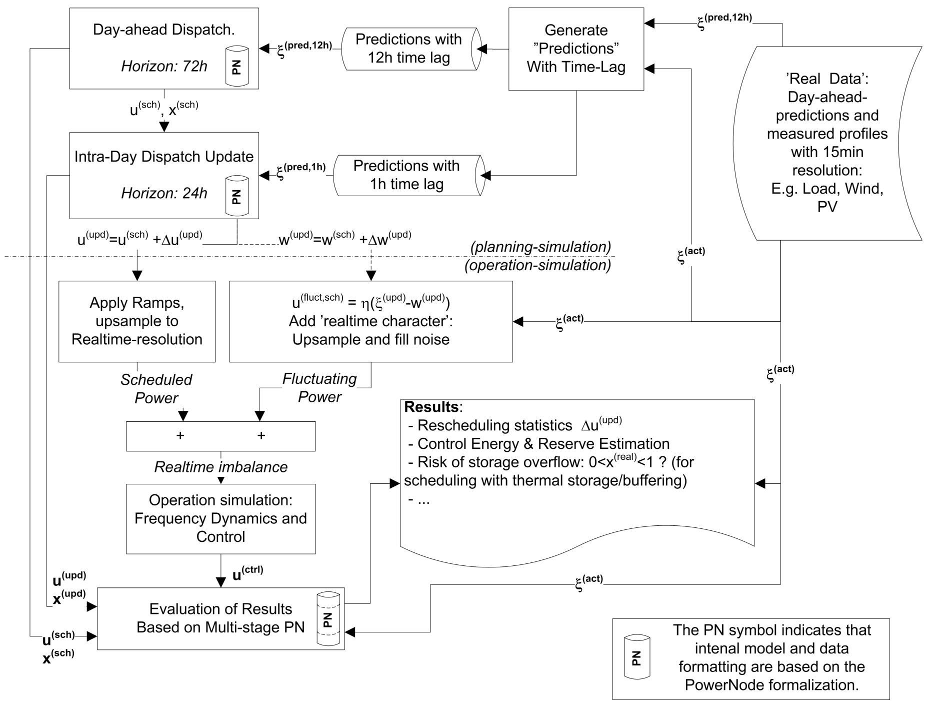

Figure 8.5: Flow diagram of simulation framework. Note the separation between planning-simulation and operation (execution)-simulations. The input reference for the dispatch is generated on the basis of artificial forecasts and the real-time operation is based on the actual reference data plus artificially generated fluctuations to mimic the characteristic behaviour of load and fluctuating renewable energy.

has been implemented on a Model Predictive Control platform for efficient schedule computations based on in-feed and load forecasts in two separate stages with different horizons and time lags (schedule-resolution: $\Delta t = 15$ min); b) a "real-time" operation simulation including power system frequency dynamics and control, based on load and in-feed realizations ($\Delta t \approx 1$s). The flow diagram in Figure 8.5 illustrates the structure of the simulation environment. Note that the dispatch simulation is built entirely on specifications utilizing the power nodes concept and notation and ist therefore highly suited for scenario-oriented studies.

The simulation framework and a case study evaluating energy content of control signals is presented in [PN-II].

8.4 Chapter Conclusion

Based on insights gained by analysis of concrete energy scenarios in the CEESA context, the importance of energy storage and, accordingly, energy constraints for power system operation became apparent. As conventional power systems have been operated on the basis of dispatchable generation, the focus used to be on power constraints modeled e.g. by load-flow equations and the only relevant energy buffer/constraint has been the system frequency. In a future of fluctuating power generation, the trade-off between transmission capacity and local energy storage becomes increasingly important. Energy storage behaviour depends on operation strategies. With the generic modeling framework developed here, a platform for the study of energy-logistics in power system operation has been provided.

It was shown, by means of the MFM representation of Power Nodes, that the concept can seamlessly be integrated with different levels of detail of the power system modeling, such as models of power system balancing (Section 4.2) or more detailed grid models (Section 4.3).

CHAPTER 9

Conclusion

This chapter provides a general conclusion of this Ph.D. project, recapitulating the main results and discussing the key findings. Finally, possible extensions of the work reported here and ideas for further research that result from the findings of this project are suggested.

9.1 Summary of Contributions

The contributions, illustrated in Figure 9.1 as adaptation of Figure 1.5, can be split into three parts: Firstly, an architectural perspective on control structure design has been established; secondly, a modeling methodology enabling this architectural perspective has been developed; lastly, a strategy for integrating scenrio design with operation design has been proposed and a new modeling framework supporting operation-design has been introduced.

What is Control Architecture and why should we care to understand? As introduction and background, a overall analysis of the requirements to the design of control and operation strategies for future power systems was performed.

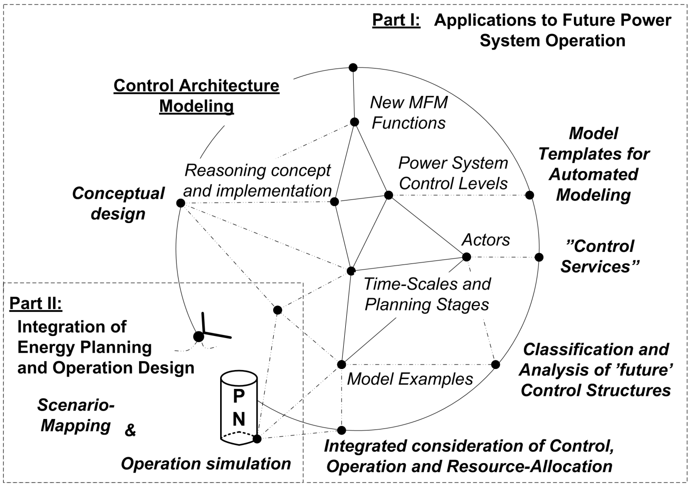

Figure 9.1: Illustration of contributions. The metaphor of in-roads is used to illustrate relations between methodological and and application-oriented contributions. The methodological contributions to control architecture modeling inside the circle are associated with power system related applications.

The analysis motivated the need for both deeper and broader conceptual understanding of control architecture in general, which was outlined in Chapter 2 and associated with conceptual modeling approaches in Chapter 3.

Conceptual Modeling for Control Architecture. Part I of the dissertation has dealt with conceptual modeling of control structures. The means-ends modeling of power system control architecture with MFM was motivated and developed Chapter 4, in particular:

- The reasons for means-ends modeling in context of control have been clarified;
- A multi-levelled representation for stereotypical power system control has been developed, featuring: frequency control, congestions management, power-system-stabilizers and voltage control, modeled with both explicit and implicit control functions and interdependencies.
- Several extensions to Multilevel Flow Modeling (MFM) have been introduced, and general guiding principles for the modeling with MFM regard to control were identified.

- The utility of MFM with regard to modeling of multiple perspectives introduced and applied to a formalization of control services.
- A new concept for reasoning about influence-propagation in MFM models has been proposed and implemented (reasoning about controllability for control design, details in paper [MFM-IV]).

Chapter 5 extended the modeling perspective to operation-planning and supervisory control by operators. In particular, a behaviour-oriented perspective on the functional model has been introduced to model power system operation including real-time control and planning-functions:

- A mathematical formulation for discretization, time-scales, schedules, fluctuation and deviation, performance and statistical smoothing;
- A resulting classification of role-splitting and role-transformations with respect time-scale- and planning-stages was developed.

The discussion of supervisory control by power system operators has been discussed in reference to previous work with MFM and supervisory control. The applicability of the resulting methodology was then demonstrated on case studies in Chapter 6:

- A modification of area-control known to improve wind power integration called 'area diversity interchange' has been modeled;
- A problem with the principle of balancing responsibility for market parties was identified, and a temptative solution has been suggested;
- The explaining power of functional models has been illustrated on the cases of virtual power plants and cell-based control structures, with particular emphasis on the function-structure distinction;
- A small design case for distribution system control has been developed.

The cases serve as a proof of concept for the developed models, but they also show that further design-oriented case studies could be useful.

Scenario Design vs. Operation Design. In Part II, the planning and design problem of future power systems in context of energy scenarios has been adressed. Energy scenarios, such as the 100% renewable energy supply for Denmark developed in the CEESA project, are based on strongly simplified energy system models. The value of such simplified scenario models in the scenario-development has been discussed in light of the paradigm shift potentially required in the energy sector to meet the challenges of dangerous climate change (and, to a lesser extend, that of energy-independence).

For power systems, this paradigm shift has far-reaching consequences also for power system operation and control structures, which justifies a reconsideration of planning methodology as design-methodology. To describe the general structure of this re-design, the terms *formation* and *transitioning* have been coined, to distinguish the planning and design aspects from the challenge of actually deploying the changes to the power system. The role of conceptual models in supporting a systematic approach to the formation process has been discussed. By introducing these concepts of operation-design in relation to energy scenrios, a *vantage point* has been established from which the challenge of adapting power system operation to scenario requirements is more clearly visible in relation to energy planning.

Finally, in Chapter 8, a new modeling and simulation framework, the Power Nodes model, has been introduced. It adresses some of the needs for supporting the redesign of operation strategies has been introduced and related to the conceptual modeling method.

9.2 Discussion

The research on this thesis touched upon many single subjects, where some insights have been gained. In several places throughout the text, room was given to the discussion of the respective results. Here we shall highlight insights and challenges with respect three specific aspects of the modeling methodology and its relation to future control structures.

Modeling Advancement vs. Modeling Needs. Throughout this work, the modeling-perspective applied to MFM models has been *performative*, that is, the relations between process-functions during their execution has been described. The planning perspective applied to these models has therefore been limited to using the models for the conceptual description/design of structures executed in parallel.
The formulation of functional models, however, is also very useful for conceiving the startup (e.g. power system blackstart) or the transition between operating modes (e.g. intentional islanding) for example. The understanding of these types of operations requires the consideration of function-dependencies and se-

quence for activation and de-activation of functions, understood in context of the *action phases* model (cf. 3.2.4). When this *modal* perspective on the function-models is applied, further applications for (online) planning and coordination can be expected. Then also the availability of function-structure relations will be important.

New ways of using MFM models and approaches to generate them. MFM modeling has been considered in a new, previously underdeveloped context, as a model for design representation. It was found that the modeling approach is very useful for drafting control structures and in particular to formulate a process representation that corresponds to the purpose of the control function. The flow functions can easily drawn, re-arranged and interconnected. Hereby, the syntactic rules for MFM, including the newly introduced rules for causal roles, guarantee that a consistent process representation is found. There is a potential for future tool development that supports the interactive modeling with MFM.

Another avenue of applied research that has been opened up in the work of this thesis is the identifications of domain-specific patterns that enables a mapping between domain-based process descriptions (here, a load-flow specification) and MFM models. Domain-specific libraries could be developed to support the rapid modeling and integrated consideration of process and control structure that is enabled by MFM.

Function vs. Structure in Future Operation Strategies. The function vs. structure distinction has been a central theme throughout this thesis. Current conceptions in power systems often assume an alignment of structural and function (the "one component–one function" paradigm). We had observed a difficulty of formulating a meaningful classifications of novel aggregation approaches (the virtual power plants, microgrids, etc.) beyond recognition of economic vs. engineering aspects in the current literature (cf. the classification attempt in [33]). It was found that the functional modeling approach developed here offers a concise, and seemingly natural, way of formulating the aggregations happening either of these novel control structures. The difficulty in other modeling apporaches is not the understanding of the function concept, but the challenge of formulating a conceptual model that explains of control functions in context of the system under control.

Functional aggregation can be meaningful for the specification of control services. The modeling approach developed here can formalize some interface requirements for control services, but more importantly, it defines the system-

context in which a control service specified.
Some interface requirements, however, are strongly bound to structure. Structural aggregation and decomposition has the character of exclusive sub-systems. However, the orientation on structure does not necessarily mean exclusion. For example, in case of distribution-level congestion management, a coordination with respect to system structure can be aligned with planning and coordination within a virtual power plant that is aims to provide services at another level.

Here it is, again, important to consider the function-structure relations, which can mean that arbitration and sharing, as discussed in [148], should be possible for some function-structure relations. The overlay of virtual power plants providing functional aggregations, disregarding structure, and cell-based systems, which require structural considerations, can co-exist as functional structures sharing a resource. However, the parallelism of these competing/exclusive control structures cannot be modelled in a *performative* system view. To fully model these relations, further work on the *modal* aspects of functional modeling is required.
In relation to this discussion of modal one should recall that power system operation is not only defined as 'normal operation' but that several operating modes are considered. Further, even in normal operation, continuously discrete switching operations take places that, depending on the model-perspective, would imply the enablement or disablement of a function. This perspective can also be utilized with respect to safety and adaptive protection systems.

Another aspect that should be revisited, is formulation of actors/agents in relation to MFM. The introduction of the 'actor-boundary' seemed to provide a surprisingly simple and effective formalization of control services. The relation between actor-modeling introduced to model control services and its relation to the value modeling (the *e3value* methodology) and other conceptual models that focus on actors, roles and interactions, promises to yield some further practical modeling concepts, also for further multi-perspective case studies in the power sector.

9.3 Recommendations for Future Work

As this work has touched upon several of research avenues, a number of new research opportunities have been identified that had to remain un-resolved. Here a few larger and more promising open research topics are highlighted.

Further Meaningful Extensions to MFM. A natural extension of MFM is the explicit consideration of safety functions. As has been discussed in several instances of previous work on MFM [44, 125, 143], MFM offers several facilities of modeling safety (safety functions, procedures, or barriers in general). However, it is not very visible because goals are formulated positively, in terms of *achievement*. As safety is formulated in terms of *avoidance*, a form of 'negative' goal-structure could be introduced, to formulate a decomposition hierarchy of (external) *threats*. This might necessitate the introduction of some new antagonist relations between objectives and threats, but would be very sensible for the formulation and documentation of a design.

Work on control functions could be continued with respect to two –separable– directions. Firstly, the work on *formalization of control levels*, the control-structure "folding" or explicit vs. implicit control issue, originated in this thesis could be continued toward a full formalization and implementation for an interactive modeling software. As this folding requires a *performative* modeling perspective, it can be supported further by the execution levels. In a bigger picture, this formalization would corresponds to the definition of model transformations that constitute a "whole" in the sense of Goguen and Varela [91].

A second path that has been ignored throughout this work, is the consideration of a *modal* perspective on control functions. This work can be viewed as continuation of earlier applications of MFM on *planning* [124, 54], *alarm design* [234] and *diagnosis* [67, 153].

Work Toward Applications of MFM and Conceptual Design. In context of this work, three types of uses for MFM-based representation have been considered that each point to further research need and application opportunities: the use in context of control structure design, its potential as a flexible conceptual representaton in a greater planning context, and its use as an internal representation for situation awareness and coordination of intelligent agents.

MFM as a Representation for Conceptual Design for Control Structures in power system applications. Several case study on the conceptual design of new control structures should be performed, to provide a big picture for the integration novel control technology with new and existing market structures. In particular, the following three challenges should be adressed:
a) Active demand in distribution network delivering transmission-level balancing services.
b) Emergency-transition from the virtual power plant to cell-based control structure.
c) A coordination strategy for intra- and inter-synchronous areas HVDC links.

Whereas new control designs are under development (e.g. [62]), the considerations of what kind of control strategies should be applied for a pan-European supergrid. This last study case probably should be viewed in context of a larger study were alternative configuration options are evaluated. However, as HVDC links are controllable with respect to reactive and active power, the control design could well be reflected in MFM models.

The role of MFM as intermediate representation in the formation process largely depends on how tightly integrated such a formation process would be in practice. So far it has been shown that the formulation of simulation components and the explicit consideration of assumptions has been enabled by MFM representations. MFM-based drafting could prove a useful for exactly that process: the requirements analysis, formulation of assumptions and simplification of simulation studies.

Formulating control plans for multi-agent coordination and control. Earlier work on the formulation of control plans by means of MFM was performed by Larsen [125] and de Souza [56]. The potential of using MFM for reconfiguration and control planning, however, reaches much further. Control plans for the coordination of agent based control has been suggested in [214] and translated to a MFM-oriented concept for control plans in [MFM-APP-CP]. The formulation of such plans on the basis of MFM is not a near-future reaearch goal, but it emphasizes the potential of using MFM (and related concepts and methodologies) as a coordination and planning representation. In particular, it hgihlights what MFM-related methodology could enable:
- the formulation of a desired control structure (as in the models developed here),
- the evaluation of feasibility on the basis of available capability information (by reasoning about function-structure relations and possibly applying model-transformations),
- evaluation of control plan cost and performance (based on calculative devices that are structured by the MFM representation of a control plan),
- planning of action sequences for transition (using MFM-based planning).

As, apart from the first item, the features are not yet available in the required form, this list should rather be viewed as a research agenda.

Research toward Coherent Planning and Operation Design The need for calculative devices in relation to planning and design evaluation is obvious. The Power Nodes framework presented a generalized domain representation, and included a set of evaluation measures. But it did not include a representation of the control and operation structures that would be subject to evaluation, or according performance evaluation criteria.

Firstly, a more *complete simulation environment* could be desirable, which would cover all relevant time scales and planning stages, and use a generic information model for control structure simulation, to achieve proper contextualization.
A particularly important "control structure" that requires simulation for the assessment of control structures would be a module that could *simulate the discrete control actions by system operators* (e.g. tertiary control dispatch). An understanding and integration of this decision-process in time-domain simulations could enable the (temptative) evaluation of effects of changes to the planning sequence and new ancillary services on the utilization of the various reserve types.

Risk-oriented assessment/evaluation of operation strategies. The applied means-ends modeling framework could be associated with a variety of different calculative approaches. The behavioural perspective demonstrated in Chapter 5 is only one example. The mathematical formalism to support planning decisions is the calculation of risk – the co-consideration of likelihood and cost [110]. Probability-oriented calculations are essential for power system reliability analysis. As control structures become more complex and distributed, ever more operating-modes, depend on various communication technologies – and thus also failure-modes need to be considered. Further, a time-domain based analysis has become a requirement due to the stochastic properties of wind power and similar resources. These developments vastly increase the complexity of the system to be analyzed for reliability.
Addressing this challenge, the means-ends models could be employed to provide a problem decomposition for the calculative device of risk-assessment, where, for example, the causal relations can be interpreted as Baysian networks for conditional probability. As risk calculations in themselves are complicated, the challenge could possibly be simplified and mechanized by developing mapping from the risk calculus to the means-ends concepts provided by MFM.

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APPENDIX

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Control Architecture of Power Systems: Modeling of Purpose and Function

Kai Heussen, *Student-Member, IEEE*, Arshad Saleem, *Student-Member, IEEE*, and Morten Lind

***Abstract*—Many new technologies with novel control capabilities have been developed in the context of "smart grid" research. However, often it is not clear how these capabilities should best be integrated in the overall system operation. New operation paradigms change the traditional control architecture of power systems and it is necessary to identify requirements and functions. How does new control architecture fit with the old architecture? How can power system functions be specified independent of technology? What is the purpose of control in power systems? In this paper, a method suitable for semantically consistent modeling of control architecture is presented. The method, called Multilevel Flow Modeling (MFM), is applied to the case of system balancing. It was found that MFM is capable of capturing implicit control knowledge, which is otherwise difficult to formalize. The method has possible future applications in agent-based intelligent grids.**

***Index Terms*—Functional Modeling, Requirement analysis, Modeling methods, Frequency Control, Smart Grid Concepts**

I. INTRODUCTION

THE transition of power systems today to the "smart" energy systems of the future has received much attention from industry, research and public institutions in recent years. The interest is a result of the need for replacement of old equipment on one side, and of new requirements associated with sustainability for future energy systems, on the other.

In this context, particularly in the US and Europe, many projects have been started that aim at developing new technologies and concepts to shape the idea of the "Smart Grid". US projects tend to emphasize on the development of new concepts and architectures[1] for grid components, business interoperability as well as restructuring markets for more realtime operation. In comparison, the focus in the European Smart Grids platform[2] is rather on the active integration of renewable energies (REN)[3] and distributed resources (DR)[4] and to bring about an evolution of the existing system architecture.

In Denmark specifically, the political goal of 50% share of wind energy by 2025 has inspired the ECOGRID project. This project, funded by the danish transmission system operator[5], aims at preparing the danish power system for this challenge [1].

The recently ended Phase I of the ECOGRID project included a work package on "System Architecture". This work package was comprised of a review of "innovative technologies", a "requirement analysis", and an outlook on "possible solutions". It has been emphasized that there is a need for identifying the requirements to define the architecture of the future system [1], [2]. When discussing system architecture, enabling technologies should be known. It is crucial, however, to assess the technologies and to analyze the anticipated needs in order to redefine the overall goals and to specify the functions required of solutions. This specification of functional requirements must be clear, concise and generic to leave freedom for future design innovations, especially for the adoption of future sustainable technologies. Further, it was concluded that concepts, methods and tools are needed that enable design and evaluation of system architecture.

A. Accommodating New Technology

Major shifts in technology motivate system redesign. For instance, power electronics revolutionize the way energy flows can be controlled, both in power generation and transmission. Also, with the increased amount of REN and DR, a large number of technologies have been and are being developed that enable a controllable consumption and generation of energy in general (e.g. frequency responsive demand, demand clusters, vehicle to grid, etc.). Another class of new technologies regards the supervisory control of power systems on the larger scale [1], such as PMU measurements and online state estimation. Here, also control theory has brought potential for "smarter" power system automation, improving both stability and resource utilization [3]. Information and communication technology (ICT) can be regarded as an enabling technology for many of the new concepts listed here.

Many of these new technologies bring desirable capabilities [4], which are not naturally supported by the traditional power system and energy markets. And often they are of a scale too small to be recognized by energy markets or to be controlled by grid operators.

B. Challenges for Control Architecture

A major issue for system integration is manageability or controllability of these technologies in the context of an already complex power system. The active integration of these additional resources requires new concepts for control and supervision.

In recent years many new concepts have been developed that aim at tackling this challenge. Most of these concepts can be categorized as aggregation approaches of two kinds:

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[1]e.g. EPRI's Intelligrid http://intelligrid.epri.com/ or the GridWise Alliance (http://www.gridwise.org/)- particularly the associated Architecture Council (http://www.gridwiseac.org/)

[2]http://www.smartgrids.eu/

[3]e.g. EWIS (http://www.wind-integration.eu/) and TradeWind (http://www.trade-wind.eu/)

[4]e.g. the projects FENIX (http://www.fenix-project.org/) or ADDRESS (http://www.addressfp7.org/).

[5]Energinet.dk

(1) Aggregation based on the physical location of resources (in the grid)[6], and (2) commercial aggregation concepts rather based on the generation patterns and capabilities resources [5], [6][7]. The former are aimed at improving the technical operation of the system, and research in this area is of rather technical nature. Whereas, the latter are striving for a profitable participation in energy markets, such that research in this direction focuses on the economical and market-operation principles.

It is generally difficult to evaluate and integrate such complex technologies, particularly when originating from different backgrounds. In order to do that one needs to understand purposes and functions these systems.

In this paper, we present a framework and modeling approach for describing the relations between purpose and functions. A particular strength of the modeling tool used here, called Multilevel Flow Modeling (MFM), is that it provides a meaningful representation of control functions.

By applying this functional modeling approach to the frequency control mechanism, as described in the literature, we show how the network of control objectives and functions composes the system to function as one unit. The modeling technique can be a bridge from values to design as it makes possible to explicate the relation between purposes and functions of the technical system.

In Section II the modeling method is introduced and explained. The rest of the paper is devoted to illustrating the application of functional modeling to power systems. In Section III-A we analyze power system goals on the highest level, in order to gain a clear formulation of the "ends" of electrical energy systems. Next, as the main contribution, a MFM model of frequency control is developed in Section III-B. Finally the presented results and are discussed and future work is motivated in Section IV.

II. Multilevel Flow Modeling

Multilevel Flow Modeling (MFM) is an approach to modeling goals and functions of complex industrial processes involving interactions between flows of mass, energy and information [7]–[12]. MFM has been developed to support functional modeling [13] of complex dynamic processes and combines means-end analysis with whole-part decompositions to describe the functions of the process under study and to enable modeling at different levels of abstraction. Process functions are represented by elementary flow functions interconnected to form flow structures representing a particular goal oriented view of the system (Figure 1a)). Flow structures are interconnected in a multilevel representation through means-end relations, causal roles and control functions and structures (Figure 1b)). MFM is founded on fundamental concepts of action [11] and each of the elementary flow and control functions can be seen as instances of more generic action types. The views represented by the flow structures, functions, objectives and their interrelations comprise together a comprehensive

[6]i.e. MicroGrids, Cells, Technical Virtual Power Plants, ...

[7]e.g. (Commercial) Virtual Power Plants

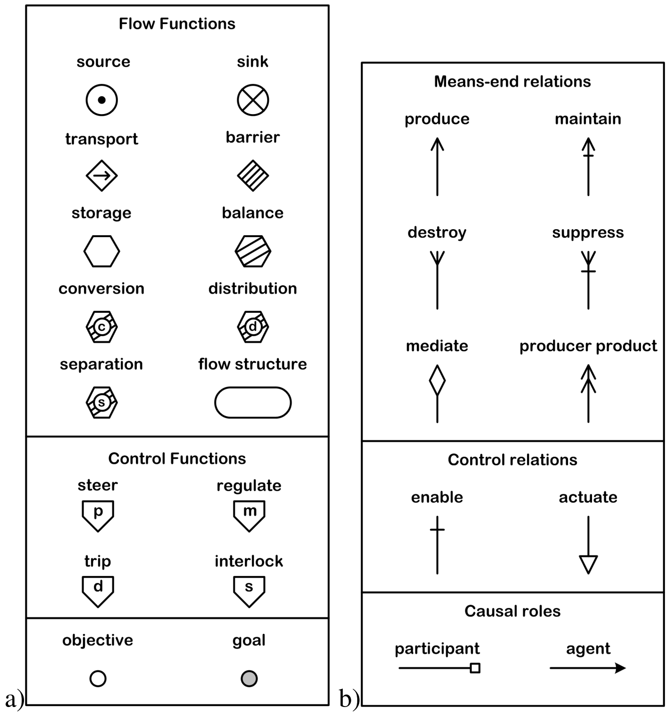

Fig. 1. a) MFM entities and b)MFM relations

model of the functional organization of the system represented as a hypergraph. It should be noted that MFM is a formalized conceptual model of the system which supports qualitative reasoning about control situations [14], [15].

MFM has been used to represent a variety of complex dynamic processes including fossil and nuclear power generation [16]–[18], oil refineries [19], chemical engineering [15], [20] and biochemical processes [21].

Application of MFM includes model based situation assessment and decision support for control room operators [22], hazop analysis [23], alarm design [24] and alarm filtering [25] and planning of control actions [16], [26]. MFM is supported by knowledge based tools for model building and reasoning [12].

MFM has been applied in power systems by Larsson [27] without explicit representation of control functions. Here we show that the capability of representing control is essential for capturing the functional complexity of power systems.

Application of MFM in power systems is envisioned to further intelligent agent solutions in power systems control. MFM models could support situation-awareness of agents, for example to enable reasoning about appropriate responses in fault situations.

A. Demonstrating MFM principles by a small example

Application of the MFM concepts is illustrated in the following by a simple example in Figure 2 below. The model represents the objectives and functions of a water circulation loop in a heat transfer system. It is assumed that the water is circulated by an oil lubricated pump. The example illustrate how the MFM model provides a comprehensive understanding of the purpose and functions of the circulation loop and its subsystems. On an overall level the model can be seen as composed of three sub-models representing different views on the water circulation system.

The first view (starting from the top) represents systems aspects related to water circulation and comprises the flow structure labeled MFS1, the produce relation and the objective O1. This part of the models represents the overall objective of the water circulation, which is to produce a flow of water. The flow structure contains the functions provided to circulate the water. In this simplified model the transport function T1 is the means used for water circulation.

The second view is partially overlapping with the first view because what is seen here as a means (the transport T1) is in the second view seen as an end. Transport T1 is related to the means of transport which is the pumping represented by the energy flow structure EFS1). T1 and EFS1 is therefore related by a type of means-end relation called a producer-product relation in MFM. The flow structure EFS1 is decomposed into the flow functions representing the services provided by components of the pump system (including the energy supply) in order to achieve the end, the transportation of water represented by T1.

The third view is related with the second view through an enabling relation and an associated objective O2 which is the end to be achieved by the functions contained in the flow structure MFS2. The flow structure MFS2 represents the functions involved in the lubrication of the pump and the objective O2 represents the condition that should be fulfilled in order to ensure that the pump is properly lubricated. A condition which should be satisfied in order to enable the pump to provide its functions. The flow functions inside MFS2 accordingly represents the functions of the pump lubrication system.

Even though the example does not utilize all the concepts of MFM, it demonstrates the power of MFM to represent in a clear and logical way knowledge about the goals and functions of a system. The MFM modeling language has a strong syntax which define rules for combining the different entities and relations of the language into a consistent model.

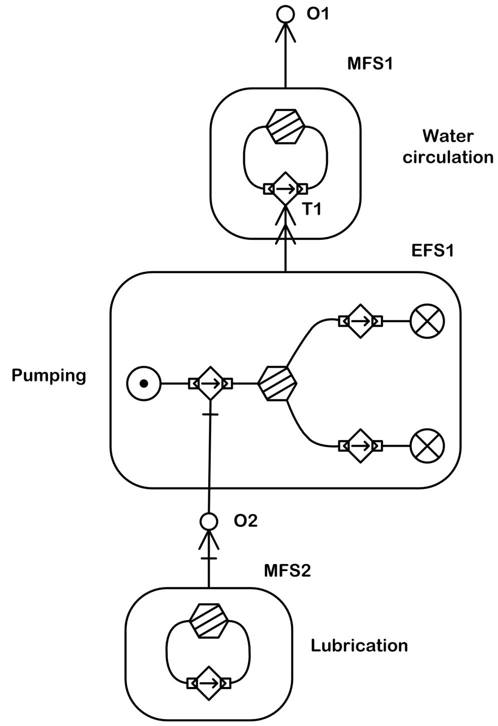

Fig. 2. MFM model of a water circulation loop

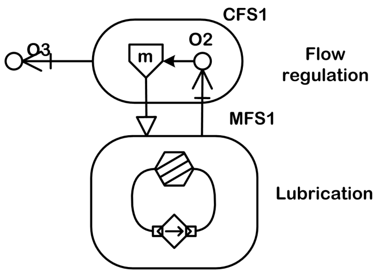

Fig. 3. MFM model of the regulated lubrication system

B. Control Functions

The modeling example above described the functions of the components and subsystem which contributed to the overall objective of the system (deliver water flow). No consideration was accordingly given to the purpose and function of control systems in meeting this objective. As is well known control systems are important for ensuring that process objectives are met in spite of uncertainty and disturbances in the process. This is actually the basic reason for using control systems. MFM has a set of functions which can be used to represent control system functions. We will use the example above to illustrate how some these concepts are used.

Assume that we need to keep the lubrication flow in the pump within specified limits in order to avoid pump problems. An engineering solution to this problem could be to use a regulator measuring the oil flow and controlling the speed of the oil pump. The function of the regulator is to maintain oil flow within limits. This function can be modelled in MFM as shown in Figure 3.

Note that we have introduced a new objective O3 in addition to the original objective O2. It is very important to emphasize the fundamental difference between these two objectives. O2 is "process" objective specifying the value range within the lubrication flow should be kept. In contrast O3 in a "control" objective specifying the performance required of the regulated process. The control objective could specify stability margins etc. and other control attributes specifying the desired performance of the regulator (see also Lind [9]).

It should be stressed that the "loop" formed by the maintain and the actuate relations connecting the mass flow and the control flow structures are conceptual relations and is therefore not a representation of the function or structure of a feedback loop. The concept of feedback is connected with signal or information flow. Control functions shown here do not describe information flow but the purpose of the control action (to regulate).

III. Purpose and Functions of Power Systems

In the following we will demonstrate, how MFM can be applied to power systems. In order to refer to a rather generic power system the modeling was based on the descriptions derived from reference [28].

The process of modeling in MFM is an iterative process, it can be started in principle at any level of means-ends decomposition. An outcome of the modeling is a clear understanding of functions at various levels of abstraction.

The results of the analysis are presented in two stages: First, high-level system objectives are discussed, and then the it will be shown how MFM can be used to model the frequency control hierarchy.

A. Objectives of an Electrical Power System

Usually the location of energy sources is distant from where energy is needed. Electricity is a natural choice for energy delivery, because it can be transported effectively and it can be converted from and to mechanical energy with high efficiency[8].

The *purpose* of electrical energy systems is thus the timely provision of electrical energy to satisfy the demand for different forms of energy. The *function* of the electrical energy system describes how the system serves its purpose. That is,

> *the function of an electric power system is to convert energy from one of the naturally available forms to the electrical form and to transport it to the points consumption.* [28]

Kundur further elaborates that the power system should meet "fundamental requirements" as follows (p.9, [28])

1) *... meet the continually changing load demand of active and reactive power ...* [while considering that, *(edt.)*] *electricity cannot be stored conveniently in sufficient quantities.* [...]
2) *... supply energy at minimum costs and minimum ecological impact*
3) *The "quality" of power must meet minimum standards with regard to* [...]
   (a) *constancy of frequency*
   (b) *constancy of voltage;*
   (c) *level of reliability*

The scope of these requirements encompasses different time ranges and scopes of planning and comprises technical, economical and societal (ecological) goals.

Technical objectives tend to dominate the operational requirements, whereas economical objectives tend to be oriented more on scheduling and planning. Ecology considers the whole life cycle, but it is not always straightforward how this requirement is to be interpreted in practice. Let us therefore further differentiate objectives by: *operation*, *scheduling*, *planning* and *system design*.

The categorization of requirements and goals into "economical" and "technical" can actually be derived from different values that are associated with these goals [29]. In abstraction from economical, technical and societal categories the authors identified the following values in the context of energy systems:

1) Security of energy supply;
2) Overall resource efficiency of the energy system; and
3) Sustainability of system structure, operation and planning.

These values express the most fundamental sources of "requirements" we could derive, and they are technology independent. The suggested prioritization was observed for instance by how these values have been considered historically in the electrical power systems context[9].

Let us elaborate a bit on the interpretation of these three values:

1. *Security (availability) of energy supply* relates to the basic human value of security, the security that energy is available when needed. In a more long term perspective, it also means *security of access* to energy resources, for example.

2. *Resource efficiency* relates to the general understanding that resources are limited and that efficient utilization frees resources for other purposes. Resources could be natural (e.g. energy or material), but could also be human or monetary resources. A typical means of evaluating system efficiency is the creation of institutions or market instruments to enable means of monetary resource allocation and evaluation. Economical evaluation is however limited to the extent in which costs and benefits can reasonably be quantified.

3. The concept of *sustainability* is rather new in the context of power systems, but it has a long tradition in the provision of energy resources. It is important to include objectives of this kind to give space for reasoning about appropriateness of technologies and the application of methodologies that go beyond the capacity of econometric tools.

Criteria formulated in terms of values are pervasive in principle. That means, they affect all system objectives, functions and realization independently.

Now, given these value-criteria and categories, how do we interpret the "fundamental requirements" quoted above?

1) "Meeting the continually changing demand" clearly is an operational objective and it relates to *security of energy supply*. We take this as the central goal of a power system:
   $\mathbf{g_1}$: *Supply electrical energy as demanded.*
2) The requirements regarding "costs" and "ecology" are high-level criteria and are basically equivalent to the value statements on *resource efficiency* and *sustainability*, respectively.
3) The requirements relating to the "quality of power", are rather mixed. Quality requirements (a) and (b), constancy of voltage and frequency, respectively, are strictly functional requirements. Point (c) "reliability", however, can be interpreted in many ways:
   - If subordinated to power quality it is a functional requirement.

[8]The transformation of thermal or chemical energy is not as efficient. District heating systems are a good counter-example, that illustrates that electricity is not always the most efficient form of energy distribution.

[9]It may not be a "natural" prioritization, but it is unclear if a such a "natural" prioritization exists after all.

- It can also be seen as a high-level objective, derived from *security of supply / availability*.
- Some aspects of reliability could characterize the specification of control objectives, such as *performance*, or *stability*, which includes those objectives related to stabilizing the network as a whole. These objectives which would be subordinated to $\mathbf{g_1}$ as a purpose.

The following modeling focuses on achieving an *operational* understanding of objective $\mathbf{g_1}$.

B. Control Functions for Balancing Generation and Demand

Following the discussion above, we now start developing a functional model of the control structure of electrical energy systems. The focus is on the frequency control mechanism, which is directly related to the high-level goal of supplying as much energy as demanded. To put this model in context, we shall first analyze common representations of these control structures from the literature as given in [28].

A common and detailed illustration of the power system control functions is given in Figure 4. It shows a composition of several subsystems (boxes) interconnected by signals (arrows). It may be interpreted as follows: On the top of the diagram we find the "System Generation Control" which receives a set of input signals and issues "supplementary control" signals to as inputs to generating units. One of the input signals is called "generation schedules", which should represent the operating points of all generators participating in the system control. The other inputs comprise information on the system operating state, received from the "Transmission Controls". The central part of the diagram shows subsystems of a power plant (Generation unit) considered relevant for power system control. This includes the prime mover as source of energy and generating torque and the associated generation control system, which receives the rotor speed and supplementary control as control inputs. The generator, receiving this torque from the prime mover (shaft power), feeds back the rotor speed. The generator further receives inputs and feeds back to its excitations system and controls, and finally, it emits an electrical power and voltage as outputs of the power plant subsystem.

Further, the "transmission controls" receive this electrical power as input information for their control responsibilities, which includes the control of voltage and reactive power. This simplified view suggests a subordinated role of the transmission controls , for example, omitting the role of the generation units in voltage control. In this paper we also limit the scope of modeling to the active power / energy related system functions. That means the subsystems and signals marked with thin dash-dotted lines are only included implicitly in the following.

The model in Figure 4 is based on the signal-flow type of diagram, where the arrows present *signals* and the boxes represent *systems* which generate or transform signals. This type of diagram origins from signal processing and is often used to explain the composition of control systems. The naming of the boxes and signals ascribes meaning to them, and

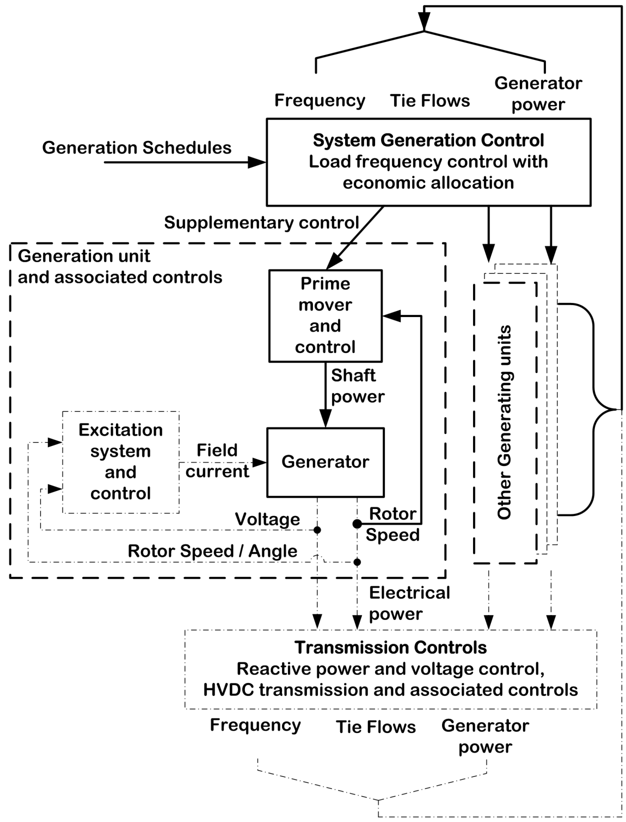

Fig. 4. Subsystems of a power system and associated controls (adapted from [28], Fig.1.2). The subsystems shown with dash-dotted lines are not modeled explicitly in this paper.

their relation with each other can be interpreted as command-chain or physical interconnection. This kind of interpretation of Figure 4 was given above.

However, the functions represented in this type of diagram can formally only be interpreted as signal processing functions. One could argue that it is often possible to interpret the intentions implemented in the design of a control system from a signal-flow diagram. In this case, the intentions are then inferred from conceptual schemes of control engineering. Yet, the intentionality is only *implicit* in the ordering of signal flow structures. In fact this type ordering is prone to mis-interpretation, for example when a system redesign is attempted without considering the underlying design objectives [11].

Signal-flows are also used to suggest control hierarchies and control roles in the modeled system. Figure 5 illustrates the hierarchical structure of power system control by a flow of command signal flows and a command hierarchy in an organigramme. This control hierarchy can be divided systematically into control levels, depending on level of abstraction, the relevant time scales and type of control tasks performed [3], [30], [31]. This approach is meaningful for complex automation systems and it can also be found in other industrial automation systems [32].

1) Functional Structure of the Energy System: In contrast to the types of diagrams used above, functions and purposes of systems and subsystems are modeled explicitly in functional

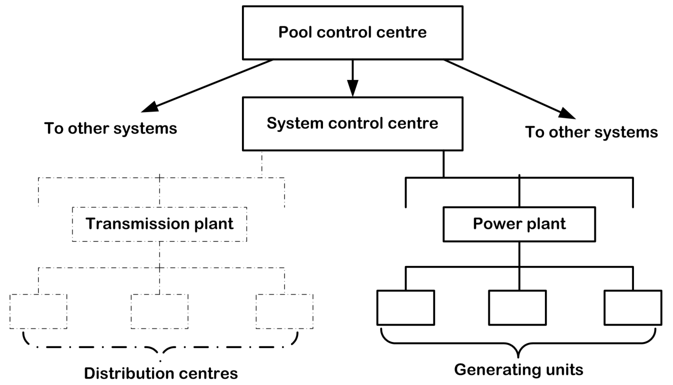

Fig. 5. A representation of control hierarchy in power systems from the literature (adapted from [28], Fig. 1.4).

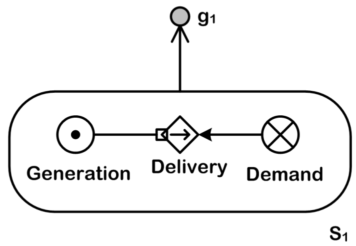

Fig. 6. High-level view of the energy system (MFM model).

models. Multi-level Flow Modeling (MFM) provides rich semantics to model the relations of utility between systems and subsystems. The means-ends decomposition is possible both in terms of intention, as goal-oriented action, and in terms of intentional composition of physical functions in energy and mass flow functions.

The most high-level view of the multilevel flow model is shown in Figure 6. The energy system is here described by an *energy flow structure* $\mathbf{S_1}$, describing the process view, and its association with *goal* $\mathbf{g_1}$: *Satisfy energy demand*, employing the means-ends relation: *produce*. $\mathbf{S_1}$ comprises three energy flow functions: A *source* (Generation), a *transport function* (Delivery), and a *sink* (Demand). The flow functions are interconnected by causal relations: Generation is a *participant*, supplying energy to the transport function, whereas Demand is an *agent* causing the energy flow. These causal roles imply that generation is supposed to be following the load demand. This causal role is realized by the frequency control functions that will be analyzed below. The transport function in $\mathbf{S_1}$ represents the action of power-delivery at any time.

2) Abstract Model of Frequency Control: The flow structure and goal introduced above represent the overall function of the electrical energy system. This function is of course dependent on mechanisms that bring about the intended causality, to satisfy the goal. That mechanism is frequency control.

The purpose of frequency control is accordingly represented by the causal relations between generation and demand in the flow structure $\mathbf{S_1}$ in Figure 6. This purpose is achieved by a cascade from centralized to decentralized control and coordination functions. The decentralized, low-level, control functions are implemented on the generators and are known

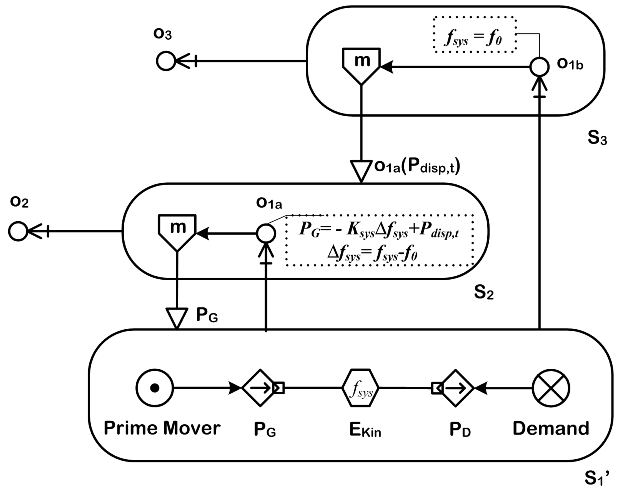

Fig. 7. Abstract MFM model of the system balancing hierarchy.

as *frequency droop control* or primary frequency control. The more central control functions are associated with secondary frequency control, inter-area balancing, economical allocation *et cetera*. Control functions on this level have been generalized as "corrective control" in [3]; in the following we will refer to it as *system balancing*. The coordination of these two control functions is possible due to the kinetic energy stored ($\mathbf{E_{kin}}$) in the generators of the power system and the associated synchronous[10] frequency f_{sys}.

An MFM model of this composition is shown in Figure 7. Here, the flow structure $\mathbf{S_1}'$ shows an expansion of the flow structure $\mathbf{S_1}$ in Figure 6, where the energy source (Generation) has been expanded. The frequency droop control is represented by the *control flow structure* $\mathbf{S_2}$ and system balancing is modeled as control structure $\mathbf{S_3}$. The objectives associated with $\mathbf{S_1}'$, $\mathbf{o_{1a}}$ and $\mathbf{o_{1b}}$, are a decomposition of the above stated purpose of frequency control. This purpose can be formalized as follows:

$$\mathbf{o_1}: \quad P_G \overset{!}{=} P_D \ , \tag{1}$$

where P_D is the power consumed by the demand, and P_G is the shaft power of the generators. This equation is a statement of intention, which is expressed by the exclamation mark ($\overset{!}{=}$).

The separation between frequency droop control and system balancing is based on a decomposition of (1):

$$P_G = -K_{sys}\Delta f_{sys} + P_{disp,t} \ , \tag{2}$$

with $\Delta f_{sys} = f_{sys} - f_0$ is the frequency deviation, $K_{sys} = \frac{1}{R_{sys}}$ is the system droop constant and $P_{disp,t}$ is the total power dispatch by the system balancing function. This decomposition leads to the objectives $\mathbf{o_{1a}}$ and $\mathbf{o_{1a}}$ of droop control and system balancing, respectively.

Droop control or primary frequency control is necessary for the mitigation of larger short-term deviations in the balance between load and demand. The response is coordinated by an adequate stetting of the droop constants, such that a required system droop constant $R_{sys} = \frac{1}{K_{sys}}$ is achieved

[10]This synchronous operation is a load-sharing mechanism, realized by lower-level functions.

(Section III-B3). The objective is thus to achieve the droop characteristic:

$$\mathbf{o_{1a}}: \quad \Delta f_{sys} \stackrel{!}{=} P_G = R_{sys} \cdot (P_{disp,t} - P_D) \ , \qquad (3)$$

The primary frequency-control ($\mathbf{S_2}(\mathbf{o_{1a}})$, $\mathbf{o_2}$) ensures that the frequency deviation matches the droop setting and power dispatch. It does so by means of adjusting the prime mover $\mathbf{P_G}$, the shaft power input to the generators, using control according to the performance specified in $\mathbf{o_2}$. As a result, the frequency reflects the mismatch between demand and dispatched power. The power dispatch is to be adjusted by the system balancing $\mathbf{S_3}$.

Following (2), the objective $\mathbf{o_1}$, i.e. matching dispatched generation with demand, is equivalent to returning the frequency to its nominal value:

$$\mathbf{o_{1b}}: \quad f_{sys} \stackrel{!}{=} f_0 \ , \qquad (4)$$

Thus, system balancing is aimed at bringing the frequency back to its nominal value by means of adjusting the power dispatch. The performance objective $\mathbf{o_3}$ specifies *how* the control structure $\mathbf{S_3}$ should achieve the control objective $\mathbf{o_{1b}}$, which could be, for example, a formulation of the time-scales associated with primary, secondary and tertiary frequency control, or economic allocation criteria.

3) De-aggregation to Represent Individual Units: Above, all generators were aggregated into one. In this section we show the system view of frequency control for an individual generator. The aggregation of the previous section is split into two sources and two transport functions: G1, P_{G1} and P_{Grest}. The inertia (energy storage) remains aggregated in this view (Figure 8).

For this case, equation (2) can be decomposed into

$$P_G = -(\sum_{i=1}^{N} K_i)\Delta f_{sys} + \sum_{i=1}^{N} P_{disp,i} \ . \qquad (5)$$

We have therefore two system constants that can be coordinated independently on the higher aggregation levels:

$$1) \ \frac{1}{R_{sys}} = K_{sys} = \sum_{i=1}^{N} K_i \qquad 2) \ P_{disp,t} = \sum_{i=1}^{N} P_{disp,i} \ . \ (6)$$

The coordinated droop of all synchronous generators is the sum of the individual responses. The balancing control $\mathbf{S_3}$ actuates the generators independently of their contribution to primary control. The frequency gets restored by balancing control, as a result all primary controllers get back into balance.

IV. Discussion and Conclusion

The analysis of power systems presented here presents a new angle on control design starting with the question: What is purpose of power systems? This seemingly remote analysis of values revealed two important facts: (1) there is a hierarchy among the typically believed standard objectives of power system operation; and (2) whenever new power system (control) objectives are defined, a choice based on values is made. This rigorous ends-means approach set an anchor for the analysis using MFM. The following analysis of the frequency control clarifies the concepts of frequency control. Seen in the larger picture, this model could contribute with categories of control functions for new active power control technologies (for example for of Wind Turbines).

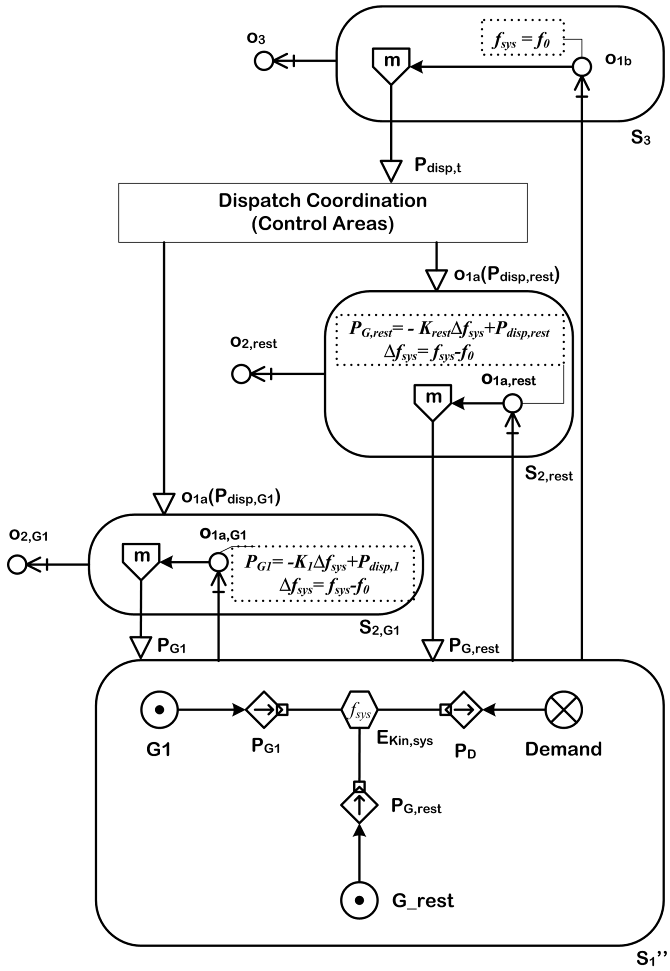

Fig. 8. Distributed frequency control. The generator control structures $\mathbf{S_{2,G1}}$, $\mathbf{S_{2,Grest}}$ locally adjust their generation according to their respective power setpoint and local droop setting, based on the common system frequency.

So far, with frequency control, only a model of one of the simplest control functions in the domain has been presented. Some of the further modeling challenges addressed in future work are:

- Load-angle stability: a deeper analysis of control functions that enable synchronous operation.
- Reactive power and voltage control: this modeling task comprises two challenges: (1) a MFM model of reactive energy flows needs to be developed that is consistent with the common understanding of reactive power; and (2) a model of the spatially distributed control of voltage.
- Even though the balancing functions described here are in line with the description derived from [28], the complex coordination patterns of inter-area balancing and program responsibility require a more detailed modeling of the control structures.

This is the first study of control functions in power systems using MFM. The study is part an ongoing work and will be expanded to more control functions in order to obtain a comprehensive understanding of control architecture in power systems. We conclude that MFM can be an effective analytical tool in the development and evaluation of new technologies for existing and future power systems.

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Decomposing Objectives and Functions in Power System Operation and Control

Kai Heussen, *Student-Member, IEEE* and Morten Lind

***Abstract*—The introduction of many new energy solutions requires the adaptation of classical operation paradigms in power systems. In the standard operation paradigms, a power system is seen as some equivalent of a synchronous generator, a power line and an uncontrollable load. This paradigm is being questioned by a diverse mix of challenges posed by renewable energy sources, demand response technologies and smart grid concepts, affecting all areas of power system operation. Both, new control modes and changes in market design are required eventually. A proper redesign should starts with a coherent approach to modeling. This paper presents a mean-ends perspective to the analysis of the control structures and operation paradigms in present power systems. In a top-down approach, traditional frequency- and area-control mechanisms are formalized. It is demonstrated that future power system operation paradigms with different generation control modes and controllable demand can be modeled in a coherent way. Finally, the discussion is opened up toward a formalization of service-exchange between market participants.**

***Index Terms*—Smart Grid, Functional Modeling, Power System Control, Area Control, Distributed Resources, Controllable Demand**

I. Introduction

Traditionally, the overall objective of power system operation is reliable supply of electrical energy to a passive consumer. Modern energy systems combine this objective with the goal of a sustainable and economical allocation of energy sources. Many of the concepts and technologies that have been introduced in this field imply a paradigm shift: Generation may be disturbing the system balance if it is sustainable energy, and demand may be active in restoring the balance. The new situation may be commonly accepted amongst researchers in the field and in the view of todays' small to medium scale penetration of renewable energies. However, taken to a larger scale a new understanding of power system operation is required and possible barriers should be faced.

The power system and its future challenges can be viewed from different standpoints, relating to different technology backgrounds and focus areas (e.g. electricity and grid operation, generation and balancing of large scale renewables, information technology focusing on means of communication). Virtual power plants, smart grids, microgrids or virtual utilities are all synonymous with the need for a shift toward a new operational paradigm.

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The work presented in this paper is a result of the research project Coherent Energy and Environmental System Analysis (CEESA), partly financed by The Danish Council for Strategic Research.

Smart grid technologies affect all levels of system operation, and is driven by trends toward further economic deregulation, the advent of more renewable and distributed energy technologies and the additional overall sustainability goals (e.g. [1]). The emergence of these smart grid technologies emphasize the need for a deeper understanding of how these increasingly complex power systems are composed, and how they could be re-composed.

In fact, advanced information technologies are becoming key for the smart grid [2]–[4], and a tighter integration between information systems and grid operation will be required. The design of this integration, however, requires knowledge about the decomposition of the control systems and an understanding of the roles of new (distributed) resources [5], [6].

A large number of smart grid concepts are based on some principle of aggregation. Two types of aggregation concepts can be found in most solutions: (1) Aggregation based on the location of resources in the grid (physical/electrical), and (2) commercial aggregation concepts directed toward a market integration. The former are aimed at improving the technical operation of the system, and research in this area is of rather technical nature. The functions aggregated here are mostly ancillary services, including frequency- and voltage- control functions. Commercial aggregation concepts (2) are striving for a profitable participation in energy markets, and research in this direction focuses on the economical and market-operation principles. In this type of aggregation, subsystem functions are understood and aggregated as tradeable resources. Aggregators typically establish a marketplace or issue price signals directly.

It is in the nature of aggregation to move away from a specific implementation to a more general understanding of the roles or functions a component has in a system context. These roles need to be reconsidered from a system integration point of view, which requires a shift in perspective: Formulating the functions of the system and its subsystems, rather than the technical capabilities and structure of the components [7]–[9]. Modeling in terms of functions helps to understand and expose the complex interactions between information flows and component capabilities.

The insight that a more fundamental understanding is required leads back to the analysis of overall goals, yet these general goals do nothing in defining the structure of a power system. A goal-decomposition must be based on the physical and engineering concepts that constitute an electrical energy system. Different types of models and system understanding are accordingly required at different levels of decomposition.

In this paper we show how a goal-decomposition can be done by reframing power system operation into a formal means-ends perspective. The result is a model of energy flows

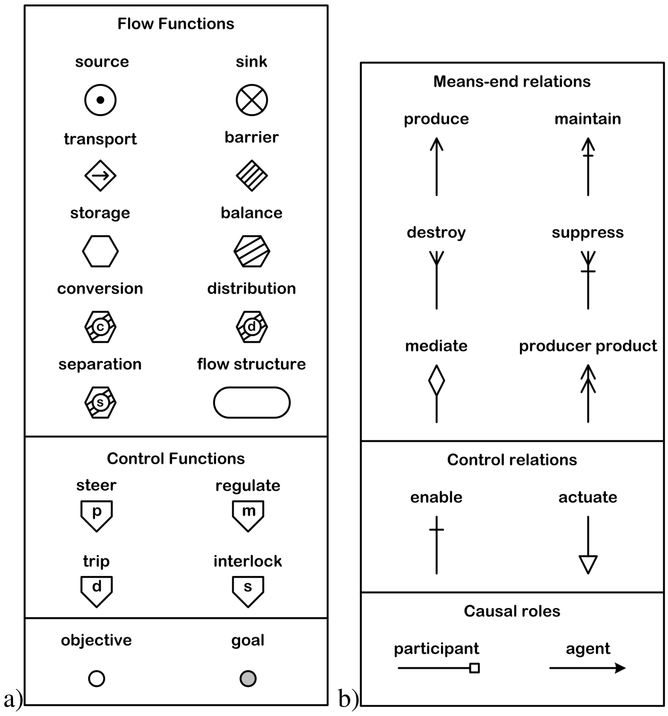

Fig. 1. a) MFM entities and b)MFM relations

and control functions that can reveal the integration of underlying physical and engineering design concepts into a goal-oriented structure. The subsequent presentation of examples for the modeling of typical functions of sustainable generation technologies illustrates that a modeling of sustainable energy systems is possible in the same framework.

At first the modeling will follow a textbook description of frequency control, extending on results of an earlier paper by the authors [10]; further operational practices are modeled according to the Operation Handbook of the UCTE system[1]. In a next step, the model is extended to represent the special roles of uncontrollable generation and controllable demand. The result is a top-down, multi-level decomposition of power systems in terms of control objectives and means for their achievement.

In a final discussion, the role of markets in the integration of control structures constituted by independent entities is analyzed with a means-ends point of view.

II. Multilevel Flow Modeling

Multilevel Flow Modeling (MFM) is an approach to modeling goals and functions of complex industrial processes involving interactions between flows of mass, energy and information [11]–[16]. MFM has been developed to support functional modeling [17] of complex dynamic processes and combines means-end analysis with whole-part decompositions to describe the functions of the process under study and to enable modeling at different levels of abstraction.

In MFM, process functions are represented by elementary *flow functions* interconnected to form *flow structures* with a common flow object (*energy* or *mass*). Connections between functions within flow structures can be assigned with *causal roles*, indicating the assignment of an active or passive participation in the transport of the flow object. Each flow structure represents a particular *goal*-oriented view of the system (Figure 1a)). *Objectives* can be combined with elementary *control functions* to form *control flow structures*. Flow structures are interconnected in a multilevel representation through *means-end relations*, and *control relations* (Figure 1b)).

MFM is founded on fundamental concepts of action [15] and each of the elementary flow and control functions can be seen as instances of more generic action types. The views represented by the flow structures, functions, objectives and their interrelations comprise together a comprehensive model of the functional organization of the system represented as a hypergraph. It should be noted that MFM is a formalized conceptual model of the system which supports qualitative reasoning about control situations [18], [19].

MFM has been used to represent a variety of complex dynamic processes including fossil and nuclear power generation [20]–[22] and several kinds of chemical processes (e.g. [23]).

Application of MFM includes model based situation assessment and decision support for control room operators [24], hazop analysis [25], alarm design [26], alarm filtering [27] and planning of control actions [20], [28]. MFM is supported by knowledge based tools for model building and reasoning [16].

Application of MFM in power systems is envisioned to further intelligent agent solutions in power systems control. MFM models could support situation-awareness of agents, for example to enable reasoning about appropriate responses in fault situations [29]. It has been shown in a previous paper by the authors that the capability of representing control is essential for capturing the functional complexity of power systems [10]. Here we extend the results from the previous paper to control areas and expose some first alterations that enable to represent modern sustainable energy ressources.

III. Power System Objectives, Values and Means

Energy systems are a means to the end of supplying and distributing energy to all members of society. We value energy being permanently available and thus the main objective of power systems ought to be the *reliable* supply of electrical energy; today most would agree, that this objective should be pursued with due respect for future generations and not at all costs. We say it should be *sustainable* and *economical*.

As an entry point for the later analysis it is important to clarify our understanding of values, goals/objectives and the different categories of means.

A goal states the intention associated with a system[2]. Values are valid without a given system context and they generally qualify goals. The attributes “reliable”, “economical” and “sustainable” further qualify the way in which the means

[1]Using P1: Load Frequency Control and Performance, and P2: Accounting and Scheduling, as well as the appendices A1 and A2. Available at http://www.ucte.org/resources/publications/ophandbook/

[2]In MFM, goals and objectives are distinguished: Goals are more general, rather value-driven, whereas objectives are more formal, rather process-driven.

(power system) should be organized[3]. These attributes relate to values that are associated with our energy supply. These values may be generalized to (1) Security of Supply, (2) Resource Efficiency and (3) Sustainability [10]. On the one hand, a power system is a technical infrastructure, dealing mostly with a very specific form of electric energy. On the other hand, because it provides fundamental services to society, the system also reflects the values its users associate with their energy supply.

Means as analyzed in the context of MFM are functional means – a function is the role of an entity in an action directed at an intentional change of a systems's state.

Generally, means are actions or things used to achieve an end. Means are therefore naturally fitted for specific types of purposes, which means that one could talk about categories of means by purpose:

- *electric technology* means: grid, generators, active / reactive power, control, supervision, system balancing, ...
- *information technology* means: networks, protocols, software agents, ...
- *control* means: measurement, actuation and decision-making equipment.
- *economical* means: markets, bids, money value, ...

The means of electric technology come to define the structure of the electricity systems. It is typical, that the general objective and the values get into the background in the process of technology development, sometimes due to a lack of appropriate decision making tools. It can be observed that "reliability" is often evaluated and implemented directly by the technologists with a focus on the secure operation of the system power system. Economical means are used to coordinate efficient use of resources. One may add another category of means: Means of sustainability (evaluation), such as "life-cycle analysis" (LCA).

However, any modeling approach that focuses on one particular type of means tends to give an incomplete view of the overall workings (interactions) of a system. An action-based perspective reveals, that in fact all means of technology, economy and control are intertwined on virtually all levels of decomposition.

We see functional modelling as a tool that can reflect and expose the complex entanglement of these means.

IV. MFM MODEL OF STANDARD FREQUENCY CONTROL

In this section we formalize the existing operation and control paradigms of power systems. The control functions presented here are known and well described in the literature [30]–[32].

This formal understanding may lend itself to a number of uses, including the types of applications stated in Section II, such as situation awareness in disturbance situations or automatic planning of control actions for intelligent agents.

The most abstract view of the multilevel flow model is shown in Figure 2. The symbols used in this diagram are

[3]Other attributes often stated include: competitiveness, CO_2-reduction, wind-integration, etc. These qualifiers are overly specific and may well reflect a lock-in to typical and existing solutions.

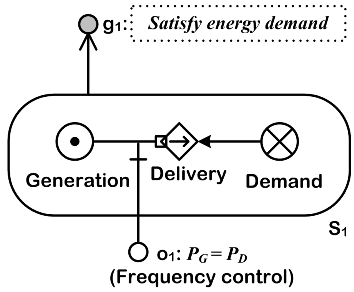

Fig. 2. Abstract view of the electrical energy system (MFM model). Here, "Generation follows demand" is logically represented by the assignment of causal roles. The passive causal role of "Generation" is enabled by frequency control.

introduced in Figure 1. The energy system is here described by an *energy flow structure* $\mathbf{S_1}$, describing a process view, and its association with a *goal* $\mathbf{g_1}$: *Satisfy energy demand*. Flow structure and goal are connected by a means-end relation: *produce*, which expresses that this goal is to be achieved by the system.

$\mathbf{S_1}$ comprises three energy flow functions: An energy *source* called "Generation", a *transport function* called "Delivery", and an energy *sink* called "Demand". These elements represent basic function types: be a source (provide), transport and be a sink (consume).

The flow functions are interconnected by causal relations. A box or arrow at a transport function indicates the causal roles of a connected function. An arrow shows the "agent" role, i.e. the capability of causing a state change in the transport function; a box means (passive) partication. In Figure 2 "Generation" is a passive *participant* or sender, supplying energy to the transport function, whereas Demand is an *agent* influencing the energy flow. These causal roles imply that generation is supposed to be following the load demand. This causal role is enabled by the frequency control functions that will be analyzed below. The transport function in $\mathbf{S_1}$ represents the function of power-delivery at any time.

The objective $\mathbf{o_1}$ represents the purpose of frequency control. This purpose can be formalized as follows:

$$\mathbf{o_1}: \quad P_G \overset{!}{=} P_D \ , \tag{1}$$

where P_D is the power consumed by the demand, and P_G is the shaft power of the generators. This equation is the statement of intention that is P_G shall equal P_D (not the other way around). Reading from left to right, this is expressed by the exclamation mark ($\overset{!}{=}$).

Power generation is brought to follow demand ($\mathbf{o_1}$) by means of frequency control. Frequency control is separated between frequency droop control (primary frequency control) and system balancing (secondary frequency control). This separation is based on a decomposition of (1):

$$P_G = -K_{sys}\Delta f_{sys} + P_{disp,t} \ , \tag{2}$$

with $\Delta f_{sys} = f_{sys} - f_0$ is the frequency deviation, $K_{sys} = \frac{1}{R_{sys}}$ the system droop constant and $P_{disp,t}$ is the total power dispatch by the system balancing function.

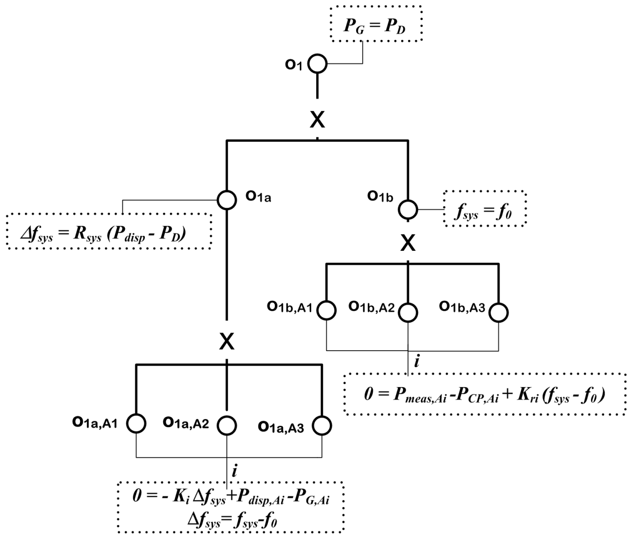

Fig. 3. Goal decomposition of frequency control.

The decomposition leads to the objectives $\mathbf{o_{1a}}$ and $\mathbf{o_{1b}}$ of droop control and system balancing, respectively. This decomposition of frequency control objectives is shown in Figure 3. Applying control engineering notions, here the system frequency control has been split up into separate proportional and integral controllers.

A. Control Functions: Primary Frequency Control

Droop control or primary frequency control is necessary for the mitigation of larger short-term deviations in the balance between load and demand. Droop control, as the frequency, is shared within the complete synchronous region of a power system.

Frequency droop control is represented by the *control flow structure* $\mathbf{S_2}$ shown in Figure 4.

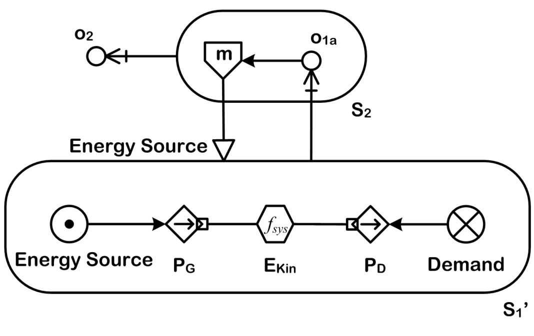

Fig. 4. MFM model of primary frequency control. Note the different causal role of the energy source: In this view, the energy provided to the system and the energy removed from it may mismatch, which will result in a change of the storage-level in the kinetical energy storage.

The response is coordinated by an adequate setting of the individual generator droop constants, such that a required system droop constant is achieved. The objective is to achieve the droop characteristic:

$$\mathbf{o_{1a}}: \quad \Delta f_{sys} \stackrel{!}{=} \frac{1}{K_{sys}} \cdot (P_{disp,t} - P_D) \ , \tag{3}$$

The primary frequency controller ($\mathbf{S_2}(\mathbf{o_{1a}}), \mathbf{o_2}$) ensures that the frequency deviation matches the droop setting and power dispatch. From a system perspective, this corresponds to a proportional control input.

It does so by means of adjusting the power inflow to the prime mover, $\mathbf{P_G}$, the shaft power input to the generators, using control according to the performance criteria specified in $\mathbf{o_2}$. As a result, the frequency reflects the mismatch between demand and dispatched power. The power dispatch is to be adjusted by the system balancing $\mathbf{S_3}$.

B. Control Functions: Secondary Frequency Control and Inter-area balancing

System balancing is aimed at bringing the frequency back to its nominal value by means of adjusting the power dispatch. It is achieved for example by automatic generation control (AGC) on larger generators. From a system perspective, this objective corresponds to integral frequency control.

Following (2), the objective $\mathbf{o_1}$, i.e. matching dispatched generation with demand, is equivalent to returning the frequency to its nominal value:

$$\mathbf{o_{1b}}: \quad f_{sys} \stackrel{!}{=} f_0 \ , \tag{4}$$

In larger power systems, this system balancing is more complex, as the system is structured further into control areas. A representation of control areas can be developed in MFM by a step-wise expansion of the flow structure in Figure 2. The expansion is shown in Figure 5 for three control areas. The expansion is done in four steps according to MFM transformation rules: (1) expand transport function “delivery” (series connection); (2) split energy-source “Generation” and energy-sink “Demand”, together with associated transport functions by three (parallel connection); (3) re-order into pairs of “Generation” and “Demand”, representing energy sinks and sources in the control areas; (4) expand central energy-balance: This expansion accounts for the definition of exchange across the border of control areas; the bi-directional transport function is new in MFM.

The result of the expansion represents the same causal structure as in Figure 2, but already accounts for the definition of the boundaries of control areas. The purpose of control areas is to balance a mismatch between scheduled demand and supply within the area. This control objective constrains the possible flows, and thus changes the causation of the flow structure. In the abstract model (Figure 6), this is represented by a limitation of the transport function which serves as an agent causing the limitation to the scheduled exchanges for each area.

Therefore, the objective of area control is to return its power exchange with other regions to the scheduled values. In the UCTE this is done by the so-called network characteristic method [32]. This method defines an area control error (ACE) for each area (ACE_i) that is to be returned to zero by the area-controller.

$$\mathbf{o_{1b,Ai}}: \quad 0 \stackrel{!}{=} ACE_i = P_{meas,i} - P_{CP,i} + K_{ri}(f_{sys} - f_0) \ , \tag{5}$$

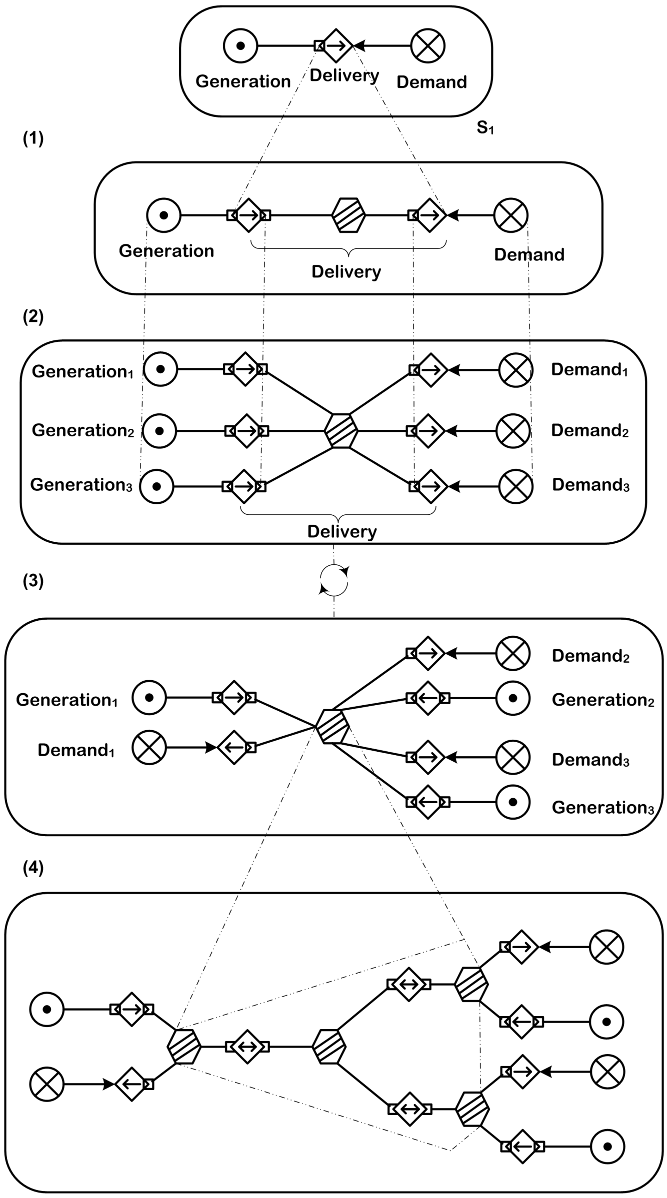

Fig. 5. Expansion of energy system flow structure ($\mathbf{S_1}$ in Figure 2) to represent three control areas.

here the "K-factor" $K_{r,i}$ is the area's primary frequency control contribution, corrected by a "self-regulating effect" of the area (e.g. 1%).

Note that the network characteristic method is used to decouple the objectives of the primary and the secondary control, which is necessary because they belong to the same "control loop". Yet, this decoupling is only static and the two control functions should also be decoupled dynamically, such that the control functions do not disturb each other. That is, in addition to the static decoupling objectives, an additional "performance requirement" needs to be established in order to fully decouple those control functions.

The MFM model in Figure 7 shows the cascaded control flow of primary and secondary (area) frequency control. The above mentioned performance requirements would be stated in $\mathbf{o_{2,Ai}}$ and in $\mathbf{o_{3,Ai}}$, respecectively. The author could not find

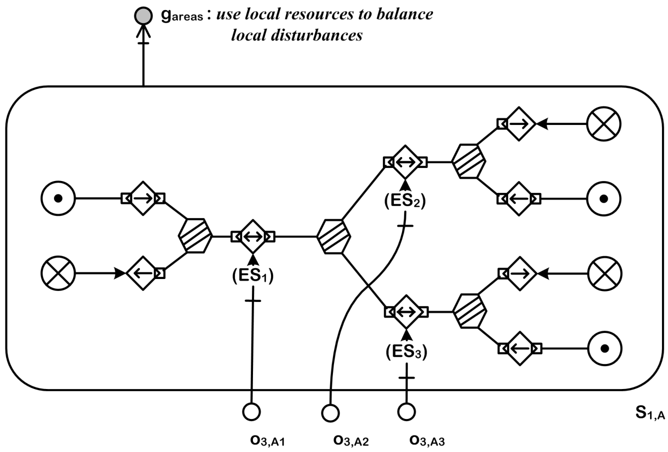

Fig. 6. Abstract MFM model of the system balancing with control areas indicating causal relations. Boxes and arrows at transport functions indicate the causal roles of the respective connected function in the transport-action. An arrow refers to the "agent" role, causing a state change; a box means (passive) partication.

such requirements stated in the UCTE Operations Handbook [32] and must assume that these requirements are implicit knowledge.

It has been shown in a formal model, how the original integral control is enhanced to a distributed control method.

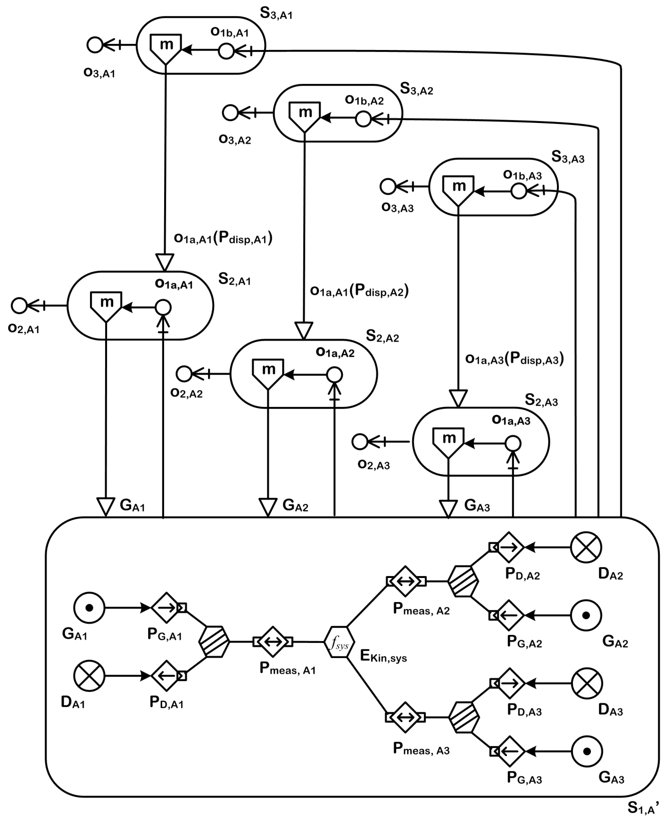

Fig. 7. Control hierachy and flow structure of the system balancing with control areas.

V. New Roles in Present and Future Sustainable Energy Systems

The analysis above gives a compact illustration of the present control architecture of power systems. In the following we will demonstrate how MFM also can help defining the functions and aggregations of new and distributed energy resources.

A. Uncontrollable Generation and Controllable Demand

The models developed above are based on the background assumption that generation at large is controllable (and controlled) and that demand is uncontrolled (and uncontrollable); i.e. system imbalances in normal operation are caused by demand. This corresponds to the textbook perspective on power system control. Nevertheless, the performamnce criterion for frequency control is given by a design-disturbance, which typically determined by the N-1 criterium. So for disturbed operation, in fact the performance requirements are also guided by the size of the generators in operation.

Most types of renewable electricity generation do not fit this classic picture, as their energy-output is not controlled[4]. One of the central measures for the integration of renewable energy is the introduction of controllable demand. Just as controllable generation this measure increases the adjustable range of power flows.

Figure 8 shows how the basic energy flow structure of Figure 2 is to be expanded for a representation of additional disturbance and controllability in a modern power system with uncontrolled renewable power generation and controllable demand units.

The functional representation of controllable generation and controllable demand shows on one hand how both can be similar with regard to operation; on the other hand it shows also that this similarity only holds for one property of the function.

B. Abstract functional representation of co-generation

An interesting case that also illustrates the relevance of causal roles can be found for co-generation.

A co-generation plant can in principle be run in two control modes:

a) Production driven by heat demand, and

b) production driven by electricity demand (e.g. when sufficient heat storage is available).

Typically, it is possible to run the same plant in one mode or the other. The MFM model in Figure 9 shows the implication of these two control modes for the causal structure of this system. These representations may contain valuable information for decision support systems.

The notion of control modes introduces a welcome ambuiguity to the functional models. A unit's functional representation should always reflect its capabilities. Another example

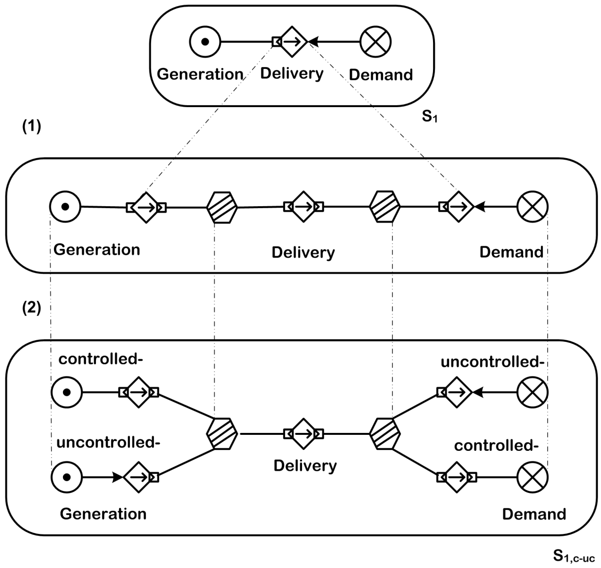

Fig. 8. Expansion of the abstract view to represent additionally controlled demand and uncontrolled generation. Step (1): expansion of transport function (series connection); step (2a): split both energy-source "Generation" and energy-sink "Demand", together with associated transport functions in two; step (2b): modify the causal roles to represent uncontrolled generation and controlled demand.

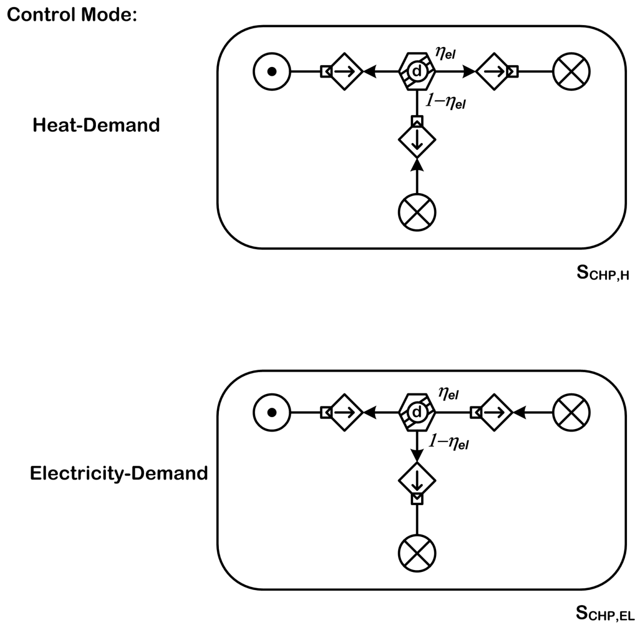

Fig. 9. This view represents a functional model of a co-generation plant (e.g. Micro-CHP).

for this situation: "uncontrollable generation", such as modern wind turbines, may well provide a limited controllability, for example for for short term balancing. In this case, the functional representation can be adapted for this particular control mode.

VI. Discussion

With the results presented above a new modeling approach has been demonstrated in application to power system. Functional modeling has potential in the modeling of a much

[4]Note the distinction between "controllable" and "controlled". The functional model describes which role is assumed in a given operational timeframe. Thus, it may be the case for modern wind turbines to provide a controllable active power output range - in this case they would be aggregated under "controlled" instead of "uncontrolled" generation

wider range of promising application fields. In the following we discuss the possibility of applying functional modeling supåported by MFM in two specific areas of difficulty:

a) economic deregulation: representation of controllable and uncontrollable generation in power markets

b) decentralized generation and "aggregation" of control functions

A. Decomposition of Control Functions into Market Entities and Exchanged Services

In a market place people meet to exchange goods for money. One can say that a market place is established where at least one *seller* offers a good of his own, one or more *buyers* are interested in (value) that good and all share a common means of valuation (money). A deal is made when ownership of money and the good are mutually exchanged between the two market entities, typically under the condition that the good-valuation of the buyer meets or exceeds the good-valuation of the seller. We talk about "buyer" and "seller" because of the role each individual assumes in the market place. In fact, roles are defined through the market exchange process, not through the individuals taking part in this process.

Yet, the requirement that a good can be exchanged may depend on more than just the notions of ownership and money. Often a number of mutual requirements need to be fulfilled before a deal can be made. For example a market place traditionally provides support functions to ensure safety and simplicity of deals. Further properties of both seller and buyer may be required to enable the exchange of a specific commodity.

This corresponds to the difficulty in defining service agreements: If the good exchanged is not naturally self defined (a piece of something, or subject to a common standard), then buyer and seller need to agree on a definition of the service being provided. "Energy" would be a relatively simple commodity, but it requires a specification of the energy carrier. If the carrier is coal, the good is nearly self-defined (a piece of something). If it is electricity though, the specifics of the system function (e.g. the lack of storage) require a strong definition of requirements: the power system as the "exchange system" requires a cooperative approach to reliability in order to establish the system function that is necessary for the energy exchange.

In MFM, entities are related to the realization of a function. That is, a flow structure captures the functional composition of a system, not its realization; a flow structure or a single function may be associated with a physical entity or a virtual aggregation of many. On the other hand, any entity can have one or several functional self-representations. That is a self-representation of its functions would enable a self-interested entity to identify requirements when providing and accepting external functions (services).

To illustrate the idea using MFM, Figure 10 shows a simple MFM model of energy exchange between "producer", "consumer" over an "energy system". The three basic energy flow structures (source-transport-sink) are interconnected by a "Janus-relation".

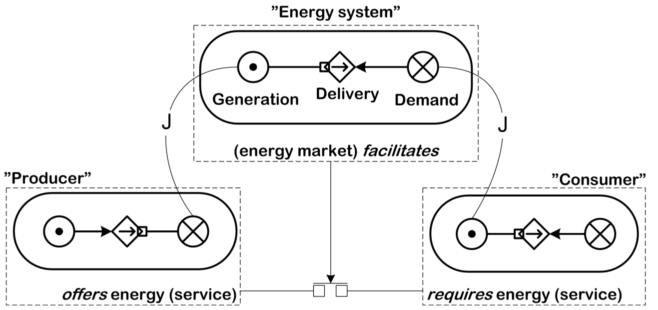

Fig. 10. Sketch of the correspondence between MFM flow structures and market entities. The "Janus-relation" (-J-) establishes a connection between the Producer's sink and the *Generation* function, as well as between the Consumer's source and the *Demand* function.

The "Janus-relation" (-J-) establishes a connection between complementary functions in different flow structures. The two functions connected by a Janus-relation represent the same functional-entity from different perspectives. For example, an energy-sink is an energy source for another perspective. The two functions share all factual properties, but functional requirements, would be tied to the respective flow structure. Thus the physical realization of the energy-sink of this producer would be identical with the the physical realization of the energy-source of the energy system and the consumer's energy source is identical with the sink of the energy system. The formulation of requirements instead would be with respect to the respective flow structure.

The parallel between the functional (energy) connection of producer, consumer and energy system on one hand, and the their roles with respect to the market operation on the other, is illustrated in Figure 10. As outlined above, there is a potential in formulating such economical relations in the same action-theoretical framework as the technical functions treated in the remainder of this paper. The roles of the given entities in the commodity-exchange-process are indicated.

B. "Functional Aggregation"

As shown in Section IV-B and in Figures 5 and 8, MFM provides formal rules that guide the expansion and collapse of flow structures. An expansion of a flow function corresponds to a more detailed view of the functional structure of a system, which led to a neww control opportunity in case of the secondary frequency control. From a bottom-up perspective, an area's energy source aggregates all generators in the respective area. Detailing and aggregation follows along with new control structures.

Aggregation is natural in the representation of functions and it lends itself immediately to formalize aggregation concepts. MFM has been developed as a combination of means-ends and whole-part abstraction levels. Current work on MFM formalizes these different representation and abstraction levels into a flexible data structure.

Information models that should integrate information about diverse units require a more abstract formalization of the properties of their subsystems. MFM provides a natural framework to carry and organize such information.

VII. Conclusion

The results in this paper show a further development of MFM toward a promising modeling tool in the application to power systems in the future. Work lying ahead includes a modeling of current modern control concepts such as Microgrids and Virtual Power Plants.

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Functional Modeling of Perspectives on the Example of Electric Energy Systems

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Abstract. The integration of energy systems is a proven approach to gain higher overall energy efficiency. Invariably, this integration will come with increasing technical complexity through the diversification of energy resources and their functionality. With the integration of more fluctuating renewable energies higher system flexibility will also be necessary. One of the challenges ahead is the design of control architecture to enable the flexibility and to handle the diversity. This paper presents an approach to model heterogeneous energy systems and their control on the basis of purpose and functions which enables a reflection on system integration requirements independent of particular technologies. The results are illustrated on examples related to electric energy systems.

Introduction

We anticipate that sustainable energy systems are more *intelligent* energy systems. The integration of energy systems is a proven approach to gain higher overall energy efficiency. Invariably, this integration will come with increasing technical complexity through the diversification of energy resources and their functionality. With the integration of more fluctuating renewable energies higher system flexibility will also be necessary. All this results in a demand for ever more advanced control of electric power system to handle the mix of resources with increased flexibility, while the system robustness ought to be maintained.

One approach to improve efficiency of the electricity sector is its integration with the heat sector. As heat can easily be stored, this integration also gives way for a cheaper and more effective type of energy storage: flexible demand. For example, the Danish electricity supply relies mainly on combined-heat-and-power (CHP) plants. All larger CHP plants have been equipped with significant heat storage to offset electricity production from the district heating demand. Studies suggest further an addition of heat pumps to the district heating system to enable the integration of wind power into the electricity supply, e.g. (Lund and Münster, 2006).

In recent years, many visions of future integrated energy systems have been proposed, some are based on a particular technology domain such as Microgrids or Zero-energy Buildings, others are based on an abstract planning and optimization process that does not involve the technical details of an implementation (they often assume some type of global coordination). Such integrated energy systems depend on separate domains of engineering which have their own way of representing design problems and requirements.

Integration of energy systems means the combination of systems that were previously independent and therefore have partly incompatible conceptualizations. Common system analysis is behavioural is therefore dependent on assumptions about the technical realization. The functional modeling approach applied in this paper instead allows the study of interrelations on a more general level by formalizing the semantic relations between different perspectives. The functional models are presented by Multilevel Flow Modeling (MFM). In this paper the method is outlined with a focus on the underlying semantics. The concept of perspectives is introduced and illustrated on an example related to electric energy systems.

Functional Modeling with MFM

Multilevel Flow Modeling (MFM) is an approach to modeling goals and interconnected functions of complex processes involving interactions between flows of mass, energy and information (Lind 2005)[1]. It provides means for a *purpose-centered* (as opposed to *component-centered*) description of a system's functions. MFM enables modeling at different levels of abstraction using well-defined means-ends relations and whole-part compositions (Figure 1b). Process functions are represented by elementary flow functions interconnected to form flow structures which represent a particular goal oriented view of the system (Figure 1a). The views represented by the flow structures, functions, objectives and their interrelations together comprise a comprehensive model of the functional organization of the system represented as a hypergraph. MFM is founded on fundamental concepts of action and each of the elementary flow and control functions can be seen as instances of more generic action types.

Models created in MFM are a formalized conceptual representation of the system, which support qualitative reasoning about control situations. MFM is supported by knowledge based tools for model building and reasoning.

MFM models can be and have been employed for the purposes of state identification (and representation) and action generation. State identification applications include: model based situation assessment and decision support for control room operators; hazop analysis; alarm design and alarm filtering. Further possible applications include operator support systems or integrated HMI and process-design.

[1] Please contact one of the authors for more information on MFM.

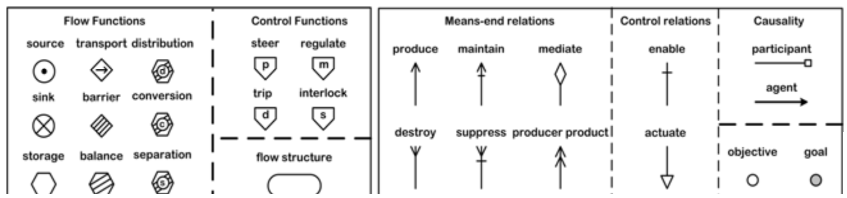


Fig. a) the box on the left lists the MFM-symbols, elementary flow-and contol-functions as well as the flow structure, which combines an interconnection of functions; b) the right box presents all MFM relations and the symbols for objectives and goals..

MFM has been used to represent a variety of complex dynamic processes, i.e. in fossil and nuclear power generation and chemical engineering (e.g. oil refineries) and biochemical processes. The method was originally conceived in the context of cognitive systems engineering as an intermediary model for work domain analysis, but has its own path of development now. Its strong semantic concepts and existing software tools make it suitable for integration with modern methods of intelligent control (Saleem et al. 2009). For IT applications it is useful to formalize all aspects of the modeling technique. An outline of this formalization is given below.

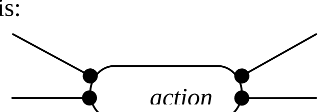
Underlying MFM Concepts

In this section we discuss the underlying concepts that establish the functional structures of MFM. The goal is to identify the basic operations on a functional description of a system.

Actions, Roles and Functions

MFM is strongly related to the semantics of action, and it is possible to formalize MFM entities in a framework of actions and action-roles. The “semantic deep structure of an action” (Fillmore 1968) has been analyzed in relation to MFM in (Petersen 2000). What is important for MFM is the concept of semantic roles, which are associated with the semantic deep structure of an action. It can be illustrated like this:

instrument (*provider, recipient, helper,* etc.)

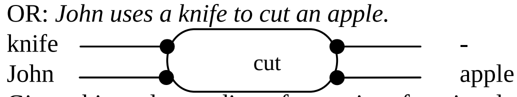


<u>*agent*</u> *object*

This illustration provides an *action* in the centre with *semantic roles* like “slots” to be filled. The kind and number of slots depend on the specific action, but *agent*, *object* and *instrument* are the most generic:

The apple is cut with a knife by John.

OR: *John uses a knife to cut an apple.*



Given this understanding of an action, functional modeling can be described as a modeling approach that formalizes meaningful combinations of actions and roles in the context of a means-ends framework. MFM provides templates for the interconnection of a number of specific actions. These templates are functions, particularly *flow-functions* and *control functions*.

Definition of *function* (Petersen 2000):

> A function of a concrete entity **E**, which is part of a system **S**, is specified in terms of the role **R** of **E** in relation to an action describing an intended state-change in **S**.

According to von Wright (1963 and 1968), elementary actions can be derived from the concept of elementary change. Given a proposition p about the state of the world the four elementary changes are { "p disappears"= $p\mathrm{T}\neg p$; "p happens" = $\neg p\mathrm{T}p$; $p\mathrm{T}p$; $\neg p\mathrm{T}\neg p$ }[2], where "$\neg p$" is "not p" and "T" stands for a transition. An *intentional action* must now be distinguished from a change that does not involve an agent A: Instead of "p happens", we say "A makes p happen, otherwise $\neg p$ happens", in short: $\{\neg p\mathrm{T}[p\mathrm{I}\neg p]\}$[3] . Particularly control functions in MFM are directly derived from elementary actions.

In summary, *propositions* about the state of the system define the effect of a *function* (action), and the *semantic roles* of the action capture the relations between entities in a system. Action *phases* structure temporal information aspects of a function.

Flow structures and Control Structures

There are energy flow structures, mass flow structures and control structures. Most commonly energy- and mass-flow structures are used to represent a particular goal-oriented view of a system.

A *flow* structure allows modeling of a process without direct reference to the agents associated with realizing the process. However, the agent role is associated with each function and can be assumed by an external agent.

A *control* structure is meant to represent the purpose of a control action. Von Wright's theory of intentional action sets a framework for the modeling of control actions. The four elementary interventions define the four possible control functions *steer*, *regulate*, *trip* and *interlock*, respectively (Figure 1a).

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[2] The latter two are non-changes, $p\mathrm{T}p$; $\neg p\mathrm{T}\neg p$, which lead to the concept of *elementary omissions*, as discussed in (Lind 2002b).

[3] Please refer to (Lind 2002b, 2004a and 2005b) for a thorough introduction.

A simple control structure is composed of one *process objective*, which is usually an objective associated with another energy or mass flow structure, and a *control function* (steer, regulate, trip or interlock, Figure 1a) (Lind, 2005a and 2005b). A. The control function has an *actuate-relation* to the agent-role of a flow-function in a lower-level means-ends level (example in Figure 8, p. 12). A control-structure has an external *objective* that describes performance requirements of the control.

Perspectives and views

The simplest and elementary form of an MFM model is an energy- or mass-flow structure connected with an objective via an achieve-relation (produce, maintain, destroy or suppress). The objective or goal is an expression of the intention (the "Why") that is associated with the functional structure and the system it represents. A flow structure contains a conceptualization of the functions the system utilizes to achieve its purpose (the "HOW"). MFM provides templates or conceptual schemes for the *representation of functions*, as well as for goals, objectives and means-end relations which form the statement of *intention*. A *perspective*, or elementary functional description, consists therefore of a set of two elements:

1. Intention (Objective+means-end relation)
2. The representation of functions in a functional view.

The suggested definition of a *perspective* is illustrated in Figure 3.

Usually, an MFM-model consists of several such *perspectives* that are connected through a number of possible relations (*mediate*, *producer/product*, *enable*, *actuate* (all in Figure 1b).

MFM model of Energy System Balancing

The concepts introduced above are illustrated in the following on a number of examples from a modeling application to power systems. The examples have been previously published in (Heussen 2009a, Heussen 2009b).

The abstract model in Figure 4 relates the overall goal $\mathbf{g_1}$ to the intended functional organization of the system. The passive role of the generation side reflects system goal, but an analysis of the realization of Generation shows that this role needs to be enabled by the objective $\mathbf{o_1}$. The enabling objective describes a condition to be fulfilled at a lower level of abstraction.

The descriptions followed abstract considerations about the system design, showing a connection between the statement of design intentions ('goals'), functional abstraction and more concrete process objectives.

The objectives are structured into an objective hierarchy, where the original objective is reformulated **o₁**.= (**o**$_{1a}$ *and* **o**$_{1b}$) with consideration of the flow-structure of the lower-level functional view, from a (mathematical) decomposition of the original frequency control objective **o**$_1$.

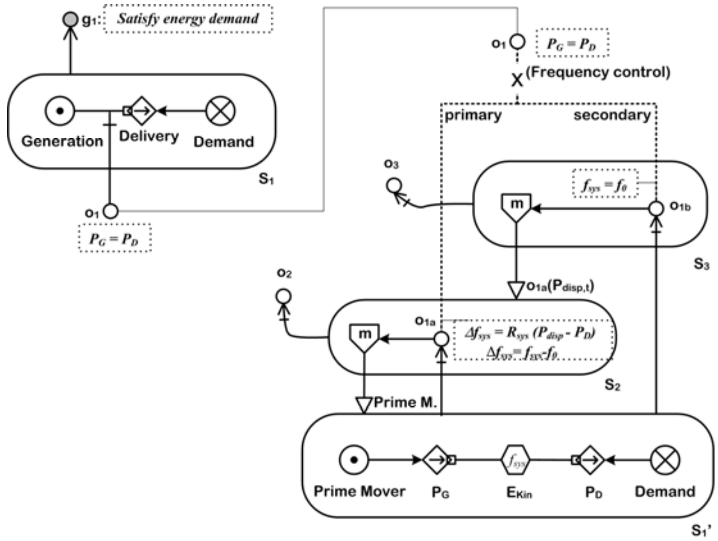

Fig. Abstract (left) and more detailed (right) representations of system balancing functions.

This decomposition is based on AC power systems with synchronous generators. In AC power systems the common frequency reflects the energy stored in the rotating mass of the generators and therefore is a measure of the energy balance. Restoring the frequency therefore is eventually restoring the energy balance.

The objectives of the objective hierarchy are achieved by a combination of a flow structure **S**$_{1'}$**,** representing the energy system, and two control structures representing primary ("droop") and secondary ("integral") frequency control (**S**$_2$ and **S**$_3$). The objectives are maintained by a cascade of control structures **S**$_2$ and **S**$_3$, which employ the system frequency measure and actuate the generators to *maintain* their respective control objectives – which means to balance the system. Note that there are three strongly connected perspectives in this MFM-model.

Conclusion

This paper presented an overview of semantic and action theoretical concepts in Multilevel flow Modeling. The concept of *perspective* as a set of *intention* and functional *representation* was introduced. This concept of perspective forms a framework for the formal representation of the role-shifts that occur in MFM-relations – integrating action-roles with the means-ends levels of MFM. An example from the domain of energy systems illustrates how these “shifts in perspective”. The work presented here forms a platform for further research. Future work branches out into two directions: A) Computer-implementation of the formalizations and development of new reasoning rules; B) The modeling approach can be applied to analyze possible integrated energy systems or “smart grid” control concepts.

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Integration of Power Systems with other Energy Systems using Multilevel Flow Modeling of Control

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ABSTRACT—The integration of energy systems is a proven approach to gain higher overall energy efficiency. Invariably, this integration will come with increasing technical complexity through the diversification of energy resources and their functionality. With the integration of more fluctuating renewable energies higher system flexibility will also be necessary. One of the challenges ahead is the design of control architecture to enable the flexibility and to handle the diversity. This paper presents an approach to model heterogeneous energy systems and their control on the basis of purpose and functions which enables a reflection on system integration requirements independent of particular technologies. The results are illustrated on examples related to electric energy systems.

I. INTRODUCTION

We anticipate that sustainable energy systems are more *intelligent* energy systems. The integration of energy systems is a proven approach to gain higher overall energy efficiency. Invariably, this integration will come with increasing technical complexity through the diversification of energy resources and their functionality. With the integration of more fluctuating renewable energies higher system flexibility will also be necessary. All this results in a demand for ever more advanced control of electric power system to handle the mix of resources with increased flexibility, while the system robustness ought to be maintained.

One approach to improve efficiency of the electricity sector is its integration with the heat sector. As heat can easily be stored, this integration also gives way for a cheaper and more effective type of energy storage: flexible demand. For example, the Danish electricity supply relies mainly on combined-heat-and-power (CHP) plants. All larger CHP plants have been equipped with significant heat storage to offset electricity production from the district heating demand. Studies suggest further an addition of heat pumps to the district heating system to enable the integration of wind power into the electricity supply, e.g. (Lund and Münster, 2006).

In recent years, many visions of future integrated energy systems have been proposed, some are based on a particular technology domain such as Microgrids or Zero-energy Buildings, others are based on an abstract planning and optimization process that does not involve the technical details of an implementation (they often assume some type of global coordination). One difficulty is that such integrated energy systems depend on separate domains of engineering which have their own way of representing design problems and requirements. Another, possibly even harder, difficulty is that the assumed global coordination may not be feasible in a market-based economy.

It is typical that control systems integrate different domains of engineering knowledge as a result of a control design process. Yet, a mathematical control design tends to ignore the conceptualization of different engineering domains. This kind of knowledge is often implicit in the mathematical formulations of control objectives and performance requirements. Such implicit knowledge makes control systems vulnerable or at least sensitive in cases of failure, system modifications or redesign.

Integration of energy systems means the combination of systems that were previously independent and therefore have partly incompatible conceptualizations. Common system analysis is behavioural is therefore dependent on assumptions about the technical realization. The functional modeling approach applied in this paper instead allows the study of interrelations on a more general level by formalizing the semantic relations between different perspectives. The functional models are presented by Multilevel Flow Modeling (MFM).

In this paper the method is outlined with a focus on the underlying semantics. The concept of views and perspectives is introduced and then a variety of possible shifts in perspective are explained and later illustrated on examples related to electric energy systems.

II. FUNCTIONAL MODELING WITH MFM

Multilevel Flow Modeling (MFM) is an approach to modeling goals and interconnected functions of complex processes involving interactions between flows of mass, energy and information (Lind

2005)[1]. It provides means for a *purpose-centered* (as opposed to *component-centered*) description of a system's functions. MFM enables modeling at different levels of abstraction using well-defined means-ends relations and whole-part compositions (Figure 1b). Process functions are represented by elementary flow functions interconnected to form flow structures which represent a particular goal oriented view of the system (Figure 1a). The views represented by the flow structures, functions, objectives and their interrelations together comprise a comprehensive model of the functional organization of the system represented as a hypergraph. MFM is founded on fundamental concepts of action and each of the elementary flow and control functions can be seen as instances of more generic action types.

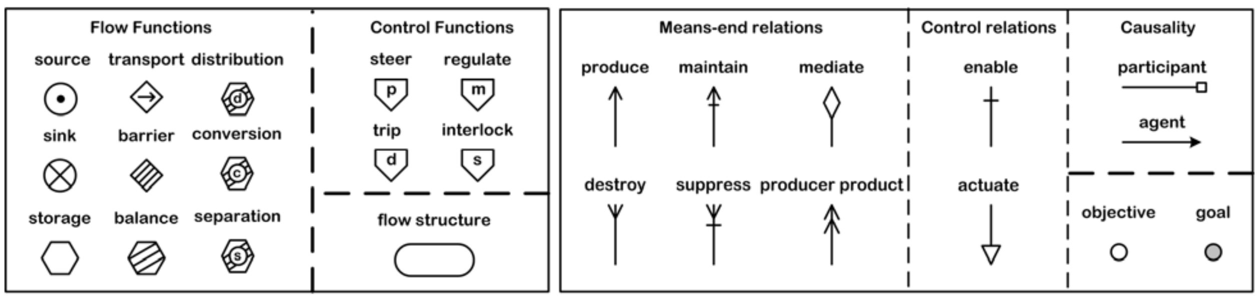


Figure 1. a) the box on the left lists the MFM-symbols, elementary flow-and contol-functions as well as the flow structure, which combines an interconnection of functions; b) the right box presents all MFM relations and the symbols for objectives and goals.

Models created in MFM are a formalized conceptual representation of the system, which support qualitative reasoning about control situations. MFM is supported by knowledge based tools for model building and reasoning.

MFM models can be and have been employed for the purposes of state identification (and representation) and action generation. State identification applications include:

- model based situation assessment and decision support for control room operators
- hazop analysis
- alarm design and alarm filtering

For action-generation, it has been shown that MFM-models can be used for

- deriving action sequences for startup
- planning of control actions (counter-action planning)

Further possible applications include operator support systems or integrated HMI and process-design.

MFM has been used to represent a variety of complex dynamic processes, i.e. in

- fossil and nuclear power generation
- chemical engineering (e.g. oil refineries) and biochemical processes.

The method was originally conceived in the context of cognitive systems engineering as an intermediary model for work domain analysis, but has its own path of development now. Its strong

[1] Please contact one of the authors for more information on MFM.

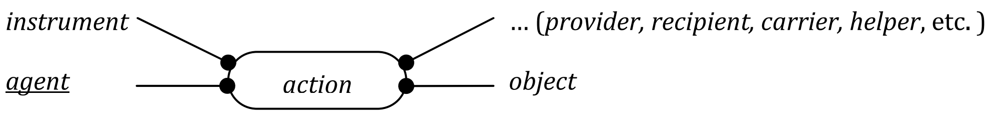
semantic concepts and existing software tools make it suitable for integration with modern methods of intelligent control (Saleem et al. 2009). For IT applications it is useful to formalize all aspects of the modeling technique. An outline of this formalization is given below.

A. UNDERLYING MFM CONCEPTS

In this section we discuss the underlying concepts that establish the functional structures of MFM. The goal is to identify the basic operations on a functional description of a system.

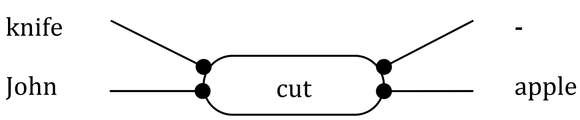
1. ACTIONS, ROLES AND FUNCTIONS

MFM is strongly related to the semantics of action, and it is possible to formalize MFM entities in a framework of actions and action-roles. The "semantic deep structure of an action" (Fillmore 1968) has been analyzed in relation to MFM in (Petersen 2000). What is important for MFM is the concept of semantic roles, which are associated with the semantic deep structure of an action. It can be illustrated like this:

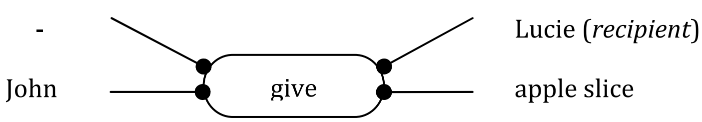


This illustration provides an *action* in the centre with *semantic roles* like "slots" to be filled. The kind and number of slots depend on the specific action, but *agent*, *object* and *instrument* are the most generic. The next few examples illustrate the relation between sentences in natural English language and their representation in actions and semantic roles:

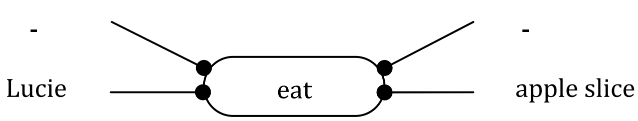
1) *The apple is cut with a knife by John.*
OR: *John uses a knife to cut an apple.*



2) John gives an apple slice to Lucie.
OR: *Lucie is given a slice of an apple from John. OR: Lucie receives a slice of an apple from John.*



3) Lucie eats an apple slice.



Given this understanding of an action, functional modeling can be described as a modeling approach that formalizes meaningful combinations of actions and roles in the context of a means-ends framework. MFM provides templates for the interconnection of a number of specific actions. These templates are functions, particularly *flow-functions* and *control functions*.

Definition of *function* (Petersen 2000):

A function *of a concrete entity **E**, which is part of a system **S**, is specified in terms of the role **R** of **E** in relation to an* action *describing an* intended state-change *in **S**.* [emphasis in original]

According to von Wright (1963 and 1968), elementary actions can be derived from the concept of elementary change. Given a proposition p about the state of the world the four elementary changes are { "p disappears"= $p\mathrm{T}\neg p$; "p happens" = $\neg p\mathrm{T}p$; $p\mathrm{T}p$; $\neg p\mathrm{T}\neg p$ }[2], where "$\neg p$" is "not p" and "T" stands for a transition. An *intentional action* must now be distinguished from a change that does not involve an agent *A*: Instead of "p happens", we say "*A* makes p happen, otherwise $\neg p$ happens", in short: $\{\neg p\mathrm{T}[p\mathrm{I}\neg p]\}$[3] . Particularly control functions in MFM are directly derived from elementary actions.

Another relevant aspect of actions, is their temporal unfolding into action-phases (i.e. *potentiality*, *opportunity*, *execution* and *completion*). This aspect is not discussed further here.

In summary, *propositions* about the state of the system define the effect of a *function* (action), and the *semantic roles* of the action capture the relations between entities in a system. Action *phases* structure temporal information aspects of a function.

2. FUNCTIONAL VIEWS

MFM views are used to represent different aspects of the system under study. MFM combines views of different means-ends and abstraction levels using means-end relations which define the relation between a functional view and it purpose. There are energy flow structures, mass flow structures and control structures. Most commonly energy- and mass-flow structures are used to represent a particular goal-oriented view of a system.

FLOW STRUCTURES

MFM flow structures combine a set of actions (flow-functions) that are performed on the same object (the object is the *energy* or *mass* that is *provided*, *transported*, *stored*, etc.). In that, a process is modeled in a specific perspective when describing the actions performed in the process, called *flow perspective*:

> *A* flow perspective *on an* action *describes the state change that the object* [of an action] *is undergoing without reference to the agent involved.* (Petersen 2000, emphasis in original)

That is, a flow structure allows modeling of a process without direct reference to the agents associated with realizing the process. However, the agent role is associated with each function and can be assumed by an external agent.

Flow structures comprise flow-*functions*. The flow-functions provide a link between the *behavioural* aspects of a process and a framework of *intentional (goal-oriented) action*. For example, there is a strong analogy between the mass-flows (water-flow) that occur in a set of interacting water tanks and a set of differential equations (flow-potential-analogy). On the other hand, a flow-function can be associated with a "concrete entity E" through a role R in the semantic deep description of an

[2] The latter two are non-changes, $p\mathrm{T}p$; $\neg p\mathrm{T}\neg p$, which lead to the concept of *elementary omissions*, as discussed in (Lind 2002b).
[3] Please refer to (Lind 2002b, 2004a and 2005b) for a thorough introduction.

action performed on an (energy or mass) flow object. Thus, a flow structure models an action-structure of a behavioural process.

When flow-functions are employed to model an existing system, they form a hypothesis on the design-intentions of the system. In addition to the action-description of a function, it is possible to associate *causal roles* with the connection of functions (upstream/downstream agent, receiver/provider). From a behavioural perspective, the causal role describes in which direction a state-change propagates through the system. From an action/function-perspective, the causal role affects semantic roles of the connected functions. For example the agent-role can be *upstream* (e.g. the storage of a tank influencing the mass-flow by its tank-level), *downstream* (such as “back-pressure”), or *external* (e.g. a pump driven by an external energy source, which isolates the interaction between communicating reservoirs).

CONTROL STRUCTURES

A control structure is meant to represent the purpose of a control action. Von Wright’s theory of intentional action sets a framework for the modeling of control actions. The four elementary interventions *produce* [¬pTpI¬p], *maintain* [pTpI¬p], *destroy* [pT¬pIp] and *suppress* ¬pT[¬pIp] define the four possible control functions *steer*, *regulate*, *trip* and *interlock*, respectively (Figure 1a).

A combination of a control-objective with a control function forms this different type of functional view (Lind, 2005a and 2005b). A simple control structure is composed of one *process objective*, which is usually an objective associated with another energy or mass flow structure, and a *control function* (steer, regulate, trip or interlock, Figure 1a). The control function has an *actuate-relation* to the agent-role of a flow-function in a lower-level means-ends level (example in Figure 8, p. 12). A control-structure has also an external *objective* that describes performance requirements of the control.

The “instead” part of von Wright’s elementary actions give rise to another point that important for control functions and control design: What is the counter-agent of a control function? Is the objective to suppress noise? Or is it to isolate one part of a system from another? The answer to these questions is an essential part of the requirement analysis, which lead to the definition of control objective and performance requirements.

Control functions change the interpretation of the connected flow structure. The intended effect of a control system is often a change in the functional structure and roles of the *controlled* flow-structure. As a result, that flow structure can be represented differently on a higher level of means-ends (See system-balancing in Section III.A: compare Figure 4 with Figure 8).

Control structures can be combined to cascades or parallel control systems (cascade-structure in Figure 8, parallel control objectives for control areas). The purpose of a control function is to realize the execution of a plan, to ensure the transformation of a command into a physical fact. When control functions are organized into hierarchies, one may speak of “levels of execution”. These levels encapsulate unwanted agents (disturbances) and structure the command-flow in a system.

3. AGGREGATION AND DECOMPOSITION OF FLOW FUNCTIONS

An existing flow structures can be simplified or detailed by rewriting the model following well-defined operations or re-writing rules.

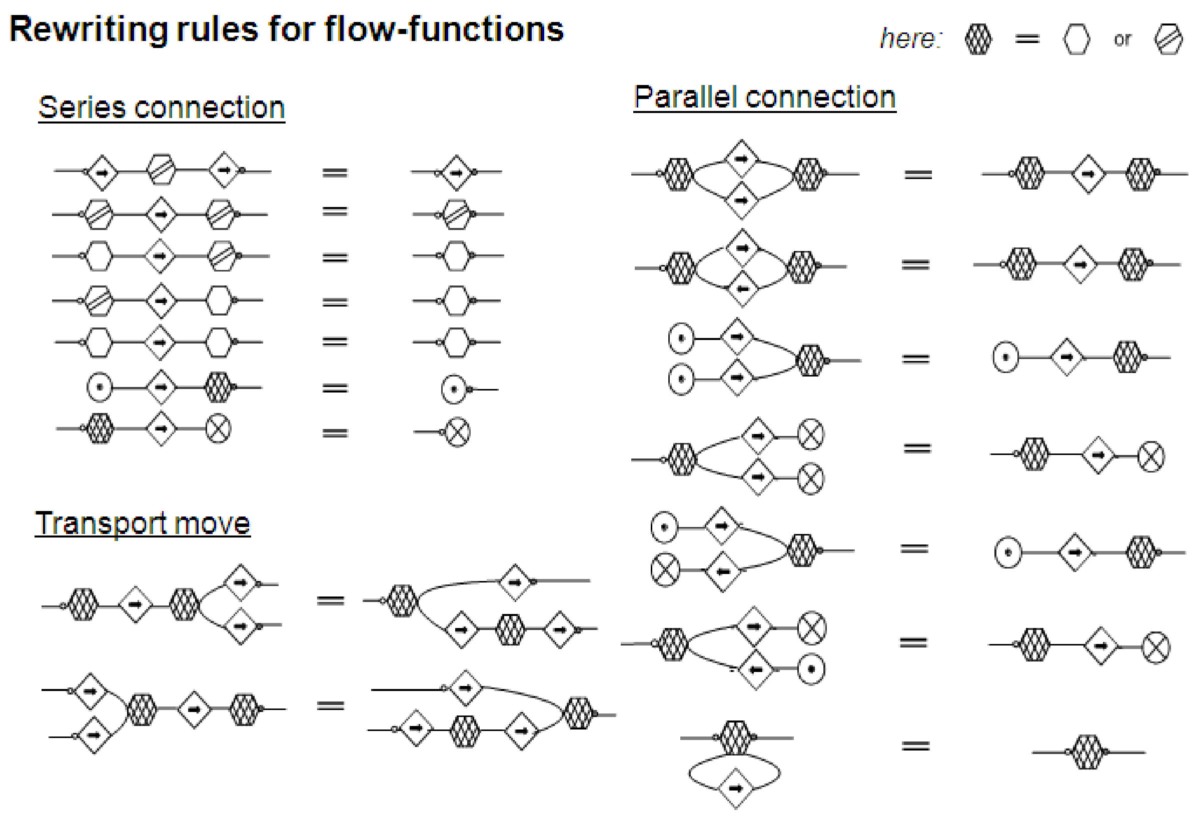


Figure 2. Rewriting rules for MFM flow-structures

For one purpose, these rules allow to extend a model to add more detailed information, or to reduce it if a simpler view is more helpful. It can also be used to alter the topology of the flow-network, in order to establish a new control-paradigm if necessary.

On the basis of these transformation rules, you can create different perspectives of the system representing different levels of detail/aggregation of functions. In this way a view can be adapted to suit the problem the MFM is used for and the level of means-ends that needs to be represented

B. PERSPECTIVES AND VIEWS

An MFM model is composed of objectives, functional views and means-ends-relations. The simplest and elementary form of an MFM model is an energy- or mass- flow structure connected with an objective via an achieve-relation (produce, maintain, destroy or suppress).

The objective or goal is an expression of the intention (the "Why") that is associated with the functional structure and the system it represents. A flow structure contains a conceptualization of the functions the system utilizes to achieve its purpose (the "HOW"). MFM provides templates or conceptual schemes for the *representation of functions*, as well as for goals, objectives and means-end relations which form the statement of *intention*. A *perspective*, or elementary functional description, consists therefore of a set of two elements:

Perspective: (*intention*/purpose (why?); : *representation of functions* / view (how?))

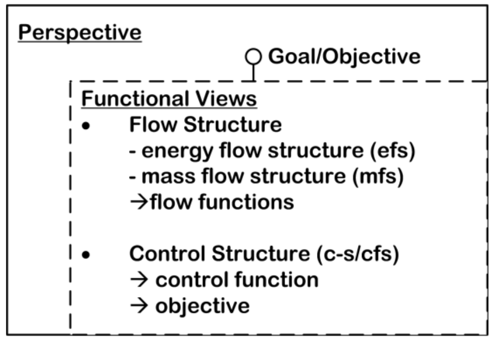


Figure 3. The elements of a perspective are: 1. Intention (Objective+means-end relation) and
2. The representation of functions in a functional view.

The suggested definition of a *perspective* is illustrated in Figure 3.

Usually, an MFM-model consists of several such *perspectives* that are connected through a number of possible relations (*mediate*, *producer/product*, *enable, actuate* (all in Figure 1b), *Janus* (connects complement-functions across flow-structures, goal-relations). These relations essentially across-perspectives and cover all possible connections perspectives (Table 1).:

Perspective 1 / **Perspective 2**	Intention1	Functional view1
Intention2	Goal structure: *Goal-subgoal, Goal-objective, objective-objective*	Means-end-relations: *Producer-product, Mediate* Control relation: *enable/disable*
Functional View2	Means-end-relations: *Producer-product, Mediate* Control relations: *enable/disable* *(symmetric matrix: means/ends loops are possible)*	*Janus-relation* *Actuate*

Table 1: Possible relations between two perspectives.

C. SHIFT IN PERSPECTIVE

A shift in perspective occurs in the transition from one perspective to another. The possible transitions between two perspectives have been listed in Table1. But what does it mean to "shift" from one perspective to another?

Assume an agent that is associated with a role of a MFM function, and the agent utilizes the MFM representation to determine its relation with another function of another flow-structure. Or, an agent that is be associated with some component's control system must determine the component's relation to a new perspective that the component has become a part of due to a system reconfiguration. Based on the set P:(*intention* ; *function-representation*), exactly two types of information need to be updated in order keep track of the perspective.

The perspective-shifts (→) that happens in a given type of cross-perspective relation can be described by the types of roles that are exchanged due to the shift:

1. Object-role →agent-role :: mediate relation
   In the mediate relation, the object of a flow-structure assumes the agent-role of a flow function in another flow structure (e.g. water becomes heat-transport agent)
2. Action (function)→agent-role :: producer-product relation
   one function in the mean-side flow structure becomes agent in a function of the ends-side flow-structure (e.g. energy-sink of a pumping process becomes transport agent)
3. Function & intention1 → Complement-Function intention2 :: Janus relation
   following a Janus-relation means to keep the same flow perspective, while inverting the state-change propositions: sink becomes source and source becomes sink; the special character of the Janus-relation is that it is not a means-ends relation in itself (Ex. In Section III.C)
4. instrument-role (of control function) → agent-role(of flow-function) :: actuate
   A concrete entity that assumes the instrument role in a control function becomes an agent with respect to the flow-function the actuate relation points to (Ex. in Figure 8)
5. intention → condition (i.e. enabler-role in act) :: enable
   The information that describes an intention for one system becomes an enabling condition with respect to another system. Note that the *enablement* is also an action-phase (Ex. in Figure 4&6)
6. intention → function :: Objective in Control structure
   an process objective in a control structure undergoes a strange transition when it is considered part of a control structure: it moves from being an intention to being a function that influences its downstream control function (Ex. in Figure 8; also formalized)

These shifts give an operational understanding of how status and role-information associated with any function are mapped in an MFM model.

The following relations are within a perspective. They clearly structure the information within the perspective-structure:

- flow-structure→objective :: achieve-relations (produce, maintain, destroy, suppress)
- flow-functions→flow-structure :: whole-part relation
- flow-function→role(agent,helper,…) :: connection-relation (participant or agent)

A compact representation of these information-relations is proposed in Section III.A on page 12.

The introduction of underlying concepts above also raised the point of rewriting an MFM model. In case a flow structure is being adapted/modified by transformation rules, the basic action is transformed. This type of "transition" is not directly related to means-ends relations as it requires a re-interpretation of the action that underlies any modified function.

- act1→ (act1a, act1b, act1c) :: e.g. shift of abstraction-level (rewriting-rules)

There are two examples in the following that illustrate the use of rewriting rules in combination with causal-role modification: Figure 5 and Figure 9. The result of such modifications is the adaption of a flow-structure for a different purpose (both higher-level and lower level).

III. EXAMPLES

A. MFM MODEL OF ENERGY SYSTEM BALANCING

The concepts introduced above are illustrated in the following on a number of examples from a modeling application to power systems. The examples have been previously published in (Heussen 2009a, Heussen 2009b).

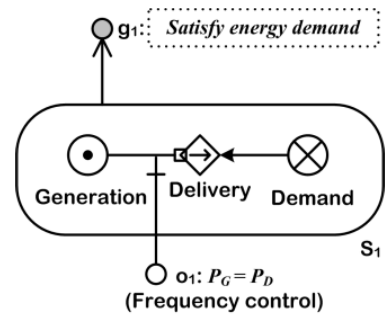


Figure 4. Abstract perspective of an energy system where Generation follows Demand.

The abstract model in Figure 4 relates the overall goal $\mathbf{g_1}$ to the intended functional organization of the system. The passive role of the generation side reflects system goal, but an analysis of the realization of Generation shows that this role needs to be enabled by the objective $\mathbf{o_1}$ (which in turn is the objective of the frequency control mechanism of Figure 8). The high-level view is established to reflect the implication of goal. The enabling objectives describe a condition to be fulfilled at a lower level of abstraction.

In larger power systems, this system balancing is more complex, as the system is structured further into control areas. The design goal can be formulated as $\mathbf{g_{areas}}$: "use local resources to balance local disturbances". In order to represent those areas in a flow structure, the flow structure $\mathbf{S_1}$ of Figure 4 can be expanded by application of rewriting rules introduced above (See Section II.A.3 and Figure 2).

The expansion is shown in Figure 5 for three control areas. The expansion is done in four steps:
(1) Expand transport function "delivery" (series connection) in order to get a balance function in the center

(2) split energy-source "Generation" and energy-sink "Demand", together with associated transport functions by three (parallel connection) to enable reasoning about alternative sources and sinks

(3) re-group into pairs of "Generation" and "Demand", representing energy sinks and sources in the control areas;

(4) expand balance (series connection): This expansion introduces a distinction between the power balance within a control area and a definition of exchange across the border of

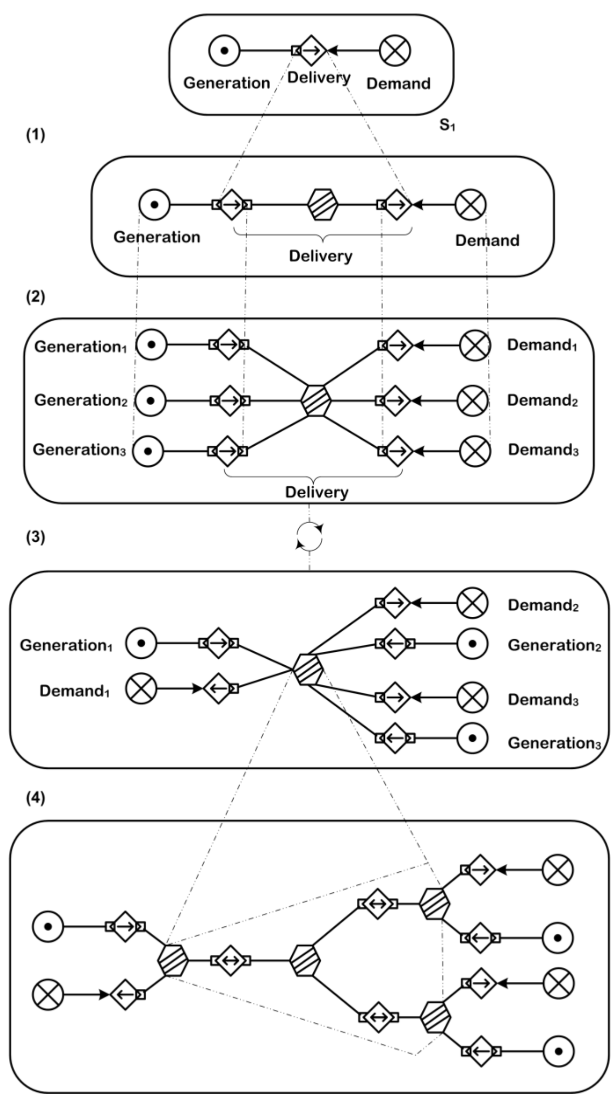


Figure 5. Model-expansion for the representation of three control areas. There could be more or less areas.

control areas; note that the bi-directional transport function is new in MFM.

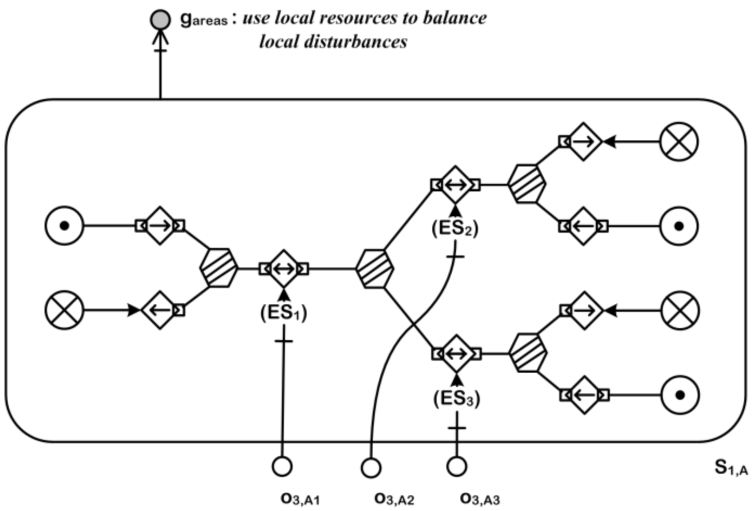


Figure 6. Perspective of the energy system with control areas and the objectives related to the local balancing.

The resulting flow structure of Figure 5 forms the core of the MFM perspective presented in Figure 6. The difference between the two flow structure of Figure 5 (after (4)) and Figure 6 ($\mathbf{S_{1,A}}$) in is in the agency description: The bi-directional transport functions where passive before and now they have been assigned an agent-role for maintaining their associated "exchange schedules" $\mathbf{ES_1}$, $\mathbf{ES_2}$ and $\mathbf{ES_3}$, which is indicated by the arrow on the bottom side of the function.

This role is enabled by the three new objectives $\mathbf{o_{3,A1}}$, $\mathbf{o_{3,A2}}$ and $\mathbf{o_{3,A3}}$.

So far, all descriptions followed abstract considerations about the system design, showing a connection between the statement of design intentions ('goals'), functional abstraction and more concrete process objectives.

The next example (Figure 7) shows a pure objective-view or objective-hierarchy, which originates from a (mathematical) decomposition of the original frequency control objective $\mathbf{o_1}$.

The objectives are structured into an objective hierarchy, where the original objective is reformulated with consideration of the flow-structure of the lower-level functional view, which is closer to the physical realization of the energy system (Figure 8).

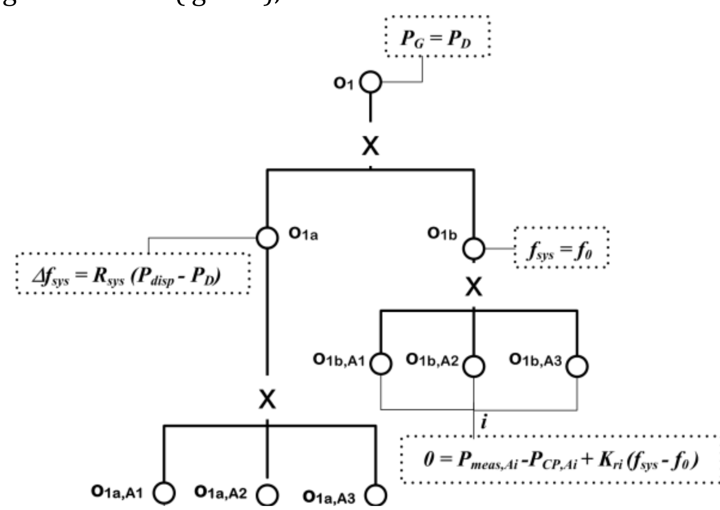


Figure 7. Objective hierarchy of frequency control. In this paper only $\mathbf{o_{1a}}$ and $\mathbf{o_{1b}}$ are realized.

This decomposition is based on AC power systems with synchronous generators. In AC power systems the common frequency reflects the energy stored in the rotating mass of the generators and therefore is a measure of the energy balance. Restoring the frequency therefore is eventually restoring the energy balance.

Figure 8 shows a combination of a flow structure $\mathbf{S_1}$, representing the energy system and two control structures representing primary ("droop") and secondary ("integral") frequency control ($\mathbf{S_2}$ and $\mathbf{S_3}$). The objectives are maintained by a cascade of control structures $\mathbf{S_2}$ and $\mathbf{S_3}$, which employ the system frequency measure and actuate the generators to *maintain* their respective control objectives – which means to balance the system.

Note that there are three strongly connected perspectives in this MFM-model. Several MFM entities are connected with two different perspectives.

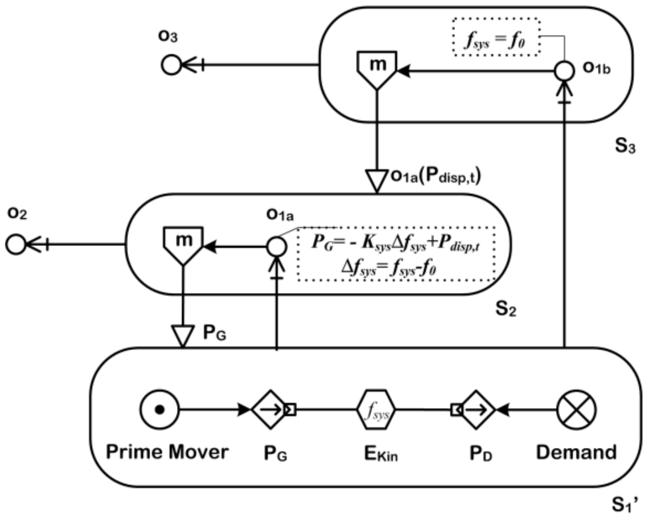


Figure 8. Aggregated view of an MFM model of primary and secondary frequency control.

Let us analyze this shift in perspective in the formal representation introduced in Section II.B. There are three perspectives in this MFM-model are **P1**, **P2**, and **P3**. Each perspective is formalized into *intention* and *function-representation*:

Px: ({*means-end-rel*:***objective*** } ; { *representation-type_Structure-ref*:{*representation*} })
^---------Intention---------^ ^--------------Function-representation-----------------^

Note the notation is kept as compact as possible, and there are different representations for flow structures and control structures:

- *Flow structures* alter between transport functions *ti* and other functions *fi*, and each transport function has two sides for attributing the causal roles (>/-/<):
  {*f1*(> /-) *t1* (< /-) … *tn*(< /-) *fn*}
- *Control structures* are more structured:
  {*objective* > *control-function:actuate(flow-structure:flow-function)*}

The perspectives of Figure 8 are then:

1) one energy flow structure:

P1: ({maintain:$\mathbf{o_{1a}}$; maintain:$\mathbf{o_{1b}}$} ; { energy-flow_$\mathbf{S_1}$:{PrimeMover >$\mathbf{P_G}$- $\mathbf{E_{kin}}$ - $\mathbf{P_D}$<, Demand} })

2) two control structures:

P2: ({maintain:$\mathbf{o_2}$} ; { control _$\mathbf{S_2}$:{$\mathbf{o_{1a}}$ >(m):actuate(S2:$\mathbf{P_G}$)} })

P3: ({maintain:$\mathbf{o_3}$} ; { control _$\mathbf{S_3}$:{$\mathbf{o_{1b}}$ >(m):actuate(S1:$\mathbf{o_{1a}}$)} })

We find several shifts of perspective: For example the objective $\mathbf{o_{1a}}$**,** which is part of the intention of perspective **P1** is also becomes a function in the control-structure $\mathbf{S_2}$, as well it is a reference for the actuate-relation of $\mathbf{S_3}$, thereby connecting the two control structures into a cascade.

B. MODELS FOR NEW FLEXIBLE DEMAND, FLUCTUATING GENERATION AND A COMPONENT-VIEW

The models above show the MFM principles applied to the traditional control architecture for system balancing from a power system perspective (frequency control). In the following, some flow-structure examples are presented that represent existing technology, but would that alter the functional organization of the system.

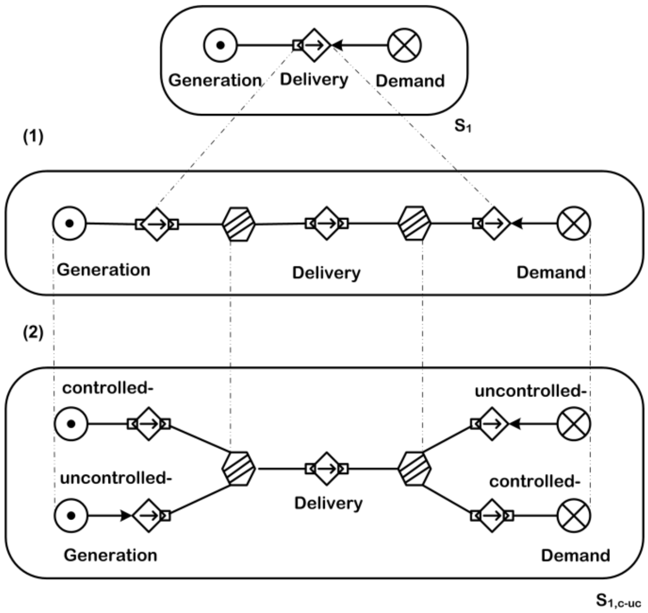


Figure 9. Another model expansion introducing un-controlled generation and controlled demand.

The basic energy-system flow structure can be extended to represent additionally controlled demand and uncontrolled generation.

Step (1): expansion of transport function (series connection), to introduce balances for generation and demand.

Step (2a): split both energy-source "Generation" and energy-sink "Demand", together with associated transport functions in two;

Step (2b): modify the causal roles to represent uncontrolled generation and controlled demand.

The transformation rules are applied within the flow structure, altering all function-representations:

S

$\mathbf{S_1}$:{So1, -Tr1<, Si1} → $\mathbf{S_{1,C\text{-}UC}}$:{ (So1a,-Tr1a1-)||(So1b, >Tr1a2-), Ba1a, -Tr1b-, Ba1b, (-Tr1c1<, Si11,)||(-Tr1c2-, Si12)}

The next example in Figure 10 can be considered a functional abstraction of a (micro-)CHP plant. It illustrates how one and the same plant may assume both an active and passive roles in system-balancing (e.g. as controlled and uncontrolled generation), using different control modes. It is also an example for a *component-perspective* that integrates two types of energy.

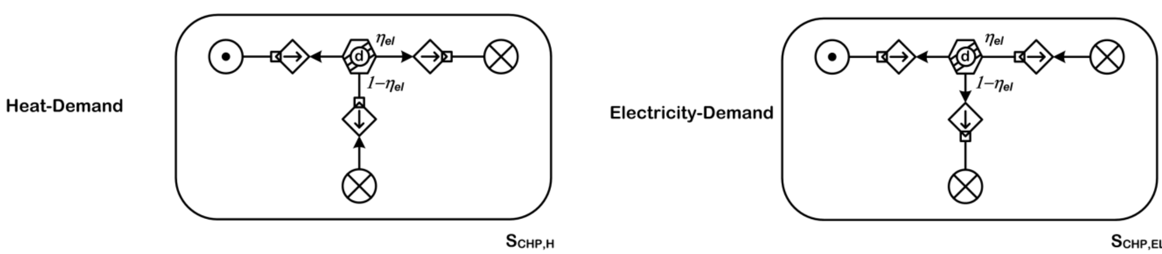


Figure 10. Two control modes for a combined heat and power production. The energy sink on the right represents electricity export and the energy sink on the bottom represents heat export. The distribution sets a fixed energy/heat ratio ratio.
In the control mode "Heat-Demand" ($\mathbf{S_{CHP,H}}$) the agent-role of the heat-sink determines the energy production from the source, as well as the electricity export; in control mode "Electricity-Demand" ($\mathbf{S_{CHP,EL}}$)the energy production is determined by the electricity-sink instead.

C. COMBINING COMPONENT PERSPECTIVE AND SYSTEM PERSPECTIVE: EXAMPLES FOR A SHIFT IN INTENTION

From the point of view of the power system, the means of providing energy and the means of consuming energy only matter to the extend they need to be distinguished electrically. However, a power plant is a complex subsystem that needs to be managed from a local perspective. The *Janus relation* connects to flow functions that relate to the same physical entity, that is, it presents a functional interface between otherwise independent perspectives.

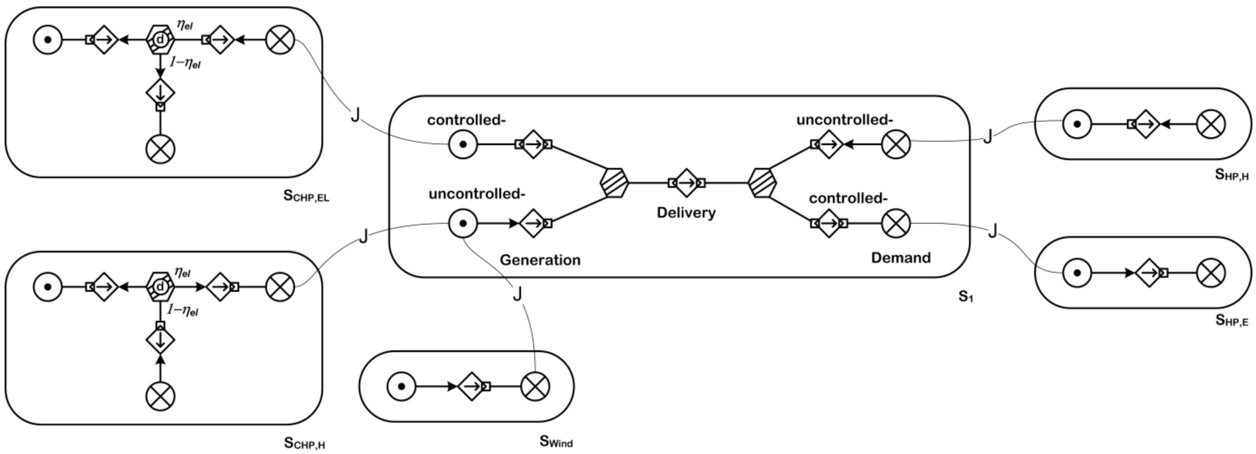


Figure 11. Five examples of abstract component-views (Heat pump as demand, Wind Power and the CHP plant of Figure 10) are connected with an abstract power-system-view (see Figure 11) via a Janus-relation. This MFM model with different objectives associated to each flow structure illustrates a combination of six different perspectives in the same model.

All flow-structures in Figure 11 are energy flow-structures. A function-based reasoning could logically integrate information from all of the flow-structures. However, the *evaluation* of a function-state depends on the objectives associated with the respective flow-structure, forming a *perspective*. For example, in the perspective of an electricity system operator it might be good to change the control mode of a CHP plant. If that is possible, however, cannot be decided from a system perspective but from the perspective of the CHP plant. The functional model shows the system in the same conceptualization, enabling a communication about functional requirements. At the same time the separation of flow structures into independent perspective enables a reflection of different interest.

A final example in Figure 12 shows another reason why it may be useful to consider perspectives as a combination of intention and function-representation. Here, the roles in an energy market are brought into a functional form. The parallels between roles in the market and roles in the functional structure are obvious. We conclude that the study of market functions may be integrated with the presented modeling approach.

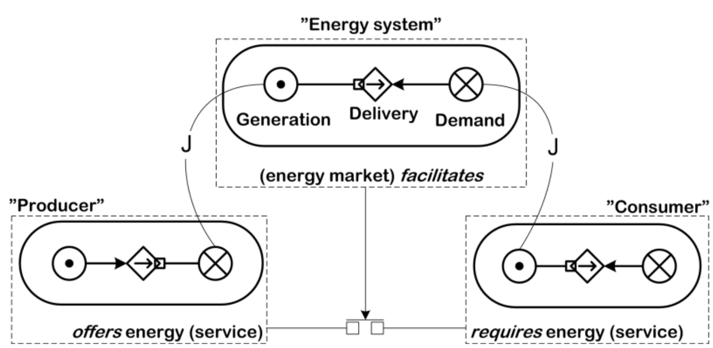


Figure 12. Producer-Energy system-Consumer model to illustrate parallel roles in a market and in the flow-structures.

IV. CONCLUSION

This paper presented an overview of semantic and action theoretical concepts in Multilevel flow Modeling. The concept of *perspective* as a set of *intention* and functional *representation* was introduced. This concept of perspective forms a framework for the formal representation of the role-shifts that occur in MFM-relations – integrating action-roles with the means-ends levels of MFM. A number of examples from the domain of energy systems illustrate how these "shifts in perspective" appear in common structures. The results indicate that the unifying character of the functional approach becomes increasingly relevant for more heterogeneous energy systems.

The work presented here forms a platform for further research and for the study of more concrete scenarios. Future work branches out into two directions: A) Computer-implementation of the formalizations and development of new reasoning rules; B) The modeling approach can be applied to analyze possible integrated energy systems or "smart grid" control concepts.

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Representing Causality and Reasoning about Controllability of Multi-level Flow-Systems

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***Abstract*—Safe operation of complex processes requires that operators maintain situational-awareness even in highly automated environments. Automatic reasoning can support operators as well as the automation system itself to react effectively and appropriately to disturbances. However, knowledge-based reasoning about control situations remains a challenge due to the entanglement of process and control systems that co-establish the intended causal structure of a process.**

Due to this entanglement, reasoning about such systems depends on a coherent representation of control and process. This paper explains modeling of controlled processes with multilevel-flow models and proposes a new framework for modeling causal influence in multilevel flow models on the basis of a flow/potential analogy. The results are illustrated on examples from the domain of electric power systems.

***Index Terms*—Knowledge-based Systems, Means-ends, Power Systems, Intelligent Control, Model-based reasoning, Causality, Functional Modeling**

I. Introduction

Security and safety of technological infrastructures and complex processes requires a thorough understanding of their basic physical principles – and just as much of the control systems enabling their operation.

The interconnection of electric power networks over whole continents creates a complex interdependent setting where incidents in one location may have an effect across continent. The control architecture of interconnected power systems therefore counteracts the propagation of disturbances, for example by activating the resources inside the grid region from which the disturbance originated. The electromechanical process interconnects alternating-current synchronous machines in a large area, but a control architecture established on top of that process modifies the causal structure, thereby reducing dangerous interdependence.

This example illustrates the entanglement between process and control systems with respect to causal explanations. Whereas the connection between causality and control is obvious to control engineers, it is only implicit in typical representations used in design documents. For example, signal diagrams which are common in control engineering are based on a strict input-output notion of causality, but their relation to process diagrams is not explicit and requires insight into the mathematical modeling of the specific controlled process.

Thinking in terms of causality is a basis for human understanding of processes. However, the specific understanding of how things are causal in a given domain cannot be generalized to other domains. This is one reason why *explicit* representation of causality becomes important when multi-disciplinary and multi-domain systems are employed.

Many developments in electric power systems, particularly the move toward more uncontrolled renewable energy sources and the so-called smart grid, tend toward a deeper integration of different domains of energy [1]–[3], where the overall system efficiency and reliability can be improved. New control approaches and changing control architecture are expected [4]; a much wider range of active devices will require a reformulation of current operation principles, which are based on very limited numbers and kinds of devices, to a more functional description of requirements [5]–[10].

These developments also imply new demands on the manageability and controllability of the overall system. Our ability to study, determine and oversee the behavior of a system depends on our ability to represent and thus to model the system's relevant features. As intelligent control is concerned with the control and supervision of systems, including systems that control other systems, it becomes vital to clearly identify the context of representation (the system-in-view).

Knowledge-based systems have a strength in representing human knowledge and thus also to represent information in context. A central challenge of knowledge-based systems application for critical infrastructures is the the lack consistent representation of processes and their control.

A. Qualitative Representation of Processes, Causality and Control

In this paper we will present a modeling and reasoning approach based on a qualitative model of both process and control systems in a common modeling framework: Multilevel-Flow-Modeling. Multilevel Flow Modeling (MFM) is a process-oriented ontology capturing qualitative functions of material and energy flow processes as well as control functions.

Qualitative representation of processes has some history connected with earlier developments in artificial intelligence. Qualitative Process Theory (QPT) [11] introduced common-sense physics to the description of physical processes. QPT also marked the departure from device-oriented modeling to a process-based abstraction to capture more generic functions of technical processes.

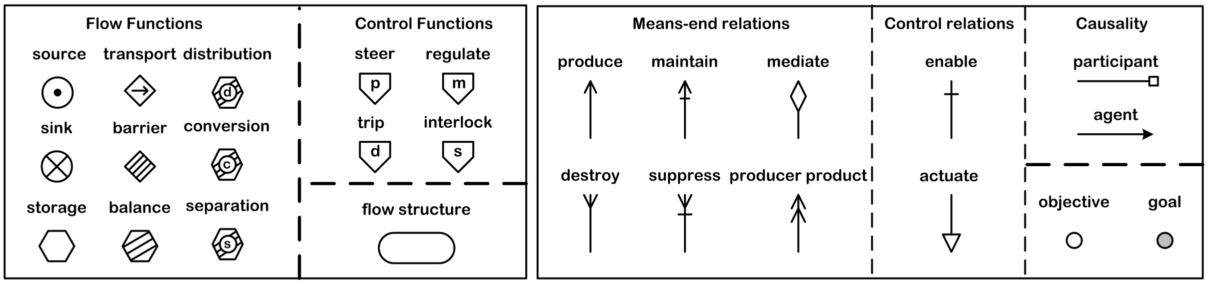

Fig. 1. MFM Entities and Relations.

Representation of material- and energy-flow processes in MFM can be compared to a domain-specific ontology in QPT. The real representational power of MFM, however, comes from its framework of explicit means-ends and part-whole abstractions: Every connected energy- or material-flow is encapsulated in a so-called flow-structure, which then is related with a purpose (an objective, or its function with respect to another flow-structure). These part-whole and means-ends patterns describe the two basic abstractions enabled by MFM. Using basic flow-functions and transformation-rules, a process can always be described in further detail; and using a means-end abstractions, a process-hierarchy, such as a control-hierarchy can be captured.

An explicit representation of causal influence within flow-structures has been considered in MFM since [12] and [13], [14]. In [13] the understanding of causal influence is related to QPT and the need for and practicality of generic causation rules are emphasized.

In this paper, a more rigorous formal basis for modeling and reasoning with MFM is proposed and new agent-roles are introduced reflecting the role of a control agents in the process.

Section II introduces Multilevel Flow Modeling and the relevant background concepts. The results of this work are presented in Section III, introducing temptative roles and the concept for causal influence and reasoning. The method is illustrated on two examples, a power plant and a power grid in Section IV.

II. Multilevel Flow Modeling

MFM is a functional modeling methodology that provides a library of control functions, energy- or mass-flow-functions and relations, depicted in Figure 1, that can be interconnected to a multi-level representation of causality and intention in flow systems [15]. Adding to the former variety of applications in process engineering, nuclear power plants and others, the field power systems has been developed recently [9], [10]. An MFM model enables situation-dependent reasoning about control situations, by relating system states to system and control objectives.

Applications of MFM include model based situation assessment and decision support for control room operators, hazop analysis [16], alarm design, alarm filtering [17] and planning of control actions [18], [19]. It has been used for knowledge

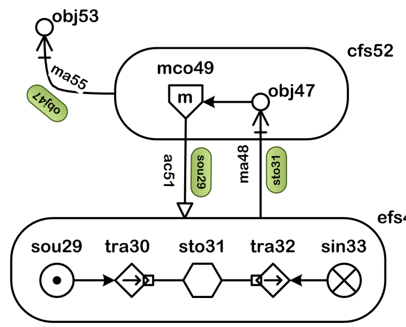

Fig. 2. Example MFM Model with energy flowstructure and control structure. The energy-flowstructure efs46 models a stereotypical balancing process, where both the energy-source on the left and the energy sink on the right influence the storage-level. In this example, the process is balanced by means of a control which aims at maintaining the storage-level by means of actuating the energy source.

representation in AI planning for supervisory control systems [20].

Altogether MFM provides a rich ontology for modeling purpose-aspects of complex processes. MFM is supported by knowledge based tools for model building and reasoning: a graphical modeling environment and a rule-based reasoning environment with graphical user interface (referred to as MFM Workbench in the following).

A. Modeling of Control in MFM

A representation of control systems based on action theory has been added more recently to MFM [15], [21], [22]. The four elementary control functions, which are based on elementary action types, are found in Figure 1.

In contrast to the classical signals and systems perspective, control functions have a special role in the perspective of mean-ends modeling: Whereas a 'flow-structure' is a functional abstraction of a process, the 'control-structure' is a representation of the *intentional structure* realized by a control system[1]. This distinction becomes essential when reasoning about control systems.

An example model of a control structure and a related flow-structure is given in Figure 2:

[1]In the control literature, the 'intentional system' is sometimes referred to as 'active' structure, whereas the the controlled system, here '(multi-level) flow-structure', is referred to as the 'passive' basis. This wording does not apply exactly for multilevel-flow-structures, as energy sources and sinks may well be part of the system.

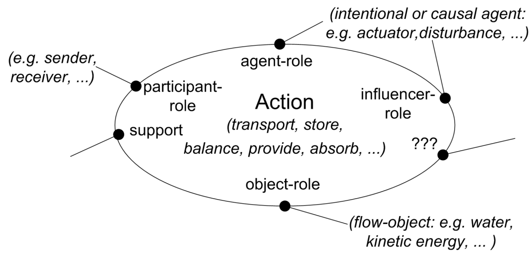

Fig. 3. Action-roles define the participants of an action. Depending on the function and context the roles considered necessary vary.

- *Control-objective* **obj47** and *control function* **mco49** are encapsulated in a *control structure* **cfs52**.
- Requirements to the performance of the control are formulated as an objective associated with the control structure (*performance objective*, **obj53**).
- The control objective is associated via a *means-objective-relation* with the *mainfunction* (here **sto31**), the state of the mainfunction is subject of control.
- The control function is connected to the flow-structure via an *actuation-relation*, **ac51**, targeting **sou29**.

In [9], [10] the authors have shown how this modeling of control can be applied to power systems.

B. Functional Roles

In [14], the connection between the symbolic representations of functions and the semantics of actions have been elaborated:

Definition 1 (Function)**.** *A* function *of an* entity E *which is part of a* system S*, is specified in terms of the* role R *of* E *in relation to an action describing and intended state-change in* S*.*

Functions model interconnected actions or action-primitives. The actions can be associated with a "semantic deep structure" [14], defining roles of an action as slots that can be filled, which is illustrated in Figure 3.

This understanding of a function as an action with a semantic deep structure implies that a number of roles can be associated with each function, such as *agent*- and *object*-roles. Further, the action-metaphor is deeper than the flow-metaphor, and potentially enables extension of MFM to other domains of representation if necessary.

Flow-structures are an interconnection of actions with a common flow-object.

Definition 2. *(Flow perspective [14]) The flow perspective on an action describes the state change that the object is undergoing without reference to the agent involved.*

Flow-functions are formulated in the flow perspective of the actions modeled. A relation between two function-structures therefore also marks a perspective-shift, in which for example the flow-object of another structure turns into an external agent of the related function [3], [23]. As will be shown later, external agents influence the causal structure of a process, and such agents can also be attributed to flow-functions on the basis of control-considerations.

C. Causality in Flow-models and Causal Reasoning

Fundamental to the understanding of causality in MFM flow-structures is the notion of agency. *Causal roles*, as introduced by [14], express the influence that a state of a flow-function has on the flow associated with an adjacent transport function. The role is always marked at the transport-side of a connection-line between two functions, ending with a box (participant-role) or with an arrow (agent-role) (shown in Figure 1, on the right: Causality).

A flow-perspective enables causal reasoning over flow-systems, in order to predict consequences or to find possible root-causes of a state-change in the system. This concept of fault diagnosis with MFM was presented in [12], and extended with explicit causal agency in [13], [14]. MFM-based root-cause analysis has been applied for diagnosis and used in commercial applications for alarm filtering.

In past implementations, the causal propagation logic considered interactions between function-pairs, but did not include the role of control agents. In the following, the causal roles introduced in [13] will be utilized, but the logic of influence will be condensed to more rigorous syntactic rules.

III. Representing Causality and Control

Even though the larger part of this paper will focus on reasoning about causality within flow-structures, it is important to emphasize the larger perspective that modeling with MFM provides, especially for the modeling of controlled processes.

MFM facilitates the definition of the roles a control system may take with respect to a process (more in Section III-A), as well as the different types of requirements that need to be formulated for a process.

The development of the causal reasoning framework is based on an extension of MFM introducing flexible agent-roles in Section III-B. The main result of this work, causal pattern classification and causal path reasoning, is presented in Section III-C. Finally, Sections III-D and III-E present the implemented algorithm and a link to controllability.

A. Control as Disturbance Encapsulation

In a means-ends framework, control structures can be understood as fact-producers, that is, they transform a goal (intention Z) into an observable fact (result Z), see Figure 4. In closed loop control, the control system is supplied with information about deviations from the objective, which enables the rejection of influences contrary to the control objective. In an agent-perspective, a successful control agent has the ability to 'overpower' this disturbance agent (successful encapsulation).

Control design anticipates disturbances and equips the controller with sufficient control resources to defeat expected

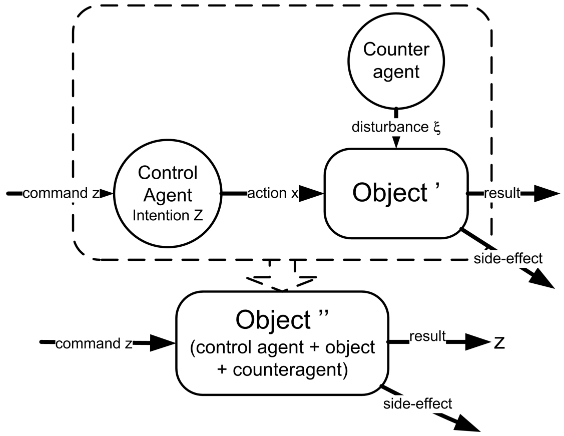

Fig. 4. Encapsulation of disturbance by a control agent. The introduction of a control agent implicitly models a virtual counter-agent.

disturbances. Figure 4 illustrates this concept of control as disturbance encapsulation[2].

Complex processes are usually composed of several levels of such encapsulation. A higher-level system acts on an encapsulated system, without a need to consider the disturbance that has been encapsulated. This leads to the notion of *execution levels*. A typical example is a cascaded control system, where the lower-execution level receives an input signal as control reference, and a higher level systems perceives the closed loop of the lower level systems again as dynamical input-output structure. Depending on the level of abstraction, subordinated control loops need not be represented explicitly. The modeling of the feedwater pump control in Example 1, Section IV-A, is another example for this situation.

Reasoning about control levels thus requires a representation of this encapsulation. A necessary condition for this reasoning is thus to frame the causality at the right level of abstraction. For the remainder of this paper we focus on the representation of causality that forms one control level.

B. Introduction of External-Agent Roles

As outlined above, the action-perspective allows a straightforward extension of multilevel-flow-models to attribute external roles. In the context of control, we establish three new roles capable of influencing the state of a function: Actuator, Disturbant and Conservant, as shown in Figure 5 a). Figure 5 b) illustrates the use of these roles in a simple MFM example, analog to Figure 2.

An *actuator* performs the commands it receives from a control agent (control function). Therefore it needs to be equipped with a reference to the actuation-relation (multiple roles may refer to the same actuation-relation). It can also be parameterized with a control-range, but quantitative aspects will not be considered in this paper.

[2]The term "disturbance rejection" of control engineering is equivalent, but supposes a control-perspective. In a process-perspective, successful control actions render the respective disturbance irrelevant.

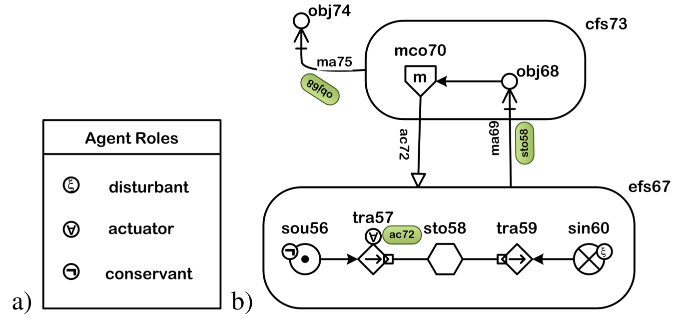

Fig. 5. a) New *External-Agent*-Roles. b) MFM model, based on Figure 2 with attached roles. Here, the distrubant corresponds to load variations, the conservant corresponds to a setpoint for the source-potential, and the actuator is influencing, not determining, the flow through tra57.

A *disturbant* represents a disturbance, i.e. the role assumed by the counter-agent. It may also be parameterized with a quantitative information.

The third role-entity, the *conservant* ensures that the variable, which a control agent would have manipulated through an actuator, is kept static, like a fixed setpoint.

The roles can be attached to these flow-functions (refer to Figure 1 for the complete set): *Source*, *Sink*, *Transport*. Attachment of a role means that a free variable of the respective function is now determined by the external agent who is represented by the role. This also means additional influence on the state-variable associated with a given function is noted, which changes the causal pattern of the function, as seen in the next section.

Storage and *Balance* do not accept an external role – there are no free variables. The other flow-functions have not been considered yet.

C. Patterns for Causal Reasoning

In this section a notion of causality is developed that is suitable for multilevel-flow-models and the modeled processes, but also consistent with underlying physical concepts. It should be noted that, similar to the notions developed in QPT, flow-functions have been defined from intuitive and generic process-engineering notions rather than from physical laws.

The reasoning system classifies patterns within the flow-structures of the MFM model and associates state-variables to the flow-functions.

1) Introduction of State Variables: In order to introduce a logic of influences, we will introduce state-variables to the flow-functions, dependent on the causality pattern surrounding them.

Two types of state variables are introduced: e-/m-*flow* (f) and *potential* (v), corresponding to the analogies: mass-flow and mass, as well as energy-flow (power) and energy (content).

The analogy is intuitive, considering an energy-flowstructure: We associate an energy-*flow* with every transport function and a *potential* with every storage function.

For the remaining functions, the state-variable assignment depends on the surrounding function pattern.

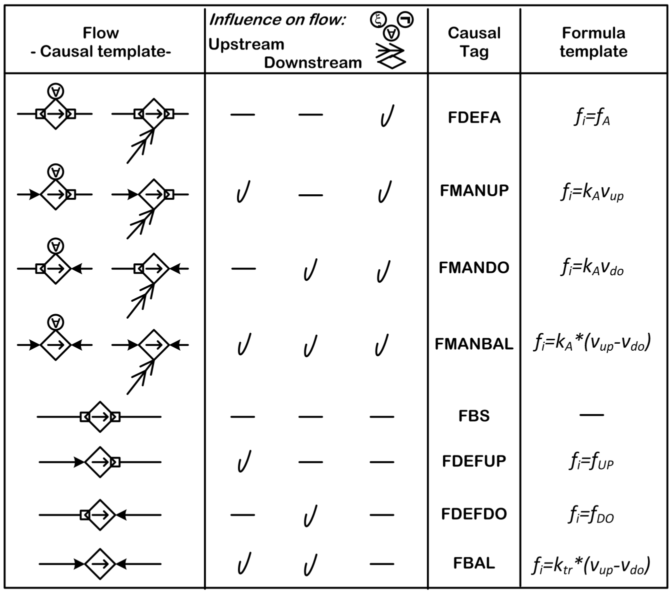

Fig. 6. Classification of causal templates. The templates are differentiated by the origins of influence on their flow: upstream, downstream or external agent.

2) Causal Context of Transport functions: The modes of causation in a MFM-flow-structure are centered around transport-functions, which represent the energy- or mass-flow between any two non-transport functions. The table in Figure 6 lists eight templates that imply a different causal context. Eight, because there are two sides of a transport (*upstream* or *downstream*) with two possible roles each (*participant* or *agent*), and in addition, there may or may not be an *external agent* associated with the function. External agents can be roles, as introduced in the previous section, or a means-function relation: *producer-product* or *mediate*.

The logic behind this classification is apparent: If only one agent is present, it defines the flow in the transport function (FDEFA, FDEFUP, FDEFD). If there are two causal agents, the flow has to be established from a difference in the potentials of the connected flow-functions (FBAL); in addition, the rate of this flow-exchange can be manipulated by an external agent (FMANBAL). The third and last case is derived from the FMANBAL case, but it requires the definition of a neutral potential (FMANUP, FMANDO). Finally, patterns with the the causal tag FBS cannot be accepted for causal reasoning, because there is no causality assigned.

All cases can be illustrated on the examples of connected water-tanks. FDEFA: A pump between two tanks is moving water from one tank to another. FDEFUP, FDEFDO: A water-source, or sink, possibly driven by a pump that would be external to the system-in-view. FBAL, FMANBAL: the classical interconnected tanks, possibly with a valve in the connecting tube. An example of the last case (FMANUP,FMANDO) would be water that is flowing from an outlet at the bottom of a tank - the flow-rate can be manipulated by a valve, but it is also dependent on the water-level.

To present a mathematical analogy of these causal influence

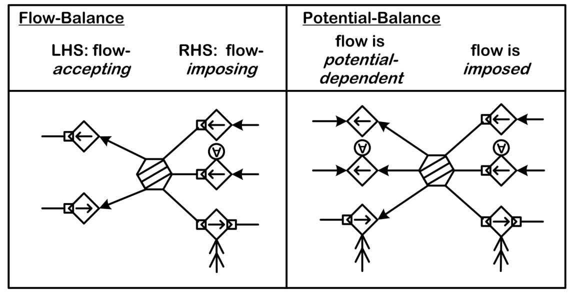

Fig. 7. There a two possible cases for a balance: Flow-balance and Potential-balance. For each type of influence there are example-transport-functions, for the acceptable patterns (causal tags).

situations, we associate flow-variables f, v for potentials and k to indicate a rate-parameter. The equations on the rightmost column of Figure 6 indicate the analogy. Note that the state of the transport, f_i, is always the result of causation. It can either be imposed directly, or result from a potential difference of adjacent functions, moderated by a rate-factor. The potential-rate model corresponds to a constitutive equation (such as Ohm's Law).

Based on these templates, state-variables can be assigned to neighboring adjacent sources and sinks: For a FDEFUP-(FDEFDO-) transport, an adjacent source (sink) is assigned a *flow*-state, in all other cases a *potential*.

3) Flow- and Potential-Balances: For Balance functions, the causal context is analyzed and two types of balances are identified:

- *Flow-balance*: Pre-assigned causality. A number of flows is imposed (RHS) and are summed up, which defines the flow through the balance: noted in the intermediate flow-variable f^*_{bal}.
- *Potential-balance*: Partly a-causal. Flow is a result of potential differences across the balance and the respective transports. The Balance is assigned an intermediate potential v^*_{bal}, analog to hydrodynamic pressure.

The patterns that establish either kind of balance are illustrated in Figure 7. For the flow-balance, a minimum of one connected RHS transport, a transport for which the balance is only *participant*, is required and the LHS requires exactly one FDEFUP/FDEFDO transport if the flow-direction is always the same, or a second transport with opposing flow-direction. The potential-balance has the same requirement for the RHS (with defined causality), but has a no directly resulting flow.

In case of the *flow-balance*, the causality structure is that of input-output: a flow-*input* (RHS: right-hand-side) defines flow-*output* (LHS: left-hand-side). This can be formulated as

$$f_{tr,LHS} := f^*_{bal} := \sum f_{tr,IN,RHS} - \sum f_{tr,OUT,RHS} \ , \quad (1)$$

where f_i refers to the flow-variable associated with the respective function i of the LHS- or RHS-category of this balance. The resulting flow f^*_{bal} is imposed on the LHS transport(s), depending on directionality. This may be formulated as follows:

$$f_{tr,OUT,LHS} = \lfloor f_{tr,LHS} \rfloor_0 \quad and \quad f_{tr,IN,LHS} = \lceil f_{tr,LHS} \rceil^0 \tag{2}$$

Practically speaking, flow-networks are common where a) system design ensures that no state-feedback happens, i.e. the system is flow-controlled, or potential-differences are too large for variations to matter, and b) there is no choice between potentially alternative flow-recipients/senders (single-output requirement).

A *potential-balance* is a-causal for a part of the connected flows. The flow through the balance is a result of the total potential difference across the balance, so the intermediate-potential at the balance v^*_{bal} is required to determine the flow. In addition, there may be flows imposed to the balance, analog to the RHS of a Flow-balance.

In case of a linear analogue, the intermediate potential v^*_{bal} for Potential-balance would be established as follows:

$$(\sum k_{Tr,UP,i} - \sum k_{Tr,DO,i})v^*_{bal} := \tag{3}$$

$$(\sum k_{Tr,UP,i}v_{UP,i} - \sum k_{Tr,DO,i}v_{DO,i}) \tag{4}$$

$$+ \sum f_{tr,IN,RHS} - \sum f_{tr,OUT,RHS} \ , \tag{5}$$

where $k_{Tr,UP/DO,i}$ refers to the rates associated with the respective transport (FBAL,FMANBAL,FMANUP/DO) connected to this balance, $v_{UP/DO,i}$ refers to the neighboring potential connected through transport i, and the RHS is analog to the flow-balance above.

A network of potential balances corresponds to a linear vector-equation, similar to the load-flow equation of an AC electricity-network, with a potential-balance assigned to each bus. For a linearized power-flow equation, the 'intermediate potential' v^*_{bal} would correspond to the bus voltage angle variation $\Delta\theta_{bus}$ (illustrated in Example 2, Section IV).

D. Propagation of Influence: Influence-tree and Causal-path

The causal-reasoning system aims at generating a causal path from assigned external agent roles to the objective, that is, to the function associated with this objective (*mainfunction*).

A system of production rules has been implemented in the MFM Workbench in the rule-based language *Jess*. The reasoning process can be divided into the following general steps:

1) Analyze causal patterns in all flow-structures in the MFM model: Causal tagging of transports, assignment of state-variables and pattern-identification for flow-/potential balances.
2) Initiate: Which control objective is to be traced? The control objective becomes root of the *influence-tree*.
3) Generate *influence-tree* for the selected control-objective. Using propagation-rules based templates and patterns identified previously, a tree-structure is generated which notes all possible influences from the model.
4) Trace *causal paths* in influence tree.

The result of this analysis is *a)* an influence-tree that contains a reference to all entities that whose state influences the fulfillment of the objective and *b)* a direct path of influence for each external-agent role with influence on the state of the mainfunction (*causal path*). This reasoning principle will be illustrated in Example 1.

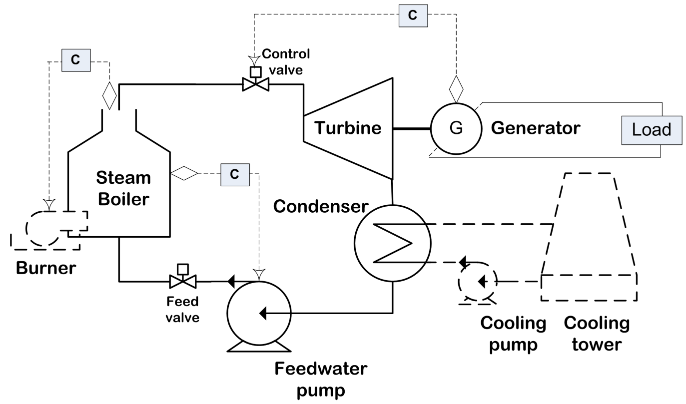

Fig. 8. Process diagram of the thermal power plant in Example 1. For simplicity of illustration, the material flow of dashed components as well as the energy recovery in the feedwater are not modeled here. The objective of the control loop between boiler and feedwater pump is to maintain a constant water-level in the boiler, thus the evaporation rate indirectly determines the water flow in the feedwater pump.

E. On Controllability and the Causal Path

The concept of controllability is fundamental to control engineering, as it formulates a necessary condition for controlling a system. A full analysis of this concept would be beyond the scope of this paper, but we may reflect on the properties of flow-structures.

A number of different controllability properties are known, including:

State controllability: A dynamical system is called completely controllable if an external input can move the state of the system from any initial state to any other final state in finite time.

Output-controllability: analog to state-controllability, but instead of the full systems state, the system's output is required to be moved.

We do understand *inputs* as assigned actuator-roles and *outputs* as the states of the mainfunction associated with the control-objective. The "system" could be considered exactly those functions that are part of the influence-tree.

Under certain -limiting- conditions, there is a mapping to output-controllability: a) there are no causal loops in the system b) there is only one actuator in the tree.

A detailed study of the graph properties of flow-structures and their mapping to linear systems could generate further structural sufficient conditions for controllability.

IV. Examples

The modeling and reasoning principles shall be demonstrated on some examples. The first example highlights the multi-level physical representation aspects of the modeling approach on a simplified power-plant. The second example

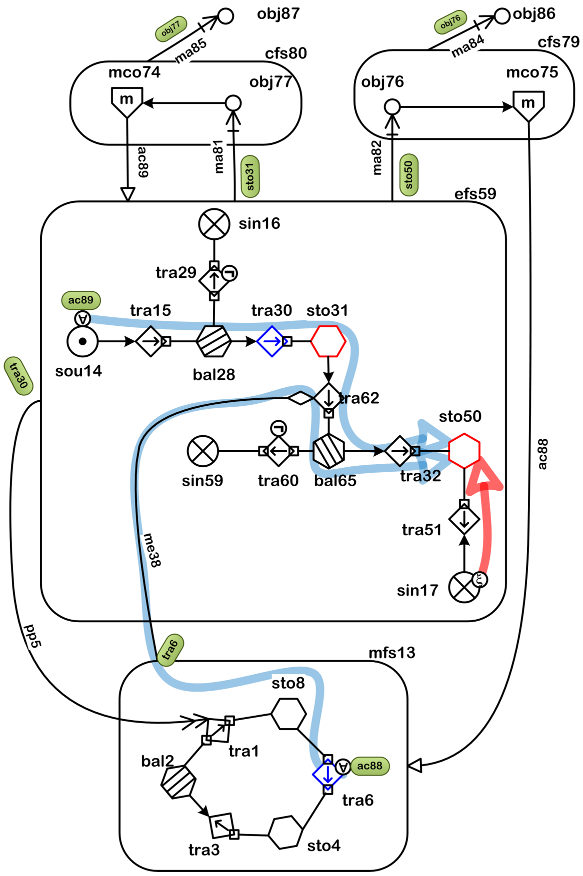

Fig. 9. MFM model for the main control loops of the thermal power plant. Please note that the green bubbles contain a reference to a related entity. The boiler-feedwater control-loop displayed in Figure 8 is not modeled as a control loop but function for the system, illustrating the consideration of abstraction levels introduced in Section III-A. The functions **bal2** and **tra3** and their causal relations, capture the effect that always as much water is pumped into the boiler as is being evaporated. The wide arrows in the background illustrate the causal paths for obj76 from the actuator- and disturbant-agents.

illustrates the opportunities of modeling mixed causality structures (*potential* and *flow*) of networks, such as electric energy systems with both DC and AC links.

A. Example 1: Power Plant

In this example we model the main control loops of a thermal power plant supplying a varying electrical load in island mode[3]. The modeled process is illustrated in Figure 8. The power plant model is simplified by assuming a fixed cooling- and smoke-power loss.

An MFM-model of the process is presented in Figure 9. The model comprises two flow-structures, modeling the process at the relevant abstraction level, and two control structures representing the main control loop objectives of the power plant: fresh-steam pressure setpoint and frequency control (to encapsulate the "disturbance" of varying power demand).

1) Model Description: The lower flow-structure, **mfs13**, models the mass-flow of the main water-circulation. There are two mass-storages in the loop: **sto8** and **sto4**, representing fresh steam mass and cold-steam/condensate, respectively. Balance function **bal2** represents the balance between evaporation **tra1**, driven (**pp5**) by the heat transfer **tra30**, and feedwater flow (**tra3**), which is enabled by the underlying feedwater pump control. The controlled turbine inlet valve is actuated by **ac88** to determine the mass-flow of steam to the turbine (**tra6**). This mass-flow mediates the inflow of energy to the turbine (**tra62**), as represented by the mediate-relation **me38**.

The energy flow-structure **efs59** models heat-inflow from the combustion of fuel (**sou14**), heat-loss into exhaust gas (**tra29**, **sin16**), heat-transfer to water (**tra30**) and the steam enthalpy in **sto31**. The energy-transport to the turbine is influenced by **sto31** and **me38** (causal-tag: FMANUP, see Fig 6), mass-flow and energy-content. Assuming a static energy-loss (**tra60**, **sin59**), a fraction of the energy-flow is transferred by the turbine (**tra32**) to the inertia of the rotating turbine-generator (**sto50**), which receives and provides energy to the load (**tra51**, **sin17**) without influence from the rotation speed.

Five external agent-roles are attached to functions in this model: *Actuators* on **sou14**determining the energy-flow, and on **tra6** determining its mass-flow; a *disturbant* determining the energy-flow into **sin17**, representing the load variation; *conservants* determining the energy-flow through **tra29** and **tra60**, representing the assumption of fixed energy-losses.

2) Controllability Analysis: The causal-path analysis (see also arrows in Figure 9) reveals that load-variation, the disturbant on **sin17** does influence the state of **sto50** (kinetic energy, frequency), but not the state of **sto31** (steam pressure). The intended behavior of the power plant, is to adjust its energy conversion setpoint (eventually, the fuel-supply, **sou14**) according to the load-demand, a demand-driven process which requires upstream-propagation of information. This upstream-propagation is provided by the two inter-leaved control-structures with control -objectives **obj76** and **obj77** aiming to determine the energy-states of **sto50** and **sto31**. By manipulation of the mass-flow of **tra6** and the supplied energy-flow of **sou14** the control functions effect the process on its upstream end.

B. Example 2: Power network

This example of an AC power network connected with an HVDC-link to another AC system (Figure 10), is presented to illustrate the value of a modeling tool that can model systems in terms of their causal interconnection. The flow across the HVDC line power can be controlled and may thus play a role in the overall control architecture.

It also shows how the flow-structure representation is analog to a "DC-power-flow", a linearized power flow formulation. Here, power exchange is solely driven by voltage-angles, corresponding to the potential-variables introduced above.

V. Conclusion

This paper presented an extension of the causality concept of Multilevel-Flow-Models and the according reasoning tool for the purpose of controllability analysis. The underlying

[3]This leads to direct "isochronous" frequency control, otherwise, the controller would adjust the power-output of the plant, see also [9], [10]

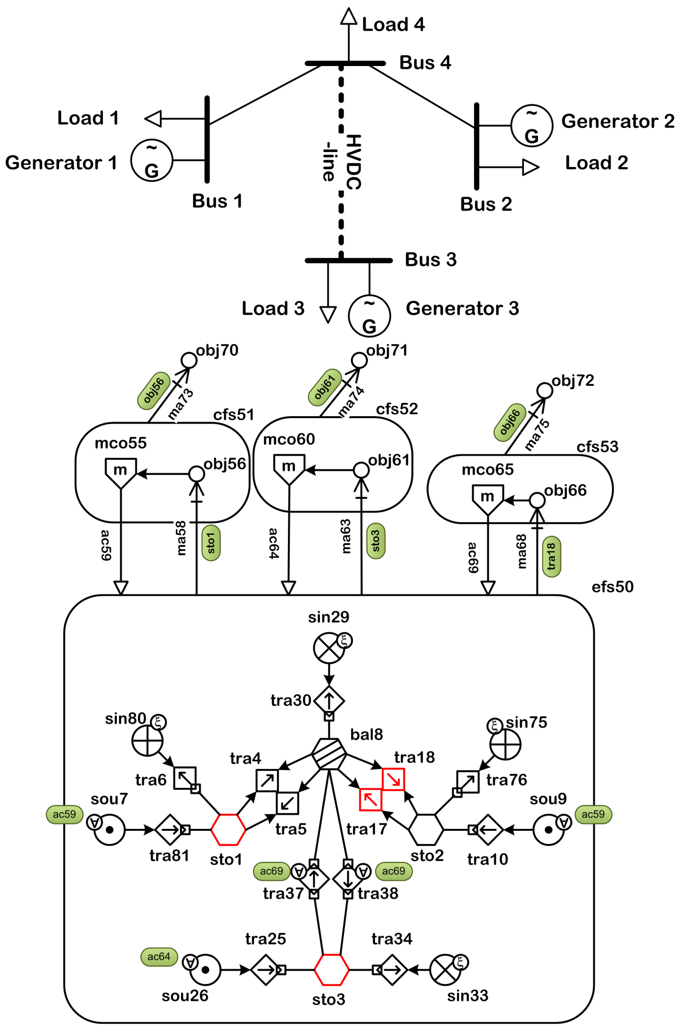

Fig. 10. One line diagram and MFM model, illustrating the network modeled in Example 2. Note the combination of two AC networks (synchronous areas) with a DC link. In the MFM model, mainfunctions associated with the control objectives are marked in red.

conceptual model introduces flow- and potential variables to make sense of the influence patterns modeled by the causal roles of an MFM model. Based on this idea, syntactic rules for function-causality configurations have been derived.

The concepts have been implemented in a software-framework which enables graphical modeling and model-based reasoning for artificial intelligence applications.

The method has been demonstrated on two energy systems examples. It has been shown that the modeling approach readily maps into the domain-specific physical frameworks.

Further we have outlined, how the causal-path concept introduced in this paper is related to the controllability concept of control engineering. A flexible assignment of agent roles allows the re-use of models and restructuring of control-loops and objectives on a given process-model.

Acknowledgment

The work presented in this paper is a result of the research project Coherent Energy and Environmental System Analysis (CEESA), partly financed by The Danish Council for Strategic Research.

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2010 IREP Symposium- Bulk Power System Dynamics and Control – VIII (IREP), August 1-6, 2010, Buzios, RJ, Brazil

System-Awareness for Agent-based Power System Control

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Abstract

Operational intelligence in electric power systems is focused in a small number of control rooms that coordinate their actions. A clear division of responsibility and a command hierarchy organize system operation. With multi-agent based control systems, this control paradigm may be shifted to a more decentralized open-access collaboration control paradigm. This shift cannot happen at once, but must fit also with current operation principles. In order to establish a scalable and transparent system control architecture, organizing principles have to be identified that allow for a smooth transition.

This paper presents a concept for the representation and organization of control- and resource-allocation, enabling computational reasoning and system awareness. The principles are discussed with respect to a recently proposed Subgrid operation concept.

I. Introduction

Trends toward more renewable and decentralized power generation, small-scale demand controllability and ubiquitous energy storage challenge system operation as we know it. These elements increase requirements to operation flexibility. Even though they also increase control flexibility, the diversification of controllable resources would make it increasingly difficult for an operator to effectively utilize these resources. This paper presents a framework for addressing the complex interactions between System Operation & Control and associated resource allocation problems in the context of a more decentralized and flexible system operation paradigm.

Historically on the grounds of their business model, vertically integrated utilities would offer reliable electricity supply. The restructuring of electricity supply led to a separation of the reliability objectives from energy trade, which, as a side effect, led to a separation of market-aspects of energy-trade and engineering questions concerning security and control. Essential functions in the provision of electricity, known as Ancillary Services, had received less attention from market-oriented literature [1].

The primary objective of a power system operator remains to achieve and maintain secure system operation, reliably and economically. Intelligent analysis, design of control systems as well as operator support systems, including visualization, have enabled the continued secure operation of these systems.

In Denmark, which intends to supply about 50% of its electricity from wind power by 2025 [2], more frequent critical grid situations are expected. In the ECOGRID project[1], it has been suggested that distributed generation and additional controllable demand, such as heat pumps, should be actively integrated into grid operation [3]. This active contribution is expected to be facilitated by a more distributed control architecture that may also allow partial islanding operation, as demonstrated recently in the CELL project[2] [4].

These developments also imply a vision of an operation framework where changing grid conditions may lead to a decomposition of grid operation objectives. Operating responsibility would then be delegated to "subgrid-operators", likely implemented by agent-based software. These agents would have to initiate control actions according to current system needs and allocate operating resources. Further, the local operating situation should be transparent to the higher-level operator.

In operation, deciding which information is relevant in a given situation, prioritizing operational objectives and keeping the overview of available control means, as well as informing higher-level operators about relevant changes in the operating situation are essential requirements. This is what we refer to as "system-awareness".

With the goal of improving operator support systems, researchers in the domain of cognitive systems engineering have been looking into the information processes involved when operators make decisions (in process control). It was found that decisions about

[1]http://www.energinet.dk/en/menu/R+and+D/EcoGrid/EcoGrid.dk.htm
[2]http://www.energinet.dk/en/menu/R+and+D/The+Cell+Project/The+Cell+Project.htm

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appropriate control actions require that information about the system state can be related to operational objectives. One influential approach, [5], established the relevance of whole-part and means-ends abstractions for operator decision-making. Moreover, the "decision ladder" explains lower and higher levels of information processing and how they relate to states of knowledge and decision-making, which has also been introduced in [5].

Future operator support systems will thus require representations, which are sufficiently simple and can be related to the overall grid situation. What is required to achieve this kind of transparency of intelligent control systems? Which types of decisions should be left to human operators, and what kinds of information do they require to make "good" decisions? These questions motivate our ongoing work on Functional Modeling and Intelligent Systems applications in Power Systems [6]–[8].

A. Relevance of ICKT for Distributed Resources

One common trend is to address these challenges to coordination and control of distributed resources by information, communication and knowledge technologies (ICKT) [3]. Notably, in the Homebots [9], CRISP[3] and INTEGRAL[4] projects the value of intelligent agents and knowledge modeling approaches for the integration of distributed generation has been developed. Also systems-of-systems engineering approaches, utilized in some American projects (e.g. Intelligrid[5], GridWise[6] and GridWise Architecture Council[7]), have been coining terms such as "interoperability" and "self-healing".

ICKT brings a different perspective into the Power Systems domain. Particularly the modeling of knowledge by classification of information is relevant to capture engineering-knowledge about the system.

Function-oriented classification and representation is useful for control-aggregation, because it allows in principle the aggregation of different types of devices into a common hierarchy, e.g. [10], and it enables the formulation of generic performance requirements [8].
Pooling and aggregation of small-scale resources is essential, both for participating in power markets and from an operation/control perspective. However, the reasons for these aggregations are motivated quite differently [11]. Essentially, it is suggested to create Commercial Virtual Power Plants (CVPP), conceived as risk-controlling aggregators toward given energy markets, independent of grid topology; and Technical VPPs (TVPP), ensuring communication with local Operators[8].

Again, a separation of security questions from market aspects and business models can be observed, as here often "market" and "technical" aspects are treated separately, and if combined, then the latter only as provider of constraints to the former. This practice becomes difficult when markets with shorter time-scales or even markets for balancing-control are suggested without specification of control performance requirements.

B. Multi-Agent-Systems Application to Power Systems

Modern control architectures in electric power systems such as Microgrids, Virtual Power Plants and Cell-based Systems etc. exhibit requirement for decomposition, modularity, decentralized/local control, self organization, high level communication and increased level of autonomy. Multi-agent systems have proven capabilities of implementing such requirements and thereby have attracted a great amount of interest for their application in operations, control and automation [3], [12].

Multi-agent-systems with intelligent software agents [13] are considered a likely software concept capable of providing useful characteristics such as modularity, distributed control and cooperation mechanisms [3], [14]–[16]. The ability to reason about possibly complex control situations is also within reach of agent technology [17].

An ICKT architecture based on software agents allows for a flexible modeling of interests, roles and behaviours of agents with respect to their embedding in the environment.
The specification of roles and required behaviours, however, cannot be based on the generic agent paradigm alone, but it must also be derived from an application-perspective.

In order to achieve a scalable architecture, it is necessary to have strong organizational principles that enable classification and organization of similar properties and tasks associated with different problem classes. For Power System operation, more "intelligence" should not imply that the operator is "out of the loop", but it should simplify the operation of increasingly complex power systems by providing the necessary transparency.

C. Scope

[3] http://www.crisp.ecn.nl
[4] http://www.integral-eu.com
[5] http://intelligrid.epri.com
[6] http://gridwise.pnl.gov
[7] http://www.gridwiseac.org

[8] The CVPP/TVPP-concept, coined in [4], was employed in the European FENIX project (http://www.fenix-project.org/) and is further pursued in the ADDRESS project (http://www.addressfp7.org).

Motivated by the anticipation of agent-based control architectures, this paper departs from a recently suggested Subgrid architecture in Section II.

With a perspective on operator decision-making derived from cognitive systems engineering, we conceptualize a Subgrid operation architecture based on intelligent software agents. It builds on the understanding of how means-ends-reasoning and the weighing of alternatives are intertwined in rational decision making [18]. The basic ingredients are the *representation* of low-level controls and power-system functions by Functional Models, agent-based *role-allocation* concepts and *performance evaluation* on the basis of the Functional Model.

In the following Section, a Subgrid architecture is motivated and the concept from [3] is outlined. Section III will introduce the relevant concepts from cognitive systems engineering and functional modeling, multi-agent system and reliability evaluation. The architecture is then developed in Sections IV and V.

II. Subgrid Operation Concept

The current literature on integration of distributed resources frequently points to an operation scenario where the power exchanges between different sub-grids would be negotiated and fixed at limited levels (e.g. [19]), a suggestion which seems to be conceived mostly in bottom-up (distribution level) control design perspectives.

However, from a market-only perspective, for example for the integration of large amounts of wind power, it would be most effective to consider regions as large as possible for mutually smoothing (predicted and unpredicted) wind power variations [20]. From a market-perspective, the only barrier to trade should be transmission limitations. Why would the power-exchange between any two parts of the power system be fixed or capped? What is the value of being able to limit the power variations in the exchange between grid regions?

The first answer is that even though energy markets allow the trade of energy across country borders, it is the responsibility of System Operators (TSOs) to keep these exchanges close to scheduled values and the acceptable deviations are defined by agreements between

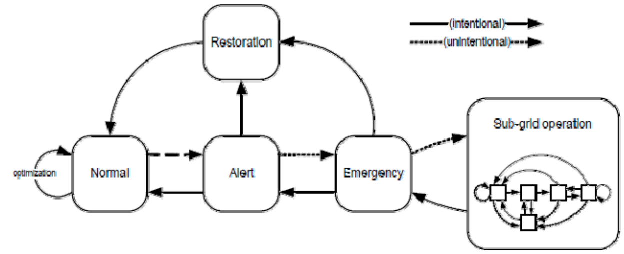

Fig. 1 High-level operating states with Subgrid operation mode.

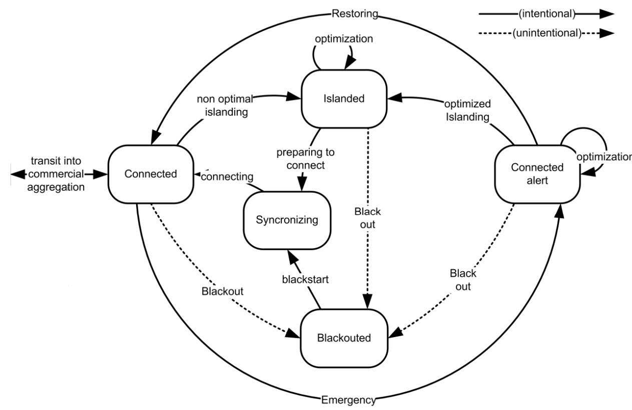

Fig. 2 Transitions within the Subgrid operation model [12].

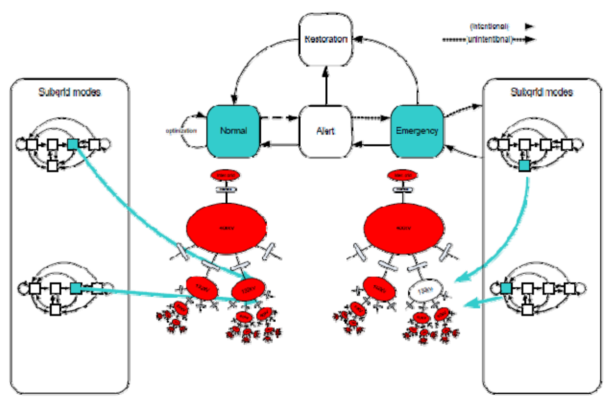

Fig. 3 Operation scenario: Interconnected operation and partial blackout with Subgrid operation.

neighbouring TSOs. Whereas exchange and mutual support is beneficial, large unplanned variations make system operation difficult and threaten stability. The question of valuation of limiting power exchange is thus also a question of valuation of operational stability.

Measures of operational stability depend on the control architecture. In [3] it has been suggested that under challenged operating conditions it could be beneficial to utilize the high penetration of distributed generation in Denmark by introducing a “Subgrid” architecture [12], in which control authority is partly delegated to Subgrids, preparing for partial islanding situations.

Figures 1, 2 and 3 illustrate the interleaved operating states suggested for the subgrid operating modes. The overall operating modes (Figure 1) are described in the following:

- *Normal operating mode*. The system is prepared for a disturbance.
- *Alert mode*. System OK but not ready for additional disturbance which will transfer it to the emergency mode. State for system operators' control actions.
- *Emergency mode*. The system collapses if immediate control action is not taken; one additional contingency leads to a collapse without enough time for the system operator to intervene.
- *Subgrid operation mode*. The system is divided in smaller islands (sub-grids) in order to survive on local resources during an emergency period.
- *Restoration mode*. System collapsed. State for black-start procedure.

This Subgrid operation concept is envisioned to be realized by an arrangement of intelligent software agents. In order to realize such a scenario, a supervisory control agent – a Subgrid operator agent - is necessary for every Subgrid. It should be equipped with intelligence features that resemble human operator intelligence.

The following sections outline some underlying principles and modeling approaches required for the realization of such Subgrid operator agents and the related roles.

III. Background

Central features of multi-agent technology are its versatility and knowledge-base capabilities. This also means that a proper domain and problem understanding is required before a multi-agent architecture can be drafted. With a focus on the control problems an operator-agent will have to address, this section introduces: System operation, system-awareness and supervisory control; the means-ends dimension and functional modeling; the multi-agent concept; reliability valuation in power systems.

A. Supervisory Control by Operators

The power system operator has control authority for the system he is responsible for. Control authority implies that every entity providing system services is liable to activate its resources according to contracted performance requirements. Further on, the operator may disconnect parts of the system if critical grid conditions require this. At the same time, the operator is also liable to compensate the loss, which is an incentive for secure operation.

As the system operator oversees the system operation by identifying critical aspects of any given operating situation, it is crucial that he is aware of both, his available reserves (resources, control-means) and the need for control. Software and display panels support system operators to make informed decisions. Data relevant in the same decision context should be displayed close enough together, the distinction between measured and estimated information should be noted, etc. On the other hand, too detailed information can easily lead to information overflow in the supervision of complex processes. Filtering the relevant data is fundamental to successful supervision.

In attempting to model relevant information for a given operation scenario, it is apparent that information about the system state needs to be valuable with respect to the operational objective [5]. Information about objectives is just as important for a situation-awareness model as data from the process.

Situation-awareness in supervisory control is thus made up of awareness of control needs and control-means [21], [22]. Supervisory control is about relating lower-level control objectives to higher-level and overall operation goals. System security is the overall goal of power system operation.

B. Decision Ladder for Supervisory Control

As noted earlier, situation-awareness is not generated from solely communicating (displaying) measured data from the system. Both in the interpretation of signals and in the generation of control inputs, a number of abstraction levels can be distinguished between raw signals from and to instrumentations and their relation to the operating situations.

The decision ladder [5], given in Figure 4, stratifies these levels of abstraction both for state-analysis and planning of control actions. The decision ladder indicates that e.g. a system operator, upon observing certain data, must relate it to a (mental) model of the system before identifying the system state. To interpret this state as the operating situation, the state is related to an intended goal-state.

The role of representations in supervisory control can be read from this model as well: all kinds of intermediate states of knowledge require an appropriate representation, so that the information processing-activity may utilize it. Different types of representations are relevant at each respective level. Seeing that an operator has a functional understanding (and intuition) about the system, an

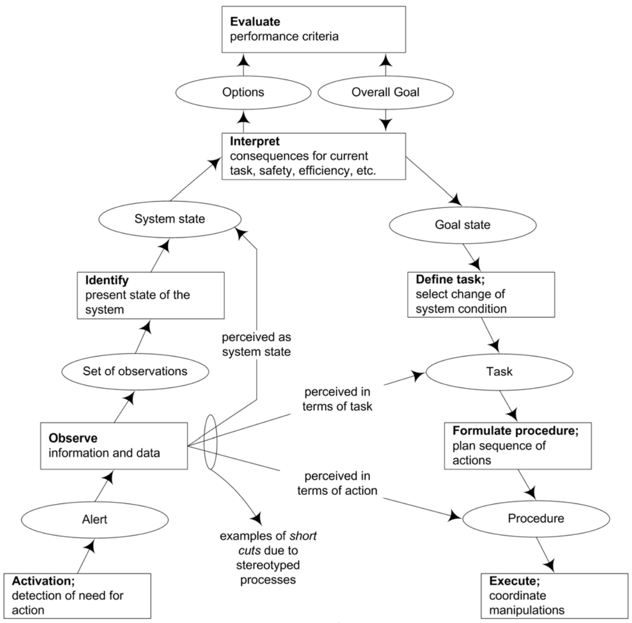

Fig. 4 Decision ladder (adapted from [5]). The boxes represent information-processing activities, while the ellipses represent intermediate states of knowledge. Classic closed-loop control corresponds to the lower "short cut" where the observation leads directly to procedure: Observed measured variables are translated by a controller (procedure) directly into control actions. For such controls, deliberation, task definition and procedure formulation belong to the control-design.

intelligent operator agent requires comparable high-level representation capabilities.

A system-state should be interpreted both with respect to control objectives and available resources. Reasoning and deliberation over alternative control objectives, tasks and procedures, choice of resources are all basic ingredients of operator intelligence.

C. Means, ends and Functional Modeling

Abstract models that represent lower levels of the control, relating control objectives to control-means, can be developed on the basis of a means-ends modeling approach.

Overall goals, process objectives and the realization of the process in components and their behaviour form a direction of ends and means. Consider a control action: In order to save the power line from overloading, the relay is programmed to open its breaker. In order to keep the system frequency at 50Hz, power system frequency control observes the frequency and alters the generators' power input. For any control actions can be said that he intention to alter the state of a system is realized by means of observing it and manipulating it. Every control action entails concepts of the means-ends dimension.

In power systems, the overall goal of reliable operation is decomposed into a number of control objectives such as power-balance (frequency stability), optimal transmission operation (voltage stability, reactive power management), etc. This decomposition of control objectives cannot be derived directly from the overall objective, but it is rooted in the engineering principles and properties of the involved electromechanical process. However, in order to understand the decomposition, a high level of abstraction (i.e. a simple model) is sufficient, as for example in frequency control [7], [8].

Functional modeling provides context to overall goals, by introducing this intermediate level of abstraction along the means-ends dimension, relating objectives to functions:

Overall goals
|
process objectives
|
control- and process- functions
|
realization (behaviour–structure)

Functional modeling is thus the modeling of activities (behaviour) in relation to their purpose, and the context of the activity.

The word function can have several different meanings, including the mathematical concept of function, which is not considered here. A stone may have the function of keeping papers on the ground, or the function of being a weapon, depending on its use. These functions are not inherent in the properties of the stone, but they are attributes of its use (possibly related to the specific set of properties of the stone, yet not by the stone, but by an external purpose). As functions are attributed to things, their origin is external to the things but related to the purpose of their use.

D. Representation of Control via Functional Modeling

The functional modeling perspective can be formalized into a functional representation. Multilevel Flow Modeling (MFM) is a way to formalize the functional representation of a goal-directed process [23]–[25].

MFM models are composed of two dimensions: *means-ends* and *whole-part*. The means-ends dimension is vertical and is modeled via a set of relations interconnecting goals and process as well as functions and processes. The whole-part dimension is expressed via "flow-structures", grouping a set of interconnected symbols (process-functions) into a process.

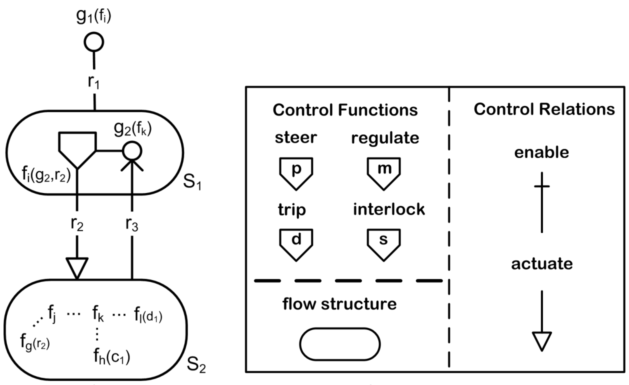

Fig. 5 Left: Control pattern with process-functions and associated roles. Right: Control functions and control relations. Modeling examples for the power systems domain can be found in [7],[8].

Semantics and symbols have been developed for control and flow-processes. That is, a library of functions and causal relations for their interconnection is available to

model processes that include control-, energy- and mass-flows. The interconnection of processes to goals and process-to-process is expressed via means-ends relations. A process, enclosed by a *flowstructure*, is connected to a goal via an achieve-relation. More precisely, objectives are connected via a *maintain*-, *produce*-, *suppress*-, or *destroy*-relation. A flowstructure is an encapsulation of a process-part, composed of elementary flow- or control-functions. Employing this representation, a means-end decomposition of a process can be formulated as goals/-objectives, means-end-relations and (flow-) processes. The explicit process-decomposition enables the modeling at different levels of abstraction.

A basic pattern of an MFM model involving control functions is given in Figure 5. Flowstructure S_1 is a control structure with a control function actuating a process S_2, as a set of interconnected functions (f_g, f_j, f_k, f_h and f_l). For the process in S_2 there exists library of flow-functions to model energy and material flow-structures, which can be applied to power systems as well [7], [8]; for the sake of this paper, the process functions are kept generic.

Functions are associated with an internal state. This state is influenced by neighbouring functions and/or by external agents. For flow-functions, causal roles have been established that indicate, how a state-change is propagated through the system of functions (via the flow-object: energy, matter).

Note that $f_g(r_2)$, $f_h(c_1)$ and $f_l(d_1)$ are functions whose state is influenced by an external agent. In the given figure, the control function f_i actuates $f_g(r_2)$. Furthermore, the state of $f_l(d_1)$ is influenced by an external disturbance (d_1) and $f_h(c_1)$ is determined by a constraint/setpoint (c_1).

The pattern in Figure 5 reveals some essential attributes involved in modeling control:

- control objective $g_2(f_k)$
- control function $f_i(g_2; r_2)$
- performance of the control function *g1(fi)*
- relations between control process *S1* and controlled process S_2: $r_2; r_3$
- disturbances to be encapsulated $f_l(d_1)$
- actuation and actuator location $f_g(r_2)$
- (dynamic) constraints $f_h(c_1)$
- configuration: relations between process functions, disturbances, actuators and constraints.

The functional model provides the relations between these objectives, roles, control- and process-functions. Also multivariable-, distributed- and cascaded control can be modeled within this framework.

This model can be employed for a number of purposes relating to supervisory control and control design. By relating the states of functions to system, control means and control objectives, MFM models enable situation-dependent dynamic reasoning about control situations. The causal relations combined with state-information enable powerful causal reasoning about causes and consequences of observed process deviations.

With respect to the decision-ladder, the model can serve as a representation of the execution-level control structures. A procedure for performance-evaluation of the represented control process can be derived directly from the means-end and causal structure of the model

1) MFM-based state identification: For root-cause analysis, function-states are discretized into normal and abnormal (high/low) states. An observed “abnormal” state will trigger the causal reasoning system, which then will generate possible causal explanations (root-causes), by matching functional information with observed data.

From a decision-ladder perspective, this reasoning function corresponds to analysis (interpretation) of the system state.

2) Causal Reasoning for Control-influence: If dynamic control functions are part of the system-in-view, the overall system-state can be evaluated directly with reference to the control-objective which is to be achieved. This corresponds to performance monitoring of a control loop. Using reasoning about causal influence, functions with the ability to influence the achievement of a control objective can be identified within the flow-structure, which may support the identification of control opportunities.

E. Operation Security: Valuation and Evaluation

Power system security is the concept that a power system operation should be resistant to failures. The classic approach to secure operation is *N-1 security*, which means that the power system operation should be able to withstand the impact of any single component outage. A system operator aims at maintaining this *N-1* criterion at all times, moving from day-ahead planning stages to minute-to-minute security assessment. It is also closely related to the state diagram of Figure 1, in which a single contingency corresponds to the transition from normal operation to alert mode. Power system operation is designed as a combination of automatic and manual reserves, which serve the operator in order to return to the normal operating condition.

The *N-1* criterion is a practical condition for estimating reserves with respect to power plant outages, where the time of outage is impossible to foresee. However, the reserve need for offsetting prediction errors of fluctuating renewable generation can only be measured on probabilistic grounds. A practical approach to scheduling reserves, here referred to as 3σ [26], is to schedule about three times the standard deviation of the prediction error. It has been shown that for high wind power penetration, the 3σ criterion may exceed the *N-1* criterion.

From an *outside* perspective, system security corresponds to reliability. Reliability is essentially a probabilistic concept estimating the likelihood of failure, in this case, the likelihood of insufficient reserves. A significant body of literature suggests that the need for reserves to provide operational security can be more effectively quantified on the basis of probabilistic approaches rather than by directly using the deterministic *N-1* criterion (e.g. [27]).

The value of access to electric energy is ultimately afforded by the value reliability has for the energy consumers (and producers) (Figure 7). The "value of lost load" (VoLL) [26], though hard to estimate, is the effective counterpart to the cost of providing reliable operation. Considering these two costs, an optimum reliability would theoretically be found at the minimum of the system cost function:

$$C_{system}(p_{rel}) = C_{LL}(1- p_{rel}) + C_{rel}(p_{rel}) \ ,$$

where p_{rel} is the reliability, and C_{LL} and C_{rel} are the costs of unreliability (Lost Load) and reliability provision, respectively. Whereas this concept explains valuation of operational security well, there is significant uncertainty and variance about the relationship between unreliability and its costs, such that it is common practice to set a target level of reliability instead of a comparative evaluation[9].

Even though it is hardly contested that probabilistic approaches are theoretically more accurate, there are practical issues inhibiting their use: a) a significant history of data is required to establish relevant statistics (for e.g. failure rates); and b) probabilistic approaches are complex: difficult to handle mathematically, require model simplifications and they are computationally expensive. Furthermore, probabilistic concepts are only descriptive, but not instructive. Real-time control room applications rely on practical consideration of worst-case outages and disturbances (*N-1,* sometimes *N-2,* for a set of selected contingencies).

A point often overlooked, particularly in stationary probabilistic estimation of reserve-capacities is the dependence of reserve needs on the structure of ancillary services markets and practical operation strategies. Not all kinds of technologies are suitable for all kinds of markets, so that the cost of some reserves will also depend on the market structure [28]. This market structure varies widely from system to system [29], [30].

On top the estimation of reserve needs, the way of allocating the resources is also relevant, as market design may also influence bidding strategies and available resources and cost [30], [31].

F. On Agent-Notions

Agent: Entity acting with intention. In the following discussion it is relevant to distinguish two separate meanings of the notion "agent". The first meaning of "agent" derives from semiotic theory of the act. In this context *agent* refers to the performing role of an action - as opposed to, e.g. the *object* role. Throughout this paper, the italic *agent* refers to this role-concept. The second is derived from the software-engineering notion of agent, which refers to an entity that has its own goals and the ability to actively pursue them. This notion will be noted plainly as agent or software-agent.

That is, a software-agent is an entity that has the ability to assume an *agent*-role. An example where the two notions come together, is the speech act, modeling the communication between software agents. Here a software-agent can be both initiating *agent* and passive *receiver* with respect to the sending of messages. Notions in MFM refer to types of roles, not to self-interested entities.

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[9] A target level, such as 99,9%, could then be understood as an average of 0,01% of "load not served", but also as "ca. 87 hours with insufficient reserves".

G. Intelligent Software Agents

Intelligent software agents are a software concept based on a human-oriented model of distributed intelligence. Agents encapsulated in BDI (Belief, Desire, Intention architecture) are situated in some environment and can act flexibly and autonomously in that environment to meet their design objectives [13].

Agents can be considered individuals, each equipped with belief (i.e. world model, state information), desires (interests/goals) and intentions (intended actions/plans). Situated in a physical- as well as in a software-context, agents communicate with other agents and act in representation of a physical or organizational entity, according to interests associated with it.

Generally, there are a number of ways Multi-Agent-Systems (MAS) can be viewed. The generic and powerful perspective of agents portrayed above is particularly suitable for knowledge-based reasoning and communication. Agents based on the BDI-architecture exhibit reasoning capabilities, to decide about alternative ways to achieve their design goals (desires). MAS can also be seen as a means of solving distributed control problems, where each agent becomes a part of a distributed computation algorithm. This view usually entails the decomposition of an originally centralized control or optimization problem into a distributed problem, where agents may or may not exchange information. This mathematical decomposition has been applied for example in [33], [34]. In these contexts, agents are viewed under the umbrella of a common mathematical framework, used to derive e.g. optimality or stability conditions.

The main difference between multi-agent systems of one kind and the other is their supposed representational intelligence. Whereas the latter 'mathematical' view focus on a mathematically implicit representation of objectives, communication and cooperation, the former 'intelligent' type of agents employs explicit semantic concepts to describe their goals and to communicate with other agents. These two views are not fundamentally opposed to each other, but rather associated with different levels of autonomy. Also autonomous agents could deliberately join the 'umbrella' of a joint mathematical algorithm. For practical study of such algorithms, the benefits of autonomy are not always required.

1) Origin of BDI-model: The idea of the BDI architecture originates from the view of agents as individuals [18], who proposed a computation architecture that combines the AI perspective on intelligence as an integration of means-ends reasoning and valuation capabilities required of rational agents under the premise of bounded resources.

Originally this meant the integration of two facets of rational behaviour. The first aspect is the planning problem or means-ends reasoning, which is employed within artificial intelligence to construct plans (a sequence of actions) that will achieve a particular goal. Second is the problem of weighing alternatives and deciding upon them, that is, given a number of feasible plans, to choose one of them. For a rational agent, this choice requires an analysis of the utility on the basis of its beliefs and desires - and implicitly on a means-ends analysis in specifying the alternatives.

Any practical problem carries both of these aspects, choices about plans and the making and refinement of plans are nested and intertwined. A software architecture that incorporates both aspects under bounded resources must also include mechanisms that control and evaluate how deep either problem ought to be computed.

Here, the plans themselves assume a special role, becoming a subject of both evaluation and reasoning. We come to distinguish *plans as recipes* from *plans as intentions*.

2) Procedural Reasoning and the Role of Plans: A software-architecture that exhibits properties of the BDI paradigm is the Procedural Reasoning System (PRS) [13]. We introduce its basic idea here so that one can anticipate some of the control flow that can be implemented on an agent paradigm.

At its core, the PRS is based on pre-compiled plans which are stored in a library. These plans are made of a *goal* (postcondition), a *context* (precondition) and a *body* representing a recipe. The recipe may include both procedure calls (primitive actions) and other goals.

An agent is equipped with an interpreter, matching facts with conditions (goals with desires and intentions, contexts with beliefs), and four types of knowledge: The plan library mentioned above, beliefs (facts), desires (design objectives, goals) and intentions, which is implemented as a stack of goals that the agent wants to achieve.

Now, once a fact and a goal match a plan in the library, the agent can proceed with its execution, which may cause further goals to come on the intention-stack. In a dynamic environment new belief facts will be added and removed over time, causing different plans to be activated.

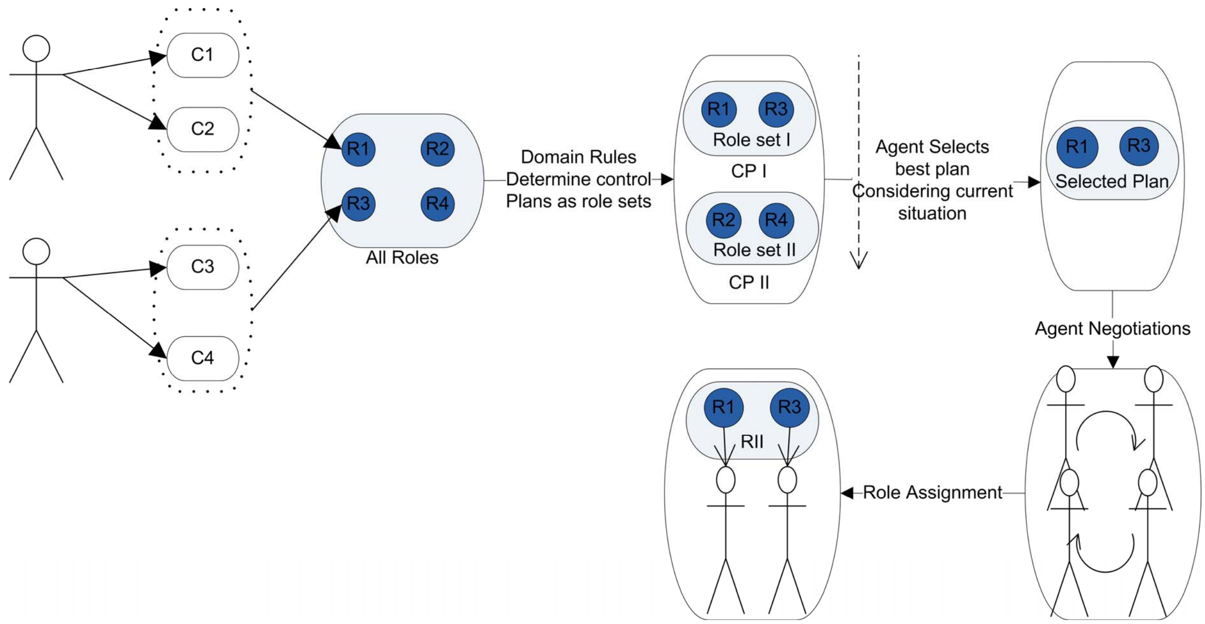

Fig. 6 Role-assignment process [32]. Abbreviations: Control Plan *CPi*, Capability *Cj*, Role *Rk*.

Note that a plan inherently is an ends-to-means structure, it can contain action sequences (function calls) and subgoals, and a plan can only be activated when its preconditions are satisfied. A comparison of the PRS to the original BDI architecture of [18], shows that PRS implements partial plans, as plan-refinement is implemented on the basis of intermediate goals. However, it is simpler with regard to the evaluation and filtering of opportunities and alternative plans, the valuation aspects [13].

3) Roles and Capabilities, Control Plans: In multi-agent problem solving, different roles can be assigned to individual agents based upon their capability to perform certain tasks. Roles and capabilities are formulated based upon a specific context. For example in the context of instrumentation there are two kinds of roles: sensor and actuator. A capability of an agent is its *ability* to function according to such a pre-specified role, here the ability to measure a required value; however, this capability may be unused at a particular time. Complimentarily, a role corresponds to a *slot* in a pattern of interactions, which would need to be filled by an entity with the respective capability. The role expresses a requirement, whereas the capability expresses a potential.

Assignment of roles to agents based upon their capabilities can be done in two fundamental ways:
i) predetermined/static role assignment and
ii) dynamic role assignment.
In predetermined or static roles assignment, roles are assigned to agents at the systems design phase and capabilities are considered permanent or unchanged. This approach results in fast execution but may suffer failure in case of agents loosing specific capabilities.

In dynamic role allocation, roles are assigned to agents dynamically based upon their current capabilities. A role-allocation process is performed whenever the current state of the system changes such that a conflict with the assumptions of the previous assignment appears.

Control roles are a representation of specific functions with respect to control, such as actuator, disturbance, constraint, including the functions providing different control tasks as well as the e.g. frequency/voltage controller as well as associated performance objectives. As well, relevant structural, topological and support roles may be included.

H. Dynamical Allocation of Agent Resources to Roles

In this paper we utilize an allocation mechanism suggested in [32], which, based on a control plan with pre-defined roles, allows allocation of agent capabilities to each role.

Generation of control plan and assignment of specific roles to agents are two different tasks. Accomplishment of a specific goal in a control scenario requires successful execution of a number of roles. A control plan defines set of such roles. Generally, a mapping between the roles and specific “world situations” is done based upon domain principles [35].

The decision of assigning specific roles to agents is taken dynamically through explicit communication, which, initiated by a facilitator agent, is done distributed through an auction mechanism.

For specific role assignment in a chosen control plan, the facilitator requests bids from all participating agents. Agents calculate their local cost functions based upon their current state and capabilities for each role they may assume. Based on the value of this cost function, agents send a bid to the facilitator, which then assigns a role to every agent in the selected control plan.

Figure 6 illustrates the process of control plan determination and role assignment. It should be noted that realization of different roles requires specific capabilities. These capabilities may be offered by one or more agents, and one agent may offer several capabilities. Essential for this algorithm is that both bidder and auctioneer have a common understanding of what the assumption of a role implies.

IV. Representation and Evaluation of System Operation

Given the role system operators have in power system operation, to ensure secure (reliable) operation, how can we value its services?

In terms of valuation of system operation cost, it is important to recognize the position of the operator in the valuation chain (see Figure 7): Grid reliability is valued both by consumers and producers; it has the character of a common good as long as its provision is indiscriminant[10].

Reliability cannot be provided without the means of a responsible entity, the system operator. The operational counterpart to reliability is the operators “certainty”. The cost of system operation is a function of the resources dedicated to system operation, but the resource need cannot be quantified directly: It depends on how the system is operated, which types of resources are employed and which types of disturbances need to be counteracted.

Assume that the operational intelligence of an operator is driven by an aim for “certainty” (corresponding to a measure of security) and the cost comes from allocation of operation-resources. It is outlined in the following, how the control flow and resource allocation can be considered in a common framework, formulated in a functional representation as introduced in Section III-D.

[10] Based on the needs of high-reliability applications, for example for data centers, some recent architecture suggestions adopt a more discriminatory view of reliability provision, e.g. in [19]. These architectures, however, usually assume a locally decoupled grid operation through power electronic interfaces

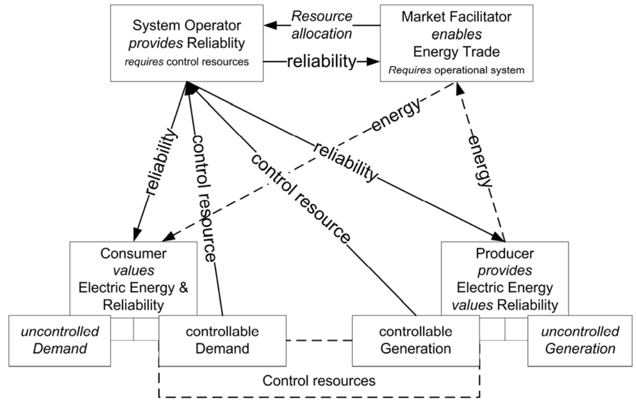

Fig. 7 Needs (ends) and resources (means) in electric energy systems. The arrow points toward the needs: Consumers value the availability of electric energy. Both consumers and producers value grid reliability - and both may offer “reliability-means” (controllable resources).

A. Tasks of an operator agent

Suppose a software agent would have to secure and coordinate Subgrid operation. Suppose also, active devices and control-function aggregators are represented by software agents. In order to design proper tasks and interactions for these agents, it can be useful to start from current system-operation approaches.

As a supervisory control agent, the Subgrid operator-agent oversees the operation of a local grid part. It is responsible for the secure operation of a local grid and is subordinated to a higher-level system operator.

System operation is also the art of securing the system by procuring control resources for uncertain future disturbances. Operation heuristics must therefore aim at “hedging” this uncertainty. Today, the main role of this hedging goes to the energy markets, yielding a scheduled dispatch. The remaining uncertainty is dominated by large power plant outages whose time of occurrence is particularly uncertain, such that the practical threat is covered by the largest unit outage. Probability concepts in operation are not so visible in the operation of conventional power systems[11]. In the case of high wind power penetration, however, it may not be the outage probability, but the uncertainty of prediction which could determine the need for reserves [26]. However, the quite different character of these disturbances might suggest that a different kind of reserve and activation model could apply for these more time-dependent disturbances.

The Subgrid architecture of [3], [12], outlined in Section II, suggests operating states analog to [36], and how the operating states and transitions of the high-level grid are

[11] Load prediction is quite accurate, and load variations do not impact the reserve need as much as the N-1-criterion.

coordinated and interleaved with the operating states of a Subgrid. This state-model is a practical discretization of grid situations that is consistent with the decision ladder introduced earlier. Each state implies a different prioritization of operation-objectives, according to the situation. In order to keep track of control objectives, asubgrid operator agent would internally represent the systemstates
as were given in Figure 2 and trigger transitions based on events observed directly as well as by reasoning about the observed information, as presented in Section III-D1. Events may be triggered by local observations only as well as in coordination with the high-level grid operation, for overlapping states or transitions.

On the basis of state information control actions need to be invoked. The type of actions accepted and necessary strongly depends on the respective state/transition. Deliberative planning, including the allocation of local controllers, is a part of the operator responsibility. To simplify the task of deciding and planning control actions, a number of control actions can be represented in the form of *control plans*. Especially for emergency situations, it cannot be expected that planning and resource allocation should be done in real-time. Such control plans should be prepared during uncritical system conditions.

B. Coordination problems

Coordination is a type of task that aims at distributing tasks and resources amongst a number of agents: Who is going to do what?

In a framework where software agents represent most relevant entities, the *who* can be identified as an agent, except for components serving non-interactive functions (e.g. a transmission-line). If tasks are modeled as a network of interactions or related actions, the *what* is a *role* to be assumed by an agent. The required coordination is thus a role-allocation problem.

As introduced above, there is static and dynamic role allocation. In the concept outlined here, the operator-agent role follows a static allocation. The system operation is also a coordination problem with respect to control, which may be decomposed into two questions: *a)* which control actions should be performed and maintained at the given state-transitions? And, *b)* which units will perform them?

The task at hand is a control problem; therefore all roles to be allocated are framed by the control task. As shown in Section III-D, control tasks can be decomposed by a functional model. The functional model can represent the structure of a control solution including also those functions that would not directly be represented by agents, such as a transmission line or other passive devices. If a functional model is employed to represent a control solution, the means-ends structure of a control problem would be defined.

According to the role-allocation mechanism presented in the previous section, a role-allocation can be performed on the basis of bids by agents that represent the respective device capabilities.

In this form, the role-allocation formulation is an abstraction, framing also solutions of ancillary-service dispatch problems such as that presented in [1].

C. Control Plans

A practical implementation to initiate actions on a state-transition can be analog to the PRS (Section III-G2). The structure of a plan is mapped by understanding a current Subgrid state as a precondition and the desired transition as a goal state (post-condition). Un-intentional transitions are triggered by a observations, and intentional transitions can be triggered by the successful execution of a control plan.

A control plan is a particular type of plan whose goals and preconditions are formulated with respect to the controlled system, specifying relevant control roles as well a system structure it applies to.

The execution of a control plan would be composed of two phases: a startup/transition phase and a state maintenance phase.

Apart from preconditions (related to activation state) and postconditions (related to goal state), a control plan has essentially two parts, according to the two phases:

1) a sequence of actions (“startup procedure”)
2) a (set of) functional model(s), defining the target topology and control structure

A startup/transition plan defines the structural and topological changes required to initialize the operating scenario described in part two. In part two, control roles would be specified analog to or directly by MFM models as introduced in Section III-D.

Such a plan could be constructed dynamically, but let us assume that all control plans parts are partially prepared.
We suggest functional models to structure the second part of the control plan, and see the possibility of planning start-up sequences using functional models as well [37].

In order for the plans to be ready for activation and timely execution when needed, these plans need to be prepared proactively. Control resources need to be allocated and appropriate plans yielding the best utility will be chosen.

As a basis for the generation of control plans, a plan-library (defining complete control structures, control recipes) should be prepared, with standard- or template-plans for all transitions, so that the range of possible control actions is confined.

A planning-algorithm may match the function-topology with the known system structure and formulate the necessary transition steps (e.g. opening and closing of breakers).

A resource allocation algorithm analog to that described in Section III-H could take bids on all these roles. A bid must include *a)* a cost-variable *b)* role-specific quantities constraining the extent to which a given role may be fulfilled.

The bid-structure has to be role-specific, that is for example, a load may offer curtailment for a critical grid-situation, whereas a generator may offer a primary frequency control function including droop, capacity limits, control performance, etc.

D. Evaluation for Resource Allocation

A control plan in the form of a functional model provides sufficient relational information to formulate an evaluation function out of the agent-bids. The role-specific quantities of the agent-bids are related through the functional model, using a mathematical formulation of the respective flow structures, e.g. a power balance can be calculated out of bids for a power generation and demand.

In the same way, control-specific information, such as control-ranges can be matched with expected disturbance behaviour. This part of the evaluation problem corresponds to the reserve allocation problem introduced in Section III-E. If probabilistic information is available for a disturbance characteristic, such as prediction error or variability expectations, evaluation of bids toward the performance evaluation of an associated control function would yield a probability with which the allocated resources are insufficient (e.g. expected load not served). If the control plan includes the expression of performance requirements, these could be matched with the respective evaluation of bids (an algorithmic approach could also be employed, adjusting the bids to match a requested performance, or optimality condition).

The overall *cost* of a given control plan after resource allocation is the sum of its allocated bids. Assuming that the performance of a control plan corresponds to a certainty with which the control plan matches the security-objectives of our operator-agent - this value is the *utility* of a given control plan. Key to this approach is the separation of the means-ends structure, as part of the control plan, from the weighing problem, which requires the evaluation. As control plans can thus be evaluated according to their performance, different control plans can be compared with respect to their cost and overall performance.

Control alternatives can thus be evaluated in a utility vs. cost framework.

V. Application to Subgrid Concept

The concepts outlined in the previous section, lend themselves for application to the Subgrid concept in an agent architecture. Here we discuss some aspects relevant for the design of this agent-based solution.

The control problems in each transition of the Subgrid concept are quite different and thus require also different capabilities and evaluation criteria. In this Section, only the states in the right part of Figure 2 are considered, that is, commercial aggregation and market aspects are left out here.

A. Agents in Consideration

Even though types of devices may vary widely, we may identify some characteristic capabilities. The use of these capabilities depends on the system organization and perspective. In the framework outlined in this paper, capabilities need to be represented by an agent in order to be acknowledged and activated.

For application in the outlined operation concept, we may consider the following types of representation agents:

- Operator Agent (reasoning & decision making)
- uncontrollable demand (offers shedding)
- controllable demand-aggregator (such as in [38])
- distributed generation (or -aggregator)
- local electric vehicles (or -aggregator)
- relay agents (topology changes and fault detection)
- market facilitator, market operator

Each agent represents a different entity and thus different capabilities. Different agents may offer the same capabilities, e.g. both a load and a generator may offer droop regulation capabilities. The list suggests that representation-agents are intended to combine interests (e.g. of a device owner) with a representation of (control-) functionalities that are relevant for the system. As these control functionalities (capabilities) are tied to the entities they represent, a further splitting by functionality seems inappropriate.

However, to increase the robustness of operation, this splitting may be considered for the different tasks that are combined in the operator agent. Here, for example, state-estimation-, reasoning- and planning- capabilities may be distributed on a number of coordinated agents.

B. Relation between Subsystem States and Control Plans

The intentional transitions (->) for each Subgrid state are

- *Connected* -> Islanded; -> Connected alert
- *Connected Alert* -> Islanded -> Connected
- *Islanded* -> Synchronizing.
- *Synchronizing*. -> Connected
- *Blackout* -(blackstart)-> Synchronizing

One can tell from these transitions, how different the control plans will be in type. For example, the "blackstart" transition is naturally a startup-plan that will bring the system into a control mode feasible for synchronization. Its precondition is Blackout, the postcondition is "Synchronizing". A local grid may also be energized from neighbouring grid parts. Then the startup-plan would be based on an incremental control sequence for closing the appropriate breakers. The "non-optimal-islanding"-transition is a protection scheme, that should be triggered locally. Nevertheless, a control plan would also be required here, anticipating the built-in resulting topology after a disruption. The protection plan will likely also include demand-shedding to quickly establish the power balance, which suggests an important decision-variable for the evaluation of alternative protection scenarios (control
plans).

A synchronizing control plan will focus on the grid-forming unit(s) in the system, and possibly include PMU-roles, which would allow for a more smooth transition.

The connected to connected-alert transition will be initiated by fault observations, particularly at a higher-level transition, which leads to suspending market-operation and invoking of local control-reserves. Inside this mode, a redispatch is performed.

All transition control plans require preparation, so that their activation may happen immediately after fulfillment of pre- and post-conditions.

C. Operation in the Time-perspective

In the time-perspective it should be considered, when to renew the plans, both with respect to their means-ends structure and with respect to the resource-allocation. Generally, the timing should be as frequent as possible, but only as frequent as relevant changes can be expected in the system.

The allocation of roles to a control plan should be triggered when a sufficient number new resources becomes available, but also when the situation of the resources changes, for example when a allocated resource looses the capability to perform a previously allocated role.

Another trigger for new renewed planning are changing requirements, such as a new predicition that differs sufficiently from the prediction utilized in the previous plan. This predictive heuristic becomes especially important, when control logic will also be based on energy-storage.

The anticipation of disturbances also determines some of the system-subsystem relations. Operation plans ought to be prepared, depending on the anticipation of challenges, i.e. based on the prediction of uncertain variables. For example, if a storm-front is expected, operators might like to "stock up" on positive reserves.

D. System-subsystem relations

Power system operators on higher level may evaluate the situation in different subsystems, offering support for some or suggesting the trade of reserves across secured lines. A range of coordination possibilities can be considered on the basis of the means-end evaluation established above.

VI. Discussion and Conclusion

We have outlined an architecture of agent-based power system operation, framing operational objectives and related economic decision problems on different levels of system decomposition (from end-users to system operators). This framework enables the representation of alternative control plans, and their evaluation under a utility vs. cost perspective.

The autarky of the agent models employed in this architecture has been limited to reflect transparent operation principles. The means-ends modeling frame-work focuses on a description of control solutions, which opens up for different algorithmic implementations. Particularly mathematical models for ancillary service dispatch such as in [1] or distributed protection as in [34] could be modeled and implemented within this framework. Also more complex hierarchical resource allocation (e.g. PowerMatcher) could in principle be interfaced with this model.

The principles presented in this paper demonstrate how an agent-based control system can be structured to create a scalable power system operation concept, capable of distributing and aggregating control authority and yet remaining transparent from an overall system operation perspective.

Resource allocation - the market aspect - is here framed as subordinated to the control structure, thus creating open interfaces and the possibility for ad-hoc markets under dynamic system operation conditions.

Important aspects to be addressed in further work toward an implementation include:
- Building a library of control plans and roles
- Extensive classification of role types
- Norms for explicit performance evaluation
- Problem specific resource-allocation algorithms
- Interpretation and visualization of control plans

In the long run, also advanced control approaches such as model-predictive control should be modeled in the means-ends framework. Further development of functional representations in power systems will also enable further and explicit benchmarking of existing and future control and resource-algorithms.

Aspects of the outlined agent architecture may form a basis for next-generation operator support systems, including the integration of Artificial Intelligence methods, such as fault-location identification or counteraction-planning. The complexity of such reasoning systems indicates that tasks of an operator-agent will need to be split into a supervisory control agent and a number of supporting agents.

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On the Potential of Functional Modeling Extensions to the CIM for Means-Ends Representation and Reasoning

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Abstract: This paper introduces Functional Modeling with Multilevel Flow Models as an information modeling approach that explicitly relates the functions embedded in components of a system to their design objectives. It is suggested that a functional-modeling based extension of CIM may form a conceptual basis for the integration of distributed energy resources with system operation and market concepts.

1 Introduction

The Common Information Model for Power Systems (CIM) [Com03] has been a major development and standardization effort by actors including the power industry, application developers and researchers. CIM is a published IEC Standard, described in the IEC-61968 and IEC-61970 series of standards, but the model is continuously extended [URSG10] by the members of the CIM User Group, which publishes new versions of the model from time to time.

Opportunities and need for extensions to CIM has been pointed out in numerous publications which consider different use-aspects of the information modeled in CIM. Extensions to the CIM are explicitly allowed, either by contributing to the public version of the CIM User Group[1], or by own extensions of the model's semantics based on the standardized syntax.

Recent research in the field of control in power systems has led to the insight that aggregation concepts are fundamental to the management and control of diverse unit portfolios (e.g. [Geh09]). Aggregators emerged also as new market actors that act as an interface between the services required for system operation (from a system perspective) and the technical operation capabilities present in the aggregator portfolios. The concept of virtual power plants extends the aggregation principle to include generalized automated services.

Standardization efforts in the power industry aiming at better (common) information models, including the CIM and also IEC 61850, take their point of departure in the technical structures and components that 'can be touched and measured'. The organization of these information models is based on physical structures of components and power system functions. In this context control is just a signal. In the modeling of business domains included

[1] http://www.cimug.org

in CIM, function-oriented representations of operations and components appear, for example in asset management and financial operations. These more abstract representations only model basic information relevant for the respective business processes. However, functional requirements specifying the context and purpose of a respective function, and its relation to specific actors and components are hardly expressed.

The conceptual separation between the function that a device provides from the device represented as a component is a necessary abstraction for the control of a heterogeneous set of components such as different types of components, different revisions, or similar components from different suppliers.

Recent work in the field of distributed power system control has pointed out the need for ‘functional’ as opposed to ‘structural’ aggregation concepts in the representation of power system operation [Geh09]. Functional aggregation means that components that are different in one way, may be able to provide one and the same service, and thus appear as ’the same’ from another perspective. Operational services, ancillary services, such as any active power regulation, are control services. Here, control governs the system state toward achievement of system operation objectives.

Power system operation as it is today relies on the careful design and tuning of the controls governing the behavior of generation units. Future power system operations, supported by a much larger diversity of co-acting devices, will require as clear a specification of dynamic requirements on the aggregate service level as it has been implicit in the design of power plants. As ancillary services are always linked to the structure of a power system, they also depend on the power system’s non-active functions (e.g. transmission constraints, inertia). A functional representation of a control system that includes reference to the passive functions of the system-in-view would provide more accurately inormation about requirements and dependencies.

Finally, additional (possibly unanticipated) control services may be introduced in the future. For example, motivated by the interest to avoid overcapacities, localized control schemes could utilize local controllable resources to reduce transformer overloading.

Functional modeling enables a means-ends representation of the system in view. Beyond representation, it makes possible to relate system states to operational goals, and a structured generic representation can serve as a foundation for reasoning about these relations. Multilevel Flow Modeling (MFM) is such a representation which has been applied to a number of technical processes.

It is the goal of this paper to introduce the semantics of functional modeling and to motivate it in context of the Common Information Model, conveying how a means-ends approach may help in preparing CIM for the requirements of a large-scale integration of distributed energy resources (DER).

1.1 Motivational Example

Consider the representation of a tap changer device within CIM. A tap changer regulates the voltage on the low-voltage side of a transformer by adjusting the winding-ratio of the transformer. Its purpose is thus typically to support the lower voltage system in maintaining a constant voltage in spite of changes on the higher-voltage (transmission) level.

In CIM, the *TapChanger* class is part of the package *Wires*. To specify its context, the description of the control goal is provided by *RegulatingControl* (package *Wires*), and its connection to the *PowerTransformer* is modeled through its association to the *TransformerWinding* class, which also provides the relation to the *VoltageLevel* class (via *BaseVoltage*). *VoltageLevel* ties the components together that live on the same voltage.

Contextual information that is not specified within CIM includes the purpose of having a tap changer. Further information not specified includes:

- Overall Goal: Stabilization of Distribution Voltage levels
- Control Objective: Maintain (lower voltage) within specified boundaries
- Control Performance: If objective missed, correction within t seconds.
- Control function: Actuate tap changer n up/down if (observed) voltage is low/high.
- Dependency: Stable voltage in transmission system.
- Possible Failure Modes

These items may be obvious for a power system engineer, because that is simply what a tap changer does and the reason for having a tap changer. This type of information has thus been considered irrelevant for the simple reason that all relevant functions match a component and all components are known if its parametrization of a load-flow simulation is complete. Reverse-engineering of power system controls is easy as long as none of the basic concepts will be modified.

As it is expected for the “smart grid”, the variety of devices along with the variety of controls that will establish the future systems will increase. If a components function is not already defined by its existence, then a functional description layer may be necessary. Additionally, functional descriptions can be helpful when different components have to work together: The components can exchange information about their purpose and usage.

2 Functional Modeling with Multilevel Flow Models

MFM is a functional modeling methodology that provides a library of control functions, energy- or mass-flow-functions and relations, depicted in Figure 1, that can be interconnected to a multi-level representation of causality and intention in flow processes [Lin10]. Adding to the former variety of applications in process engineering, nuclear power plants and others, the field power systems has been developed recently [HSL09, HL09]. An MFM model enables situation-dependent reasoning about control situations, by relating system states to system and control objectives.

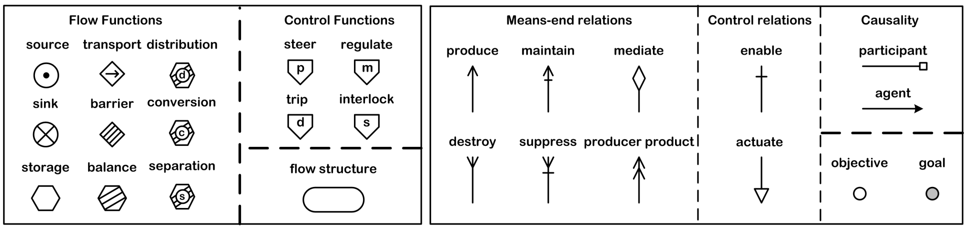

Figure 1: MFM concepts, entities and relations.

Applications of MFM include model based situation assessment and decision support for control room operators, hazop analysis [RMJJ08], alarm design, alarm filtering [Lar96] and planning of control actions [Lar93], [GT97]. It has been used for knowledge representation in AI planning for supervisory control systems [dSV96].

Altogether MFM provides a rich ontology for modeling purpose-aspects of complex processes. MFM is supported by knowledge-based tools for model building and reasoning: a graphical modeling environment and a rule-based reasoning environment with graphical user interface.

2.1 Means, ends and Functional Modeling

Overall goals, process objectives and the realization of the process in components and their behavior form a common dimension of ends and means (illustrated in Fig. 2).

Consider a control action: "*In order to* save the power line from overloading, the relay is programmed to open its breaker."

For any control action, the intention to alter the state of a system is realized *by means of* observing it and manipulating it. Every control action entails concepts of the means-ends dimension.

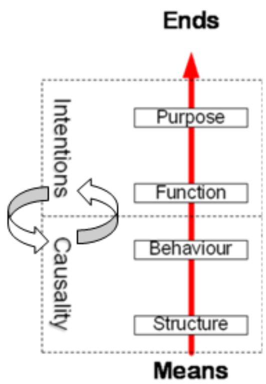

Figure 2: Functional Modeling concepts of the means-ends dimension.

In power systems, the overall goal of reliable operation is decomposed into a number of control objectives such as power-balance (frequency stability), optimal transmission operation (voltage stability, reactive power management), etc. This decomposition of control objectives cannot be derived directly from the overall objective, but it is rooted in the engineering principles and properties of the involved electromechanical process. However, the decomposition can be understood on the basis of a domain model at the right level of abstraction (i.e. a simple model). In the case of frequency control, for example, it is irrelevant to speak about voltage - the basic mechanisms are entirely based on a mechanical power bal-

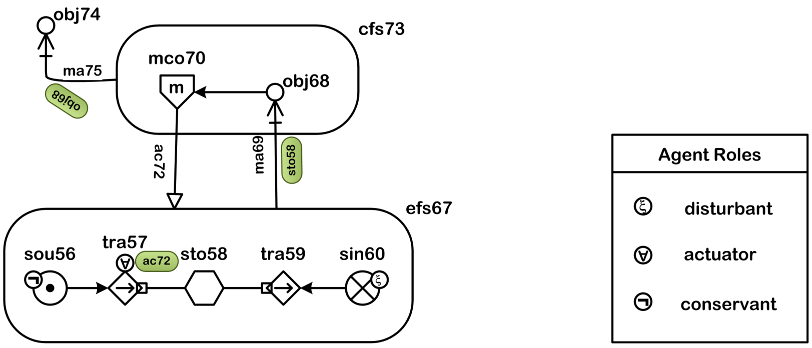

Figure 3: *Left:*Example MFM Model. *Right:* External Agent Roles (introduced in [HL10]).

ance [HSL09, HL09].

Functional modeling provides context to the goals, by relating to objectives and functions, by introducing intermediate levels of abstraction along the means-ends dimension[2]. Functional modeling is thus the modeling of activities (behavior) in relation to their purpose, and the context of the activity.

2.2 Modeling of Control in MFM

In contrast to the classical signals and systems perspective, control functions have a special role in the perspective of mean-ends modeling: Whereas a 'flow-structure' is a functional abstraction of a process, the 'control-structure' is a representation of the *intentional structure* realized by a control system.When reasoning (e.g. for fault diagnosis) about control systems and sytems with embedded controls, it is fundamental to distinguish between causal- and teleological (intention-oriented) relations. That is, when asking 'why?' to quest for the root-cause of an observed state deviation (e.g a failed component), an explanation would entail causal relations that explain state-deviations. In the case of closed-loop control, this causal explanation may typically lead back to the system-state. However, the explanation for a deviation may also be found through a the other kind of 'why?' that asks for an intention/motivation (e.g. a goal change).

A representation of control systems based on action theory has been added more recently to MFM[Lin05, Lin10]. The four elementary control functions, are given in Figure 1.

An example model of a control structure and a related flow-structure is given in Figure 3. It models a stereotypical balancing process, where both the energy-source on the left and the energy sink on the right influence the storage-level. Roles have been attached to some flow-functions indicating that the state of the respective function is determined or

[2]This abstraction is also normal in control design: Models for control should be as coarse as possible and only as detailed as necessary.

influenced by an external agent: The sink state is considered varying, corresponding to an uncontrollable load; the source-state is modeled as constant (e.g. a constant pressure) and the transport is actuated to influence the energy-flow from the source (as a valve would influence the steam-flow). The model consists of several "components" working together:

- *Control-objective* **obj68** and *control function* **mco70** are encapsulated in a *control structure* **cfs73**.
- Requirements to the performance of the control are formulated as an objective associated with the control structure (*performance objective*, **obj74**).
- The control objective is associated via a *means-objective-relation* (*maintain*) with the *mainfunction* (here **sto58**), the state of the mainfunction is subject of control.
- The control function is connected to the flow-structure via an *actuation-relation*, **ac72**, targeting **tra57**.

In [HSL09, HL09] the authors have shown how this modeling of control can be applied to power systems. In contrast to other modeling approaches, the explicit process-decomposition enables the modeling at different levels of abstraction.

2.3 UML Diagram of MFM entities and relations

For the implementation of MFM based applications a class hierarchy has been developed that may be represented in a UML diagram. Figure 4 presents a mock-up UML diagram of the MFM class concept. Both relations and entities follow strict connection rules. For simplicity of the UML diagram, not all MFM classes have been displayed, but only those which define the central structure of it. Also, for the sake of overview, the notation is not following exact UML notation, as association-classes are listed on the right, only indicating which classes they ought to be connecting.

3 Toward Modeling of Control in CIM

The modeling language MFM has been introduced above and special emphasis has been given on its capacity to represent control-related functions and roles. Even though the UML diagram shows the classes by which information is modeled in MFM, its strength is the consistent means-ends and whole part representation, which connects information to its proper context and abstraction level.

In this section we explore the implications of this deeper understanding of control for the representation of control in CIM.

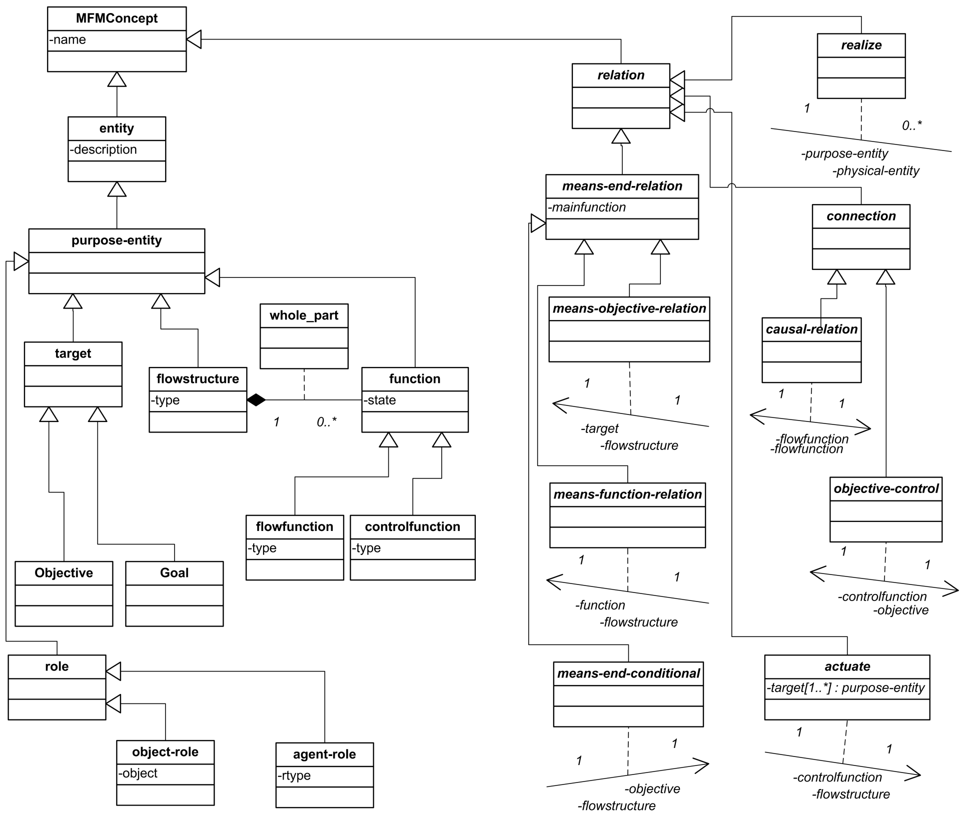

Figure 4: Sketch of MFM concepts in UML notation.

3.1 Traces of Functional Modeling and Control in CIM

The before-mentioned idea of decoupling a function from the device that provides that function exists partly in the CIM model. The *SVCAsset* is an example for that: it describes a physical asset performing the function of a static var compensator. Strangely enough, the class *StaticVarCompensator* is not connected in any way to *SVCAsset*. However, there should be connections between the classes that model the same thing on different levels (business process, asset management, structural aggregation, technical specification), because not all types of modeling stay on just one level.

The notion of function is captured in some way by the class *AssetFunctions* (package *Assets*) and its child classes (*DeviceFunction*, *ElectricMeteringFunction*, etc.), yet the focus is on asset management.

Representation of technical control in CIM is given by the *Control* class in the *Meas* package. This and its two child classes *Command* and *SetPoint* encapsulate the concept of a single control value that is sent to a device. A type of control can also be specified, yet CIM provides no specific values. This is the embodiment of the 'control is just a signal' perception.

A somewhat more functional representation of control is provided by *RegulatingControl* (package *Wires*). This class groups together some equipment which performs a certain type of regulation. Attributes of this class determine the type of regulation (reactive power, active power, ...) and the target value or range. *RegulatingControl* can be associated with classes implementing that control.

The *ControlArea* package can be used for modeling a control area, containing among others the classes *ControlArea*, *ControlAreaGeneratingUnit* and *ControlAreaTypeKind* (which can be *AGC*, *Forecast* or *Interchange*). The class *ControlArea* is indirectly connected to the class *AreaReserveSpec* (package *EnergyScheduling*), via the *SubControlArea* and *HostControlArea* classes. That class, *AreaReserveSpec*, contains several attributes defining the reserve specification. Unfortunately, these attributes are defined in respect to time frames of 10 minutes; this is problematic because grid codes differ in how they define reserve.

The package *Reservation* provides another viewpoint on reserve specifications via the class *AncillaryService*, which does not contain any technical information, but is connected to the classes *ServiceReservation*, *TransmissionProvider*, and *ControlAreaOperator*. This is clearly a business-process-oriented way to look at ancillary services.

In conclusion, the CIM offers a number of classes related to control, but with a focus on structural views in terms of components, and signals. Traces of functional perspective are found in the modeling for asset management and business relations. Process control aspects are generally not expressed explicitly, but rather as part of component parameters. For example there are a number of attributes controlling specific components, like the *governorSCD* (Governor Speed Changer Droop) attribute in *GeneratingUnit*, but these are distributed over the different types of components.

3.2 Drawing Inspiration from MFM for Functional Modeling in CIM

The means-end perspective that is essential in MFM exists only implicitly in the CIM, such as in *ControlAreaOperator* (representing the end) being interconnected to *ControlAreaGeneratingUnit* (the means).

The modeling of ancillary services is based on assumptions of control services that can be provided by a power plant. Typically today, these services and their descriptions are described in terms of conventional generating units. However, it has been shown in practice, that the same regulating services (functions) may also be offered by other types of devices. Here it shows how functional semantics become a powerful tool in recasting the relations between controlling and controllable entities. It also should be considered that the relation of control functions to devices is that of many-to-many: The same device may provide a number of control functions (or 'services') and one control function may be performed by a number of units.

This type of information is both related to 'physical' and engineering concepts and to the world of market operations and service descriptions. The introduction of an intermediary modeling layer based on functional modeling concepts enables the representation of these, possibly indirect, linkages between components, aggregators, and the services offered for power system operation.

Some elementary concepts that would form this layer can be found in MFM: Means-ends perspective, linking goals and objectives to the technical functions that enable their achievement; the modeling of control structures and flow-structures in multi-level relations as a representation of the interactions between intentional and causal functions. Further, the modeling of control functions according to MFM emphasizes the need for representing both Control Objective and Performance Objectives, the linkage of Control functions to the actuated system, including reference to the 'counter-agent': origin of anticipated disturbances.

The basic (flow) function types that MFM provides may be considered as specific states of connectedness, implicitly given by the (structural) classes that CIM provides. To list some examples, *ACLineSegment* can be assumed to provide some Transport function, a *GeneratingUnit* can be a Source of power, while a Sink function can be provided by *EnergyConsumer* or one of the different Load classes. Still, the level of abstraction in CIM is different from the one in MFM.

4 Example Cases

The following examples attempt to illustrate the type of information to be modeled. The first example is for an existing component, and the second example is for a hypothetical future scenario.

4.1 Governor Control

Frequency control in power systems is a typical example of decentralized control of large systems. The tuning of the individual controllers depends on the overall system context, beyond the individual generator.

In CIM we find the following representations: *AncillaryService* (package *Reservation*), and *Control* (package *Meas*). Further, CIM provides the context: *ControlAreaGeneratingUnit* (package *ControlArea*); *GeneratingUnit* (package *Generation::Production*); and *ControlAreaOperator* (package *Financial*).

Generation control provides frequency control, it should thus be represented in the Generation or Generation Dynamics packages. At the same time, frequency control of different types is an ancillary service (or divided into several services) to be contracted. As such it is important to specify performance requirements that define the quality of the service to be provided from a top-down perspective (system operator).

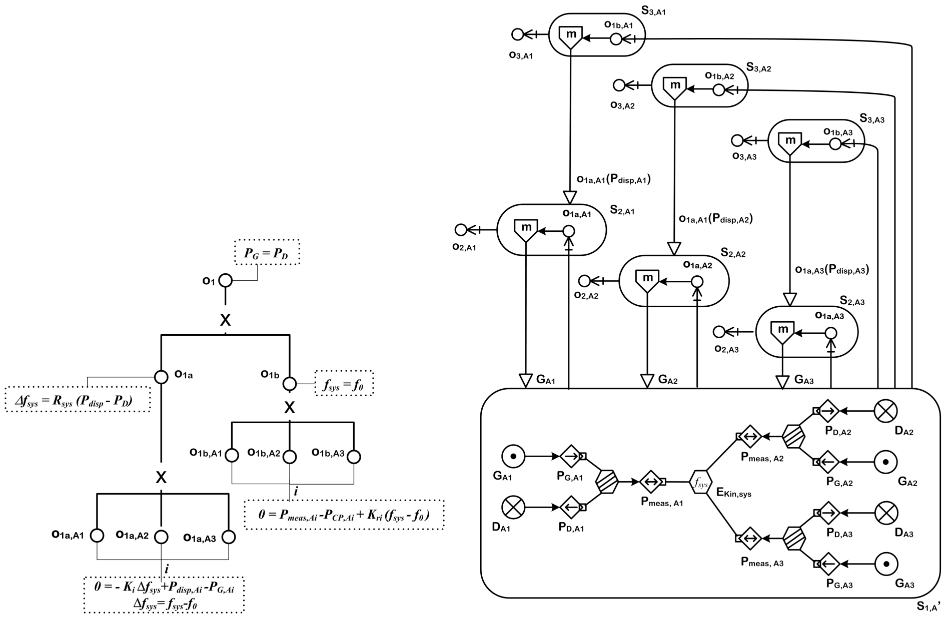

Figure 5: *Left*: Goal decomposition of frequency control. *Right*: Control hierarchy and flow structure of the system balancing with control areas [HL09].

An MFM Model of frequency regulation including a representation of control areas has been presented in [HL09] including an objective decomposition. Figure 5 shows how the overall perspective would be represented in MFM. The goal decomposition shows how the objective of overall power balancing is related to frequency control.

4.2 Overloading Avoidance of Distribution Transformer

This example describes a possible future control scenario arising when DER resources are integrated on the low-voltage level (electric vehicles, PV panels, μCHP units, ...). It has been recognized that large numbers of these new resources could be included in the control of power systems via aggregation. However, when resources on the lower voltage levels provide services to upper voltage levels, it becomes important also to respect local operating conditions and constraints. To prevent for example the distribution transformer from overloading, a number of control schemes could be thought of.

The control scenario includes power resources as well as supervisory entities that are not all represented in CIM yet:

- DER: generating units (going to be included with a structural representation), and controllable loads (CIM only has *ConformLoad* and *NonConformLoad* classes)

- the transformer (the CIM class *PowerTransformer*)
- the balance-responsible entity that wants to activate services on the low-voltage level (could be framed by existing CIM)
- the DSO (Distribution System Operator) owning the substation and transformer
- the TSO (Transmission System Operator) activating the aggregated services

It ought to be noted here that the transformer capacity acts as a constraint on the ability of the DER to provide their services, thus introducing a dependency - or conflicting objectives - between DSO and TSO, where different control functions need to be coordinated and possibly executed by the same devices.

In a functional perspective, the DER might act as a controllable device with respect to both the global control layer as well as to the local control. Its functions may be modeled separately in different functional representations. These functional representations would be sufficient to track the dependencies, simply on the basis of the cause of the dependency, but independent of component-level specifications.

5 Conclusion

The intention of this paper was to demonstrate the functional modeling approach and its value for representing power system operations within information models. It has been shown that on the basis of generic means-ends concepts, control objectives and control means can be modeled in a common framework. The modeling is meaningful with respect to representation of control functions, especially for cases in which the realization of a control function itself has to be considered a black box.

A direction toward integrating a functional representation layer with the Common Information Model has been presented and some motivating examples have been given to highlight potential benefits. A functional representation within CIM may be introduced as an intermediary layer between the representation of business processes and the current structural modeling approach in IEC 61970-301. It would induce an number of benefits, starting from asking the right kind of questions to qualify for control functions, to enabling the design and inclusion of new types of control policies which may or may not be anticipated at this time.

As this paper is a first attempt to identify a connection between previously unrelated domains of research, much ground has been left open for further elaboration and discussion. Also the potential application of MFM-based reasoning concepts has been left open for future study.

6 Acknowledgment

Functional modeling with MFM has been and is being developed by Morten Lind and his collaborators.

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Energy Storage in Power System Operation: The Power Nodes Modeling Framework

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***Abstract*—A novel concept for system-level consideration of energy storage in power grids with dispatchable and non-dispatchable generators and loads is presented. Grid-relevant aspects such as power ratings, ramp-rate constraints, efficiencies, and storage capacities of the interconnected units are modeled, while technology-dependent and physical unit properties are abstracted from. This allows the modeling of a technologically diverse unit portfolio with a unified approach. The concept can be used for designing operation strategies for power systems, especially in the presence of non-dispatchable generation and significant storage capacities, as well as for the evaluation of operational performance in terms of energy efficiency, reliability, environmental impact, and cost. After introducing the modeling approach and a taxonomy of unit types, a simulation example is presented for illustration.**

***Index Terms*—Power Nodes, Energy Storage, Dispatch, Balancing, Active Power Control, Curtailment, Load Management, Intermittent Generation**

I. Introduction

ELECTRIC power is a real-time commodity, which means that both its provision and consumption occur instantaneously. Traditionally, controllable generation units provide the necessary flexibility to achieve a continuous balance between supply and demand. While the power balance is established through an arrangement of automatic controls, integral (e.g. hourly) amounts of energy are procured in energy markets based on predictions.

The combustion of fuels with chemically stored energy enables the flexible dispatch of generators. This process is mainly driven by spot market electricity prices and marginal electricity generation costs. In the case of constraints on the producible electric energy, e.g. due to a limited reservoir size in hydro power plants, operation decisions are driven by expected opportunity costs from expected future prices and available storage levels [1]. Thus, energy constraints – inherent to all kinds of energy storage – induce a different dispatch logic. Considering the ongoing large-scale deployment of intermittent renewable energy sources (RES) [2], energy storage is likely to become a dominant factor in future power systems [3].

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A. Energy Storage in Power Systems

All forms of energy storage, except for electromechanical energy storage inherent to AC power systems with rotating machines, depend on energy conversion processes which are based on a wide range of technologies [4]. In addition to reversible energy storage in the form of batteries, flywheels etc., a very important form is heat storage. Methods to increase the controllability of loads with inherent storage are emerging, such as control strategies for household appliances with thermal inertia and for prospectively large amounts of electric vehicles connected to the power system [5]–[8]. Ubiquitous controllable energy storage is likely to have positive effects on system operation, ranging from security-relevant power reserves to loss reduction on the distribution system level [9], [10].

The economic value of energy storage is derived from the abilities to perform market-oriented dispatch and to act as a control resource in the framework of ancillary services. Especially in systems dominated by intermittent and inflexible generation capacity, flexibility is valuable [11]. However, current grid operation frameworks do not directly support and capitalize on the specific capabilities of energy storage. For instance, storage reserves are not conceptually considered in the traditional procurement of control reserves: Only power reserves are relevant, while the amount of energy required for control actions is not visible to the operator and is settled in post-operation.

B. Intermittent In-Feeds

Intermittent power in-feeds from wind turbines and photovoltaic arrays are predictable to a certain extent [12]. Nowadays, information on the predicted future power in-feed is included in the power plant day-ahead dispatch in areas with high RES penetration. Curtailment of intermittent power in-feed is usually only used as an emergency measure, not as a normal-operation control resource. Similarly, the unavoidable prediction errors are balanced via intra-day trading and conventional control reserves, not by the intermittent generation units themselves.

The utilization of on-line control measures for intermittent generation units, such as partial generation curtailment [13], [14], has been included in the grid code of countries with significant wind power penetration. This kind of controllability, however, remains limited by the availability of the primary energy carrier, i.e. wind force, which cannot be influenced. The challenge of systematically and consistently integrating such methods into power system operation and control constitutes another motivation for the present work.

C. Objective of this Work

The additional degrees of freedom that energy storage and an increased controllability of intermittent power in-feeds provide can only be utilized if an appropriate control architecture is established. Many control architectures, often utilizing aggregation principles, have been proposed in this context, such as Virtual Power Plants [15], Cells [16], [17], or MicroGrids [18]. The impacts of energy storage are particularly relevant for dispatch problems because of the storage dynamics and associated inter-temporal constraints. Here, the control methodology of (distributed) Model Predictive Control is particularly suitable [19]–[21].

A comprehensive performance comparison of different control approaches constitutes a challenge in itself [22], [23]. This paper aims at developing an appropriate evaluation framework for addressing this challenge. The concept of "Power Nodes" is introduced to represent a variety of unit types in a unified framework for the assessment of energy-storage-based operation strategies for power systems. On the basis of instantaneous quantities in the storage model, a number of power and energy balances can be formulated that allow to evaluate the overall system performance. The objective is to consider all types of energy storage relevant for system operation.

The paper is structured as follows: Section II introduces the Power Nodes framework, while Section III explains the representation of common unit types as power nodes. The benefits of the developed concept are illustrated by a simple simulation example in Section IV, followed by conclusions in Section V.

II. Power Nodes Framework

The basic premise of the Power Nodes approach is that any power source or sink connected to the electric power system requires the conversion of some form of energy into electric power, or vice versa. These forms may be termed "supply-" or "use-forms" of energy, respectively. The degrees of freedom necessary for fulfilling the power balance in the electric grid arise from the freedom that the supply- and use-forms of energy provide, either by being controllable or by offering inherent storage capacity.

Abstracting from the physical properties and the internal composition of a supply- or use-process including the associated energy conversion, we represent it from a grid-perspective as a single lumped unit with characteristic parameters, a "power node".

A. Domain Models

The introduction of a generic energy storage perspective adds a modeling layer to the classical modeling of power systems, illustrated in Fig. 1. In the resulting enhanced model, the electro-mechanical domain of the electric grid is interfaced with the pre-grid Power Node domain, which represents conversion processes and an associated energy storage functionality. A third, external, domain is formed by the use and supply processes consuming energy from and feeding energy into the Power Node domain.

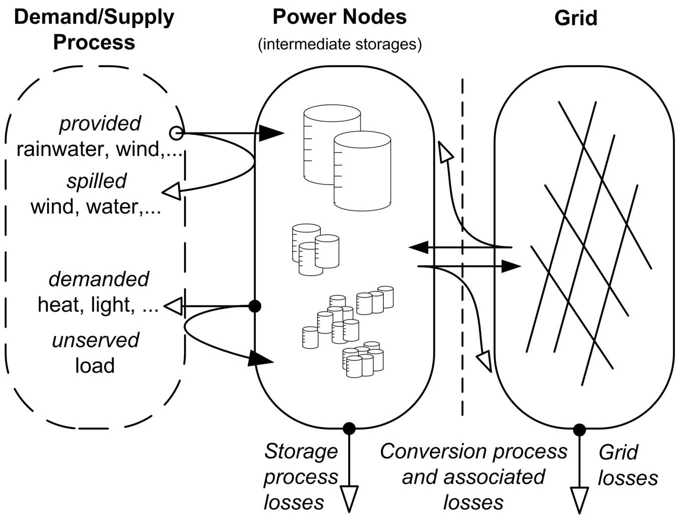


Fig. 1. Illustration of the three-domains concept. The Power Node- and Grid domains are model-internal domains and both are considered integral parts of the electric energy system. The domain of Demand/Supply processes is considered external, indicated by the dashed frame. Arrows indicate the energy (or power) flows that are accounted for, where empty arrowheads indicate energy that is exchanged with the environment, while black arrowheads indicate energy flows into or across the modeled domains.

For ensuring the consistency of the model, it is important to define unambiguous domain interfaces. Generally, these are exchanges of energy, or power, in continuous time. For instance, the exchange between the Power Node domain and the Grid domain is defined as the active/reactive power fed into or consumed from the grid. In the case of a dynamical grid model, the inertia of synchronous machines is part of the Grid domain, and thus the active power interface is equivalent to the mechanical power exerted by the prime mover of a synchronous generator. Grid losses are modeled inside the Grid domain, while pre-grid losses, such as storage and conversion losses, are accounted for in the Power Nodes domain. This clear separation allows the Power Nodes framework to integrate with a number of different physical network representations common in power systems modeling (cf. Section II-C).

All supply and demand processes are connected through a power node to the electricity grid. Consequently, the total energy provided to or demanded from the grid may differ from the actual energy served or utilized by external processes, as is illustrated by straight and rounded arrows in Fig. 1. This enables the formalized representation of real-world effects that cause supplied energy to be lost, or demanded energy to remain unserved. For example, energy conversion implies conversion losses, power in-feed from wind turbines may be curtailed, and a load may get disconnected from the grid. In order to evaluate the performance of the overall system, it is necessary to keep track of these losses and to account for the value associated with them. For this purpose, the balance terms formulated in Section II-E can be utilized.

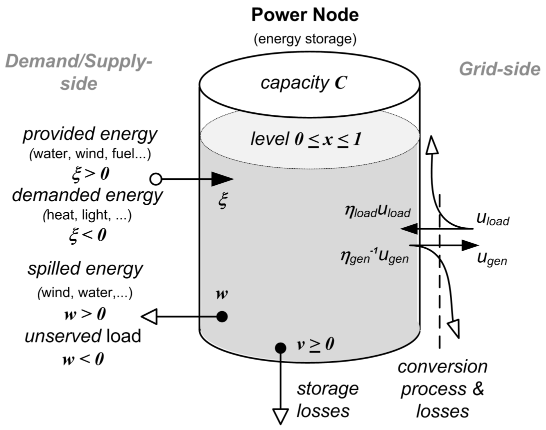


Fig. 2. Notation for a single power node.

B. Model of a Single Power Node

Consider the structure of a single power node consisting of the elements illustrated in Fig. 2. In comparison with Fig. 1, the provided and demanded energies are lumped into an external process termed ξ, with $\xi < 0$ denoting a use and $\xi > 0$ a supply. The term $u_{\text{gen}} \geq 0$ describes a conversion corresponding to a power generation with efficiency η_{gen}, while $u_{\text{load}} \geq 0$ describes a conversion corresponding to a consumption with efficiency η_{load}.

The energy storage level is normalized to $0 \leq x \leq 1$ with energy storage capacity $C \geq 0$. Fig. 2 illustrates how the storage serves as a buffer between the external process ξ and the two grid-related exchanges u_{gen} and u_{load}.

Internal energy losses associated with energy storage, e.g. physical, state-dependent losses, are modeled by the term $v \geq 0$, while enforced energy losses, e.g. curtailment/shedding of a supply/demand process, are denoted by the waste term w, where $w > 0$ denotes a loss of provided energy and $w < 0$ an unserved demand process.

1) Generic Model: The dynamics of an arbitrary power node $i \in \mathcal{N} = \{1, \ldots, N\}$, which may exhibit nonlinear effects in the general case, is described by:

$$
\begin{aligned}
C_i\, \dot{x}_i \quad &= \quad \eta_{\text{load},i}\, u_{\text{load},i} - \eta_{\text{gen},i}^{-1}\, u_{\text{gen},i} + \xi_i - w_i - v_i, \quad (1)\\
\text{s.t.} \quad &\text{(a)} \quad 0 \leq x_i \leq 1 \quad ,\\
&\text{(b)} \quad 0 \leq u_{\text{gen},i}^{\min} \leq u_{\text{gen},i} \leq u_{\text{gen},i}^{\max} \quad ,\\
&\text{(c)} \quad 0 \leq u_{\text{load},i}^{\min} \leq u_{\text{load},i} \leq u_{\text{load},i}^{\max} \quad ,\\
&\text{(d)} \quad 0 \leq \xi_i \cdot w_i \quad ,\\
&\text{(e)} \quad 0 \leq |\xi_i| - |w_i| \quad ,\\
&\text{(f)} \quad 0 \leq v_i \quad \forall\, i = 1, \ldots, N \quad .
\end{aligned}
$$

Depending on the specific process represented by a power node and the investigated application, each term in the power node equation may in general be controllable or not, observable or not, and driven by an external influence or not. Internal dependencies, such as a state-dependent physical loss term $v_i(x_i)$, are feasible. Charge/discharge efficiencies may be non-constant in the general case, e.g. state-dependent: $\eta_{\text{load},i} = \eta_{\text{load},i}(x_i)$, $\eta_{\text{gen},i} = \eta_{\text{gen},i}(x_i)$.

The constraints (a) – (f) denote a generic set of requirements on the variables. They are to express that (a) the state of charge is normalized, (b, c) the grid variables are non-negative and bounded, (d) the supply/demand and the curtailment need to have the same sign, (e) the supply/demand curtailment cannot exceed the supply/demand itself, and (f) the storage losses are non-negative. Ramp-rate constraints, especially constraints on the derivatives $\dot{u}_{\text{gen},i}$ and $\dot{u}_{\text{load},i}$, can be included for power system studies under dynamic operating conditions with a simplified representation of the local dynamics.

Apart from the constraints listed here, there may be additional ones imposed on the variables, e.g. in order to define certain standard unit types with characteristic properties (cf. Section III). Generally speaking, the explicit mathematical form of a power node equation depends on the particular modeling case. Note that the labeling for the power node equation is based solely on a generic process perspective, providing technology-independent categories linked to the evaluation functions given in Section II-E.

2) Model-Specialization to Affine Model: Specializations and simplifications of the generic model are relevant for practical tasks such as controller design and implementation. Here we present the example of a simplified affine model which is suitable for describing a wide range of processes with state-dependent losses, such as heat storages that lose energy to the ambiance due to a difference between the internal storage temperature and the ambient temperature. For this purpose, a linear dependence of v_i on the storage state x_i is assumed, and the efficiencies are assumed constant in order to eliminate nonlinearities:

$$
\begin{aligned}
C_i\, \dot{x}_i \quad &= \quad \eta_{\text{load},i}\, u_{\text{load},i} - \eta_{\text{gen},i}^{-1}\, u_{\text{gen},i} + \xi_i - w_i \qquad (2)\\
&\quad\; -a_i\,(x_i - x_{\text{ss},i}) \qquad ,
\end{aligned}
$$

subject to the same constraints as (1). The steady-state storage level $x_{\text{ss},i}$ refers to the steady state of the differential equation in the absence of inputs, e.g. the thermal equilibrium of a thermal storage with the ambiance, and a_i is a non-negative loss coefficient.

3) Modeling a Power Node without Storage: Power nodes are also useful to represent processes independent of energy storage, such as conventional generation/load, as well as intermittent generation. A process without storage implies an algebraic coupling between the instantaneous quantities ξ_i, w_i, $u_{\text{gen},i}$, and $u_{\text{load},i}$; storage-dependent loss does not exist ($v_i = 0$). Equation (1) degenerates to

$$\xi_i - w_i = \eta_{\text{gen},i}^{-1}\, u_{\text{gen},i} - \eta_{\text{load},i}\, u_{\text{load},i} \quad . \qquad (3)$$

This equation is able to describe both externally driven processes and controllable power generation.

In the case of an externally driven supply/demand process $\xi_i = \xi_{\text{drv},i}(t)$, the supplied/required energy is either directly fed into/taken from the grid, or it is spilled/not served, accounted for by the waste term w_i. This model is particularly relevant for external supply and demand processes which are not directly controllable, while there may be a choice to curtail the process. Examples are intermittent power generation ($\xi_{\mathrm{drv},i}(t) \geq 0$) and classical load ($\xi_{\mathrm{drv},i}(t) \leq 0$).

In the case of a fully controllable supply process such as a conventional generator, the grid-related variables $u_{\mathrm{gen},i}$ or $u_{\mathrm{load},i}$ are the controlled variables. The power exchange with the environment through ξ_i then accounts e.g. for primary energy usage.

C. Mapping from Power Nodes to Grid Domain

All electric load and generation units are represented by power nodes, i.e. no further injections and loads need to be accounted for. Consider a power grid composed of power nodes $i \in \mathcal{N} = \{1, \ldots, N\}$, representing a number of single or aggregated units, and buses denoted by $m, n \in \mathcal{M} = \{1, \ldots, M\}$. In order to map the N power nodes to the M buses in the grid model, power node indices are divided into sets $\mathcal{N}_m$ associated with each bus; the following properties hold for $\mathcal{N}_m$: $\mathcal{N}_m \subseteq \mathcal{N}$, $\mathcal{N}_m \cap \mathcal{N}_n = \emptyset$ for $m \neq n$, and $\bigcup_{m\in\mathcal{M}} \mathcal{N}_m = \mathcal{N}$.

The net power injection to a grid node $m \in \mathcal{M}$ is thus:

$$P_{\mathrm{netinj},m} = \sum_{i\in\mathcal{N}_m} u_{\mathrm{gen},i} - \sum_{i\in\mathcal{N}_m} u_{\mathrm{load},i} \quad . \tag{4}$$

D. DC Grid Model with Power Nodes

The Power Systems literature in general offers many options to model a power system, depending on the questions of relevance to the study. In principle, the Power Nodes domain can be interfaced with many grid model types due to the clear separation from the electro-mechanical domain.

To illustrate the approach, this section formulates a network represented by linear DC power flow equations. The DC network representation is used for example in an active-power dispatch of a unit portfolio in a capacity-constrained transmission system. The DC power flow assumes small angle differences, a constant, flat voltage profile, and neglects the resistance of lines. While voltage angles are generally small, the critical assumptions are the flat voltage profile and the negligible resistance [24].

The power flow is governed by the following equations:

$$P_{\mathrm{exch},m} = \sum_{\substack{n\in\mathcal{M}\\ n\neq m}} B_{mn}(\delta_m - \delta_n) \quad , \tag{5}$$

$$0 = \sum_{m=1}^{M} (P_{\mathrm{netinj},m} - P_{\mathrm{exch},m}) \quad , \tag{6}$$

where δ_m is the voltage angle at bus m, and $B_{mn} = 1/X_{mn}$ is the inverse of the line reactance.
The line flows may be subject to capacity constraints:

$$-P_{mn}^{\mathrm{cap}} \leq B_{mn}(\delta_m - \delta_n) \leq P_{mn}^{\mathrm{cap}} \quad . \tag{7}$$

The system frequency can be described by an aggregate inertia model:

$$H\dot{\omega} = \sum_{m=1}^{M} P_{\mathrm{netinj},m} \quad , \tag{8}$$

where H is the aggregate inertia constant and ω is the angular frequency of the system.

E. System-Level Balance Formulations

In order to establish an accounting framework for the evaluation of operation and control strategies acting on an electrical grid interfaced with a set of power nodes, a number of balance terms can be formulated. These can be established in the form of instantaneous quantities in order to characterize the current operational state of the system, or as time-integrals of the former which serve to evaluate the system performance over a certain time span.

Note that the expressions stated here are considered examples, not a complete list of possible balance terms. The list can be extended with respect to the specified power and energy performance indicators and can also include technology-dependent weighting terms for monetary cost or environmental impact. Examples for instantaneous balance terms indicating the current system state are:

- Power supplied to grid: $P_{\mathrm{gen}}^{\mathrm{grid}}(t) = \sum_{i\in\mathcal{N}} u_{\mathrm{gen},i}(t)$,
- Power consumed from grid: $P_{\mathrm{load}}^{\mathrm{grid}}(t) = \sum_{i\in\mathcal{N}} u_{\mathrm{load},i}(t)$,
- Currently stored energy: $E_{\mathrm{stored}}(t) = \sum_{i\in\mathcal{N}} C_i x_i(t)$,
- Power supply available: $\xi_{\mathrm{supply}}^{\mathrm{total}}(t) = \sum_{i\in\{i|\xi_i>0\}\subset\mathcal{N}} \xi_i(t)$,
- Power demand: $\xi_{\mathrm{demand}}^{\mathrm{total}}(t) = \sum_{i\in\{i|\xi_i<0\}\subset\mathcal{N}} \xi_i(t)$,
- Power supply curtailed: $w^+(t) = \sum_{i\in\{i|w_i>0\}\subset\mathcal{N}} w_i$,
- Power demand not served: $w^-(t) = \sum_{i\in\{i|w_i<0\}\subset\mathcal{N}} w_i$,
- Power conversion loss: $P_{\mathrm{loss}}(t) = \sum_{i\in\mathcal{N}} \left(\frac{1-\eta_{\mathrm{gen},i}(t)}{\eta_{\mathrm{gen},i}(t)} u_{\mathrm{gen},i}(t) + (1-\eta_{\mathrm{load},i}(t))\, u_{\mathrm{load},i}(t) \right)$.

All of the above quantities can be restricted to certain unit types by placing restrictions on the index i. For example, the consideration of all non-controllable non-buffered generation units would require a summation over the index $i \in \{i | C_i = 0 \wedge \xi_i = \xi_{\mathrm{drv},i}(t) \geq 0 \wedge w_i = 0\} \subset \mathcal{N}$.

Based on line flows estimated by the DC model and the assumption $R \ll X$, grid losses may be approximated by:

$$P_{\mathrm{loss}}^{\mathrm{grid}}(t) = \sum_{m=1}^{M-1} \sum_{n=m+1}^{M} |G_{mn}\,(\delta_m(t) - \delta_n(t))| \quad , \tag{9}$$

with G_{mn} being the (m, n)-th element of the bus conductance matrix.

Energy balance terms can be derived by time-integration over instantaneous balance terms in the time interval $[t_1, t_2]$, such as

- Electric energy supplied to grid: $\int_{t_1}^{t_2} P_{\mathrm{gen}}^{\mathrm{grid}}(t)\, dt$,
- Primary energy supplied: $\int_{t_1}^{t_2} \xi_{\mathrm{supply}}^{\mathrm{total}}(t)\, dt$,
- Primary energy curtailed: $\int_{t_1}^{t_2} w^+(t)\, dt$,
- Energy conversion losses: $\int_{t_1}^{t_2} P_{\mathrm{loss}}(t)\, dt$.

III. Characterization of Unit Types

In this section, we provide a taxonomy of unit types that can be modeled using the Power Nodes framework. A "unit" in this context is an arbitrary generation, load, or storage device, or a group of aggregated devices. The type distinction is established by a set of constraints on the variables used in (1), i.e. $u_{\text{load},i}$, $u_{\text{gen},i}$, C_i, x_i, ξ_i, v_i, and w_i. These constraints hold in addition to the principal constraints (a) – (f) in (1), providing a classification of units with different operational properties. First, a set of unit properties is established, then a number of possible combinations of these properties are listed, providing a link between the modeling framework and real units found in power systems.

A. Unit Properties

Table I establishes a set of basic properties defining the operational behavior of a unit modeled as a power node. The particular choice of constraints is explained in the following:

- The power node variables $u_{\text{gen},i}$ and $u_{\text{load},i}$ determine whether a power node is injecting power into or consuming power from the grid. A pure generation process would imply that $u_{\text{load},i} = 0$ at all times, while a pure load cannot inject power, expressed by $u_{\text{gen},i} = 0$. In a bi-directional conversion system, both variables can assume non-zero values. In this case, it must be further distinguished whether both conversions can happen at the same time (e.g. in a storage with two separate conversion units, such as a pumped hydro plant with independent turbine and pump), or whether one of the variables must always be zero (e.g. in an inverter-connected battery storage).
- The storage capacity C_i determines whether a unit is modeled with ($C_i > 0$) or without energy storage capabilities ($C_i = 0$).
- The sign of the external process variable ξ_i determines whether a supply process ($\xi_i > 0$) or demand process ($\xi_i < 0$) is considered. If no external process is considered, $\xi_i = 0$ holds.
- Constraints on ξ_i and w_i determine the controllability of a unit. In case ξ_i is driven by an external signal $\xi_i = \xi_{\text{drv},i}(t)$, e.g. induced by an intermittent supply, the unit may either be regarded as non-controllable (no curtailment possible: $w_i = 0$), or curtailable (no further constraint on w_i). Units are considered controllable if ξ_i is not externally driven. In this case, $w_i = 0$ can be assumed because the curtailment of a directly controllable process would be unnecessary[1].
- The storage associated with a power node is considered lossless if $v_i = 0$, and lossy otherwise.
- The grid variables $u_{\text{gen,i}}$ and $u_{\text{load},i}$ may be rate-constrained, which is reflected in continuous time by an upper and lower bound on their derivatives. This serves to model physical limitations on the rate of change of a power conversion process, e.g. due to the amount of thermal stress on power plant components.

[1]Note that more detailed sets of constraints may be established for the power node variables in order to model particular units. In this case, it may be practical to allow for a non-zero w_i even in the presence of a (partly) controllable ξ_i.

TABLE I
Unit properties determined by power node equation constraints

Variable(s)	Constraint(s)	Implication
$u_{\text{gen},i}$,	$u_{\text{gen},i} = 0$	Load
$u_{\text{load},i}$	$u_{\text{load},i} = 0$	Generator
	$u_{\text{gen},i} \cdot u_{\text{load},i} = 0$	One-conv.-unit storage
	–	Two-conv.-unit storage
C_i	$C_i = 0$	Non-buffered unit
	$C_i > 0$	Buffered unit
ξ_i	$\xi_i = 0$	No external process
	$\xi_i \geq 0$	Supply process
	$\xi_i \leq 0$	Demand process
ξ_i, w_i	$\xi_i = \xi_{\text{drv},i}(t) \wedge w_i = 0$	Non-controllable
	$\xi_i = \xi_{\text{drv},i}(t)$	Curtailable
	ξ_i arbitrary, $w_i = 0$	Controllable
v_i	$v_i = 0$	Lossless storage
	$v_i > 0$	Lossy storage
$\dot{u}_{\text{gen},i}$	$\dot{u}^{\min}_{\text{gen},i} \leq \dot{u}_{\text{gen},i} \leq \dot{u}^{\max}_{\text{gen},i}$	Ramp-rate-constr. gen.
$\dot{u}_{\text{load},i}$	$\dot{u}^{\min}_{\text{load},i} \leq \dot{u}_{\text{load},i} \leq \dot{u}^{\max}_{\text{load},i}$	Ramp-rate-constr. load

B. Property Combinations for Common Unit Types

Based on the unit properties described above, standard unit types can be defined, as presented in Table II. The unit category is followed by the set of defining power node variable constraints, as well as a unit example corresponding to each category. Note that, from a combinatorial point of view, more combinations of the constraints listed in Table I are possible. However, many of these have been eliminated because they are not meaningful from a physical or operational point of view.

IV. Simulation Example: Management of Intermittent Power In-feed

The case of managing an intermittent power in-feed to the grid is considered in order to illustrate the utilization of the Power Nodes framework together with a Model Predictive Control strategy. This simple example consists of five power nodes connected to a single grid bus:

1) A storage unit with capacity C_1 and without external process ($\xi_1 = 0$),
2) An intermittent generation unit that can be curtailed, here a wind farm ($C_2 = 0$, $\xi_2 = \xi_{\text{drv},2}(t) \geq 0$),
3) A conventional generation unit ($C_3 = 0$, ξ_3 controllable, $w_3 = 0$),
4) A thermal load with thermal energy storage capacity C_4, lossless ($v_4 = 0$), with constant demand ($\xi_4 = \xi_{\text{drv},4} = \mathit{const} < 0$),
5) A conventional load without buffer that can be curtailed if necessary ($\xi_4 = \xi_{\text{drv},5}(t) < 0$).

The power node equations are based on the affine specialization (2) of the power node equation (1). As nodes 2, 3,

TABLE II
Unit type definitions, resulting power node constraints, and real-world examples

Unit type	$u_{\text{gen},i}$, $u_{\text{load},i}$	C_i	ξ_i	w_i	Example
Buffered load w/controllable demand	$u_{\text{gen},i}=0$	$C_i>0$	$\xi_i\leq 0$	$w_i=0$	Non-time-critical thermal process
Buffered load w/non-controllable demand	$u_{\text{gen},i}=0$	$C_i>0$	$\xi_i=\xi_{\text{drv},i}(t)\leq 0$	$w_i=0$	Residential water heating
Buffered load w/curtailable demand	$u_{\text{gen},i}=0$	$C_i>0$	$\xi_i=\xi_{\text{drv},i}(t)\leq 0$	–	Res. water heating w/shedding relay
Non-buffered load w/controllable demand	$u_{\text{gen},i}=0$	$C_i=0$	$\xi_i\leq 0$	$w_i=0$	Non-time-critical production process
Non-buffered load w/non-contr. demand	$u_{\text{gen},i}=0$	$C_i=0$	$\xi_i=\xi_{\text{drv},i}(t)\leq 0$	$w_i=0$	Conventional load
Non-buffered load w/curtailable demand	$u_{\text{gen},i}=0$	$C_i=0$	$\xi_i=\xi_{\text{drv},i}(t)\leq 0$	–	Conventional load w/shedding relay
Buffered gen. w/controllable supply	$u_{\text{load},i}=0$	$C_i>0$	$\xi_i\geq 0$	$w_i=0$	Electricity-led CHP w/heat storage
Buffered gen. w/non-controllable supply	$u_{\text{load},i}=0$	$C_i>0$	$\xi_i=\xi_{\text{drv},i}(t)\geq 0$	$w_i=0$	PV/battery system
Buffered gen. w/curtailable supply	$u_{\text{load},i}=0$	$C_i>0$	$\xi_i=\xi_{\text{drv},i}(t)\geq 0$	–	PV/battery system w/shedding relay
Non-buffered gen. w/controllable supply	$u_{\text{load},i}=0$	$C_i=0$	$\xi_i\geq 0$	$w_i=0$	Fossil-fuel power plant
Non-buffered gen. w/non-contr. supply	$u_{\text{load},i}=0$	$C_i=0$	$\xi_i=\xi_{\text{drv},i}(t)\geq 0$	$w_i=0$	PV system
Non-buffered gen. w/curtailable supply	$u_{\text{load},i}=0$	$C_i=0$	$\xi_i=\xi_{\text{drv},i}(t)\geq 0$	–	PV system w/shedding relay
Storage w/o external process	–	$C_i>0$	$\xi_i=0$	$w_i=0$	Pumped hydro w/o inflow/outflow
Storage w/controllable supply	–	$C_i>0$	$\xi_i\geq 0$	$w_i=0$	Pumped hydro w/inflow control
Storage w/non-controllable supply	–	$C_i>0$	$\xi_i=\xi_{\text{drv},i}(t)\geq 0$	$w_i=0$	Pumped hydro w/stochastic inflow
Storage w/curtailable supply	–	$C_i>0$	$\xi_i=\xi_{\text{drv},i}(t)\geq 0$	–	Pumped hydro w/inflow bypass
Storage w/controllable demand	–	$C_i>0$	$\xi_i\leq 0$	$w_i=0$	Pumped hydro w/controlled irrigation
Storage w/non-controllable demand	–	$C_i>0$	$\xi_i=\xi_{\text{drv},i}(t)\leq 0$	$w_i=0$	Pumped hydro w/fresh water system
Storage w/curtailable demand	–	$C_i>0$	$\xi_i=\xi_{\text{drv},i}(t)\leq 0$	–	Pumped hydro w/blockable irrigation

and 5 contain no inherent storage, they are based on the reduced model (3). Thus, the set of power node equations for this problem is

$$
\begin{aligned}
C_1\,\dot{x}_1 &= \eta_{\text{load},1}\,u_{\text{load},1}-\eta_{\text{gen},1}^{-1}\,u_{\text{gen},1} && (10)\\
\xi_2-w_2 &= \eta_{\text{gen},2}^{-1}\,u_{\text{gen},2} && (11)\\
\xi_3 &= \eta_{\text{gen},3}^{-1}\,u_{\text{gen},3} && (12)\\
C_4\,\dot{x}_4 &= \eta_{\text{load},4}\,u_{\text{load},4}+\xi_4 && (13)\\
\xi_5-w_5 &= -\eta_{\text{load},5}\,u_{\text{load},5} \quad . && (14)
\end{aligned}
$$

All principal constraints set forth in (1) hold. The numerical values of parameters and constraints are summarized in Table III. All power quantities are expressed in MW, all energy quantities in MWh.

TABLE III
Simulation parameters

Parameter	Value	Parameter	Value
Storage capacities			
C_1	40 MWh	C_4	20 MWh
Power ratings			
$P_{\text{rated},1}$	1 MW	$P_{\text{rated},2}$	2.5 MW
$P_{\text{rated},3}$	1.5 MW	$P_{\text{rated},4}$	1 MW
$P_{\text{rated},5}$	1.5 MW		
Grid variable constraints			
$u_{\text{load},1}^{\min}$	0	$u_{\text{load},1}^{\max}$	$P_{\text{rated},1}$
$u_{\text{gen},1}^{\min}$	0	$u_{\text{gen},1}^{\max}$	$P_{\text{rated},1}$
$u_{\text{gen},2}^{\min}$	0	$u_{\text{gen},2}^{\max}$	$P_{\text{rated},2}$
$u_{\text{gen},3}^{\min}$	$0.26\cdot P_{\text{rated},3}$	$u_{\text{gen},3}^{\max}$	$P_{\text{rated},3}$
$u_{\text{load},4}^{\min}$	$0.5\cdot P_{\text{rated},4}$	$u_{\text{load},4}^{\max}$	$1.5\cdot P_{\text{rated},4}$
$u_{\text{load},5}^{\min}$	0	$u_{\text{load},5}^{\max}$	$P_{\text{rated},5}$
Efficiencies			
$\eta_{\text{load},1}$	0.8	$\eta_{\text{gen},1}$	0.9
$\eta_{\text{gen},2}$	1	$\eta_{\text{gen},3}$	0.4
$\eta_{\text{load},4}$	1	$\eta_{\text{load},5}$	1
MPC parameters			
Q	diag([0, 3])		
x_{ref}	diag([0, 0.5])		
R	diag([1, 1, 0, 20, 0, 0, 0, 0, 5000, 0, 0, 0])		
δR	diag([0, 0, 0, 0, 50, 0, 0, 0, 0, 0, 0, 0])		
N_{opt}	16		

In accordance with the unit properties established in Section III, the additional constraints on these power node equations are:

$$
\begin{aligned}
0 &= u_{\text{gen},1}\,u_{\text{load},1} && (15)\\
\xi_2 &= \xi_{\text{drv},2}(t)\geq 0 && (16)\\
\xi_4 &= \xi_{\text{drv},4}=const<0 && (17)\\
\xi_5 &= \xi_{\text{drv},5}(t)\leq 0 \quad . && (18)
\end{aligned}
$$

The power balance of the single bus system is

$$
\sum_{i=\{1,2,3\}} u_{\text{gen},i}-\sum_{i=\{1,4,5\}} u_{\text{load},i}=0 \quad . \qquad (19)
$$

The operational goal for this example is to balance storage conversion losses and thermal load setpoint deviations against wind curtailments in order to avoid unnecessary generator ramping and load shedding. A Model Predictive Control strategy is utilized for choosing optimal values for the controllable inputs of the units while maintaining the power balance in the system. This scheme respects all of the above defined constraints on power input/output, as well as on the states of charge of the storage units.

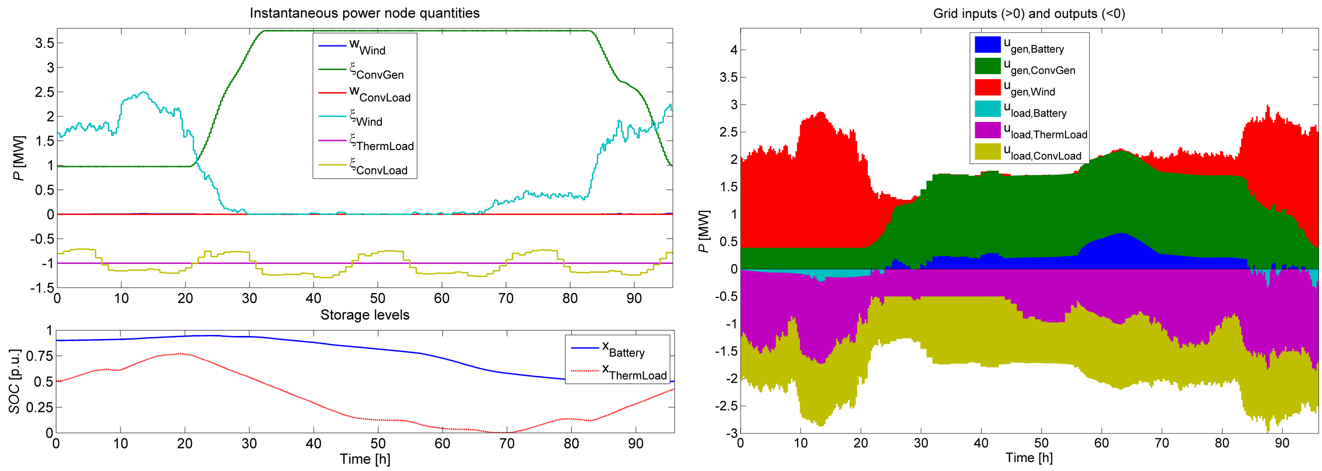
For practical implementation, vectors of decision variables are formed, which are

$$
\begin{aligned}
x &= [x_1,x_2]^{\mathrm{T}} \quad , && (20)\\
u &= [u_{\text{gen},1},u_{\text{load},1},u_{\text{gen},2},w_2,u_{\text{gen},3},\xi_3,\ldots && (21)\\
&\quad u_{\text{load},4},u_{\text{load},5},w_5,\xi_2,\xi_4,\xi_5]^{\mathrm{T}} \quad . && (22)
\end{aligned}
$$

The cost function in time step k is defined as

$$
J_k=\sum_{l=k}^{l=k+N-1}(x_l-x_{\text{ref},l})^{\mathrm{T}}\,Q\,(x_l-x_{\text{ref},l}) +u_l^{\mathrm{T}}\,R\,u_l+\delta u_l^{\mathrm{T}}\,\delta R\,\delta u_l \quad , \qquad (23)
$$

with x_{ref} being a reference value for the state variables, and the derived variable δu being the difference of the input vectors between two time steps ($\delta u_l=u_l-u_{l-1}$).



(a) Instantaneous power node quantities and storage energy levels.

(b) Grid power balance.

Fig. 3. Power node quantities, energy storage levels, and grid power balance.

TABLE IV
BALANCE TERMS FOR SIMULATION EXAMPLE

Balance term	Value [MWh]
Electricity consumed by loads	194.7968
Electricity consumed by battery	3.2907
Electricity supplied by conv. gen.	108.4607
Electricity supplied by wind turbine	72.9727
Electricity supplied by battery	16.6541
Prim. energy supplied by wind	73.1373
Prim. energy supplied by conv. gen.	271.1517
Use energy demanded by load	−196.1315
Wind energy curtailed	0.16454
Load demand not served	−0.0033

The diagonal weight matrices Q, R, and δR serve to individually penalize the optimization variables (cf. Table III). One sampling interval k has a duration of 15 min. The receding horizon N_{opt} is chosen as 16 (4 hours) with the assumption of perfect prediction. YALMIP [25] has been used for the implementation of the MPC setup.

The setup is tested for the case of an intermittent wind power in-feed, $\xi_2 = \xi_{\text{drv},2}(t)$, over a time-period of four days. Note that the wind power in-feed time series is obtained from actual measurements from a single location. Consequently, the intermittency is more significant than in the case of aggregated wind in-feeds in transmission grids covering larger areas, and one can hardly assume any reliably available wind power (capacity credit).

Fig. 3 depicts the results of the balancing simulation. The internal power node variables (instantaneous power values and energy storage levels) are shown on the left side in Fig. 3-(a), while all grid-related variables u_{gen}, u_{load} are summarized in Fig. 3-(b). It can be observed that shorter-term fluctuations are mainly balanced by actuation of the battery storage and the thermal load. Wind curtailment is small because of the relatively conservative system sizing, while load curtailment is kept at zero at (almost) all times. The weight on $\delta u_{\text{gen},3}$ causes the conventional generator to ramp up and down relatively smoothly even in the presence of steep wind ramps. Some corresponding balance terms are presented in Table IV.

Note that the used controller parameters shown in the lower section of Table III have been obtained by manual tuning in order to achieve the desired system behavior. They do not represent real monetary costs, e.g. incurred by electricity generation, generator ramping, or load curtailments. Relating the controller parameterization and the balance terms from Section II-E to an energy economics framework (e.g. in the form of unit commitment and optimal power flow) is beyond the scope of this paper and will be subject to future work.

V. CONCLUSION & OUTLOOK

In this paper, a flexible and comprehensive modeling framework for generic energy storage in power systems has been presented. The model architecture is designed such that it can integrate with existing power system analysis tools such as power flow computations. The newly introduced power nodes have been defined as a representation of units connected to electricity grids which exhibit associated storage properties and different degrees of dispatchability. The straight-forward practical applicability of the approach has been demonstrated by simulations of a small wind energy balancing example.

Further research will address the formulation of a framework to represent different control structures for flexible reconfiguration and experimentation with alternative control strategies and architectures. Also the formulation of concrete power node equations for common units in power systems, such as different types of generation units, storage technologies and clusters of thermostatically controlled loads will broaden the support for applications.

Highly interesting research opportunities include the application of the presented framework to the operation of power systems with a high penetration of a diverse portfolio of renewable energy generation units facilitated by an equally diverse portfolio of storage types. In traditional operation concepts, intermittent generation is seen predominantly as a disturbance. The presented framework is aimed at facilitating the shift from the traditional operation paradigm of controllable generation and fluctuating demand towards a more holistic operation concept that integrates intermittent generation, flexible demand and energy-constrained storage.

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Unified System-Level Modeling of Intermittent Renewable Energy Sources and Energy Storage for Power System Operation

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***Abstract*—The system-level consideration of intermittent renewable energy sources (RES) and small-scale energy storage in power systems remains a challenge as either type is incompatible with traditional operation concepts. Non-controllability and energy constraints are still considered contingent cases in market-based operation. The design of operation strategies for up to 100% RES power systems requires an explicit consideration of non-dispatchable generation and storage capacities, as well as the evaluation of operational performance in terms of energy efficiency, reliability, environmental impact, and cost. By abstracting from technology-dependent and physical unit properties, the Power Nodes modeling framework presented here allows the representation of a technologically diverse unit portfolio with a unified approach, while establishing the feasibility of energy-storage consideration in power system operation. After introducing the modeling approach, a case study is presented for illustration.**

***Index Terms*—Power Nodes, Energy Storage, Dispatch, Balancing, Active Power Control, Curtailment, Load Management, Intermittent Generation, RES**

I. Introduction

ELECTRICITY generated from renewable energy sources (RES) is often not dispatchable and the forecast of its production over time is bound to uncertainty. Today, electricity generated by wind power contributes up to around 20% of the electricity demand in some countries, meaning that wind power production at times exceeds local power demand. Solar photovoltaic (PV) installed capacity exceeded 17 GW in Germany in 2010. Considering the ongoing large-scale deployment of intermittent RES [1] as well as energy policy scenarios and government plans for up to 100% RES supply [2], [3], the consideration of system operation and economic frameworks that are oriented towards the nature of intermittent RES and energy storage become increasingly relevant.

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We further thank Philip Jonas for the strong commitment to his master's thesis, which was related to this work.

Power systems require a continuous balance between energy supply and demand. To achieve this balance, anticipated energy demand is procured in power markets based on forecasts, while the continuous power balance is maintained by an arrangement of automatic control schemes, supervised by human operators [4]. Experiences with increasing levels of fluctuating RES in-feed give a taste of the challenges power systems will face in the future [5]. What these challenges will be exactly and how they can be addressed is the topic of on-going research.

Energy storage units have long been considered as a means for improved integration of fluctuating RES. Studies have shown potential benefits of energy storage for variability and prediction accuracy improvement, each with respect to a specific operational context, such as market integration, ancillary services and power system reliability [6]–[9]. As shown in [9], the specific control law or operation objective makes a significant difference to the specific benefits energy storage may provide. The combined value of energy storage in power systems under mixed operating modes is better understood if a complete operation scenario is considered. Software tools support scenario design, varying in scope, temporal and spatial resolution [10]. Scenario tools combine central decision variables with existing data as input, to produce an output enabling scenario evaluation. Evaluation criteria typically include operation costs, total energy (produced, consumed, wasted, shedded, etc.), and CO_2-emissions, which are all important for investment or energy policy decisions.

The well-known Energy Hub concept [11] focuses on multi-carrier energy networks. It allows the study of synergies that the combination of electricity, natural gas, and network infrastructures may provide for energy dispatch [12], infrastructure reliability [13], and investment decisions under uncertainty [14]. Energy storage is one element of the concept, but is not necessarily considered. This powerful representation has a complexity that limits studies with energy hubs to defining a common level of detail (granularity) for all considered energy systems. Like the Energy Hub, the Power Nodes framework has been developed for the study of future (hypothetical) energy scenarios and is aimed specifically at the analysis of future *power system operation*, which requires a muli-stage simulation environment [15]. Prior studies evaluating power system operation with increased RES and energy storage, e.g. [16], utilized multi-stage simulation environments which were founded on existing tools and operation concepts. For future power systems, however, operation and control principles and market structure are subject to re-design. A structured simulation environment can provide the context necessary for experimental development and systematic assessment of new operation strategies. The purpose of the present work is to provide a generic framework that invites experimentation, to overcome conceptual limitations built into contemporary system operation simulators. The Power Nodes framework facilitates the consideration of energy storage, fluctuating generation and other types of non-conventional energy resources by providing a conceptual model for energy storage as well as for different levels of controllability over power system units [17]. Based on the Power Nodes extension of classical grid models, we introduce a model decomposition for operation functions in different planning stages and operation time-scales.

A. Power System Dispatch and Operation Planning

Traditionally, the dominant part of dispatchable power generation is based on energy stored in combustible fossil fuels. Dispatchable generation is scheduled in anticipation of demand. In this context, (spot) market prices are mainly driven by marginal generation cost [18].

In case of constraints on the producible electric energy, e.g. due to a limited reservoir size in hydro power plants, operation decisions are driven by opportunity costs due to expected future prices and available storage levels [19]. Thus, energy constraints – inherent to all kinds of energy storage – induce a different dispatch logic. For fluctuating RES, available energy has to be absorbed into the grid or curtailed for every time instant. As the energy itself is free, costs to be recovered are predominantly investment costs into RES conversion apparatus, limited in capacity and lifetime. All available energy will thus be offered to the market[1]. Aiming at recovery of investment cost, non-dispatchable RES therefore tend to be price-takers. Planning is fundamental to power system operation, but there is an unavoidable discrepancy between planned and actual operating conditions. With increasing intermittent RES in-feed, both prediction errors and continuous variations will increase and need to be dealt with using adequate control reserve scheduling.

B. Controllability of Intermittent RES

Fluctuating power in-feed from wind turbines and PV arrays is predictable to a certain extent [8]. Nowadays, information on the forecasted future power in-feed is included in the power plant day-ahead dispatch in areas with significant RES penetration. Forecast errors are balanced via intra-day power trading and conventional control reserves, not by the intermittent generators themselves. Curtailment of intermittent power in-feed is typically only employed as an abnormal measure. The utilization of online control measures for intermittent generation units, such as partial generation curtailment [20], [21], has been included in the grid code of countries with significant wind power penetration. This kind of controllability, however, remains limited by the availability of the primary energy carrier, e.g. the wind force. The challenge of systematically integrating such methods into power system operation and control constitutes another motivation for the present work.

[1]Current regulatory schemes often prioritize RES in energy markets, which may induce negative prices in extreme situations, e.g. inflexible power system operation conditions, as reported in e.g. [5].

C. Controllable Energy Storage for Power Systems

All forms of energy storage entail energy conversion processes. In addition to reversible energy storage in the form of pumped hydro, batteries, flywheels etc., a very important form is heat storage. Methods to increase the controllability of loads with inherent storage are emerging, such as control strategies for household appliances with thermal inertia and for prospectively large numbers of electric vehicles connected to the grid [22], [23]. Ubiquitous controllable energy storage is likely to have positive effects on system operation, ranging from security-relevant power reserves to loss reduction on the distribution system level [24]–[26]. Flexibility is valuable [6]. However, current grid operation frameworks do not directly support the specific properties of energy storage. For instance, only power reserves are considered by system operators, whereas the energy required for control actions is not visible to the operator and is settled in post-operation. Due to storage dynamics and associated inter-temporal dependencies, energy and ramp-rate constraints, as well as other controllability limitations are particularly relevant for dispatch problems. Here, the methodology of Model Predictive Control (MPC) is especially suitable [27]–[29].

D. Novel Control Structures

The additional degrees of freedom that energy storage and increased controllability over RES in-feed and loads provide, can only be utilized if a suitable control architecture is established. Several novel control structures, often utilizing aggregation principles, have been proposed in this context, including: Virtual Power Plants [30], Cells [31], or MicroGrids [32]. Comprehensive performance assessment of different operation and control approaches constitutes a challenge in itself [33].

The remainder of this article is structured as follows: The Power Nodes framework is introduced in Section II, then Section III develops a multi-stage formulation of the Power Node equations. Section IV outlines a multi-stage environment for simulation and assessment of planning and real-time operation based on the Power Nodes concepts. The concept is illustrated by a case-study in Section V, followed by conclusions in Section VI.

II. The Power Nodes Framework

The basic premise of the Power Nodes approach is that any power source or sink connected to the electric power system requires the conversion of some form of energy into electric power, or vice versa. These forms may be termed “supply-” or “use-forms” of energy, respectively.

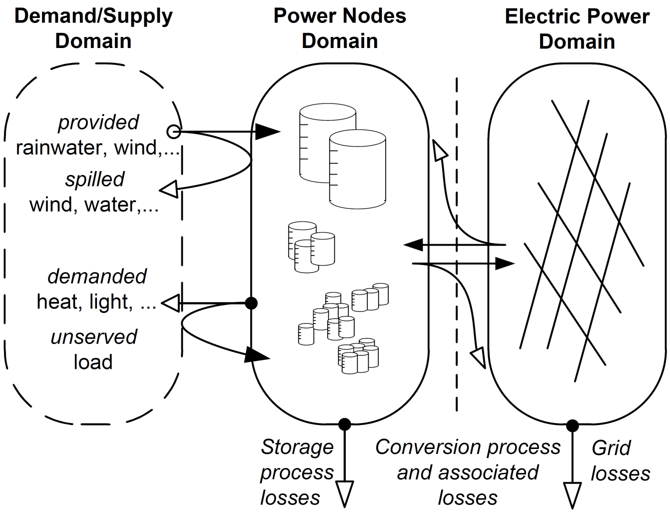

Fig. 1. Illustration of the three-domains concept. The Power Node- and Grid domains are model-internal domains, both are considered integral parts of the electric energy system. The domain of Demand/Supply processes is considered external, indicated by the dashed frame. Arrows indicate energy (or power) flows that are accounted for. Empty arrowheads indicate energy that is exchanged with the environment, while black arrowheads indicate energy flows into or across the modeled domains.

The degrees of freedom available for fulfilling the power balance in the electric grid arise from the freedom that the supply- and use-forms of energy provide, either by being controllable or by offering inherent storage capacity.

Abstracting from the physical properties and the internal composition of a supply- or use-process including the associated energy conversion processes, we represent it from a grid-perspective as a single lumped unit with characteristic parameters, a "power node".

A. Domain Models

The introduction of a generic energy storage perspective adds a modeling layer to the classical modeling of power systems, illustrated in Fig. 1. In the resulting enhanced model, the electro-mechanical domain of the electric grid is interfaced with the pre-grid Power Node domain, which represents conversion processes and an associated energy storage functionality. A third, external, domain accounts for the demand/supply processes consuming energy from and feeding energy into the Power Node domain. As shown in Fig. 1, these processes may be thought of as externally driven, e.g. intermittent renewable energy supply, or fully controllable, e.g. fuel supply for dispatchable generators.

For ensuring model consistency, it is important to define unambiguous domain interfaces. Generally, these are exchanges of energy, or power, in continuous time. For instance, the exchange between the Power Node domain and the Grid domain is defined as the active power fed into or consumed from the grid. In the case of a dynamical grid model, the inertia of synchronous machines is part of the Grid domain, and thus the active power interface is equivalent to the mechanical power exerted by the prime mover of a synchronous generator. Grid losses are modeled inside the electro-mechanical Grid domain, while pre-grid losses, such as storage and conversion losses, are accounted for in the Power Nodes domain. This clear separation allows the Power Nodes framework to integrate with a number of different physical network representations common in power systems modeling (cf. Section II-C).

All supply and demand processes are connected via a power node to the electricity grid. Consequently, the total energy provided to or demanded from the grid may differ from the actual energy served or utilized by external processes. All considered modes of energy flow are illustrated by arrows in Fig. 1 and Fig. 2. This – mathematically redundant – choice of flow modes establishes a formalized interpretation (cf. Section II-D) of real-world effects that cause supplied energy to be lost, or demanded energy to remain unserved. For example, energy conversion implies conversion losses, power in-feed from wind turbines may be curtailed, and a load may get disconnected from the grid. In order to evaluate the overall system performance, it is necessary to keep track of these losses and to account for the energy value associated with them. For this purpose, balance terms as presented in Section II-E can be utilized.

B. Model of a Single Power Node

Consider the structure of a single power node consisting of the elements illustrated in Fig. 2. In comparison with Fig. 1, the provided and demanded energies are lumped into an external process termed ξ, with $\xi < 0$ denoting use and $\xi > 0$ supply. The term $u_{\text{gen}} \geq 0$ describes a conversion corresponding to a power generation with efficiency η_{gen}, while $u_{\text{load}} \geq 0$ describes a conversion corresponding to a consumption with efficiency η_{load}.

The energy storage level is normalized to $0 \leq x \leq 1$ with energy storage capacity $C \geq 0$. Fig. 2 illustrates how the storage serves as a buffer between the external process ξ and the two grid-related exchanges u_{gen} and u_{load}. Internal energy losses associated with energy storage, e.g. physical, state-dependent losses, are modeled by the term $v \geq 0$, while enforced energy losses, e.g. curtailment/shedding of a supply/demand process, are denoted by the waste term w, where $w > 0$ denotes a loss of provided energy and $w < 0$ an unserved demand process. This labeling for the power node equation provides a generic embedding of energy conversion and storage processes.

1) Generic Model: The dynamics of an arbitrary power node $i \in \mathcal{N} = \{1, \dots, N\}$, which may exhibit nonlinear effects in the general case, are described as:

$$
\begin{aligned}
C_i \, \dot{x}_i \quad &= \quad \eta_{\text{load},i} \, u_{\text{load},i} - \eta_{\text{gen},i}^{-1} \, u_{\text{gen},i} + \xi_i - w_i - v_i, \qquad (1)\\
\text{s.t.} \quad &\text{(a)} \quad 0 \leq x_i \leq 1 \quad ,\\
&\text{(b)} \quad 0 \leq u_{\text{gen},i}^{\min} \leq u_{\text{gen},i} \leq u_{\text{gen},i}^{\max} \quad ,\\
&\text{(c)} \quad 0 \leq u_{\text{load},i}^{\min} \leq u_{\text{load},i} \leq u_{\text{load},i}^{\max} \quad ,\\
&\text{(d)} \quad 0 \leq \xi_i \cdot w_i \quad ,\\
&\text{(e)} \quad 0 \leq |\xi_i| - |w_i| \quad ,\\
&\text{(f)} \quad 0 \leq v_i \quad \forall \, i = 1, \dots, N \quad .
\end{aligned}
$$

Depending on the specific process represented by a power node and the investigated application, each term in the

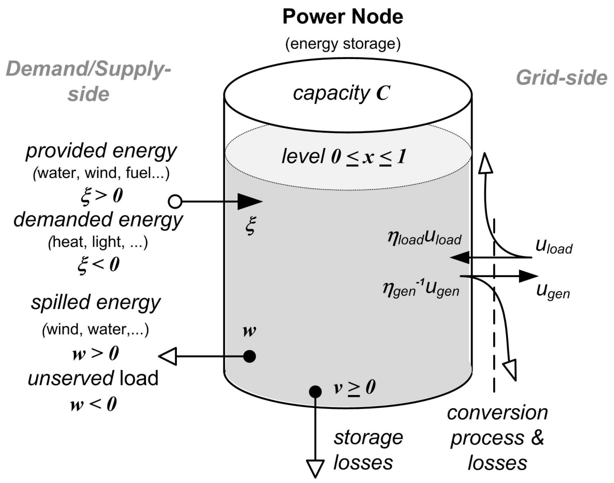

Fig. 2. Notation for a single power node.

power node equation may in general be controllable or not, observable or not, and driven by an external process or not. Internal dependencies, such as a state-dependent physical loss term $v_i(x_i)$, are feasible. Charge/discharge efficiencies may be non-constant, e.g. state-dependent: $\eta_{\mathrm{load},i} = \eta_{\mathrm{load},i}(x_i)$, $\eta_{\mathrm{gen},i} = \eta_{\mathrm{gen},i}(x_i)$.

The constraints (a) – (f) denote a generic set of requirements on the variables. They are to express that (a) the state of charge is normalized, (b, c) the grid variables are non-negative and bounded, (d) the supply/demand and the curtailment need to have the same sign, (e) the supply/demand curtailment cannot exceed the supply/demand itself, and (f) the storage losses are non-negative. Ramp-rate constraints, especially constraints on the derivatives $\dot{u}_{\mathrm{gen},i}$ and $\dot{u}_{\mathrm{load},i}$, can be included for power system studies under dynamic operating conditions (cf. Table I). Apart from the listed constraints, there may be additional ones imposed on the variables, e.g. in order to define certain standard unit types with characteristic properties (cf. Section II-D). The explicit mathematical form of a power node equation depends on the particular modeling case. Most importantly, the notation provides technology-independent categories that can be linked to the evaluation functions given in Section II-E.

2) Modeling Power Nodes without Storage: Power nodes can also represent processes independent of energy storage, such as fluctuating RES generation or conventional generation and load. A process without storage implies an algebraic coupling between the instantaneous quantities ξ_i, w_i, $u_{\mathrm{gen},i}$, and $u_{\mathrm{load},i}$; storage-dependent loss does not exist ($v_i = 0$). Equation (1) degenerates to

$$\xi_i - w_i = \eta_{\mathrm{gen},i}^{-1} \, u_{\mathrm{gen},i} - \eta_{\mathrm{load},i} \, u_{\mathrm{load},i} \quad , \tag{2}$$

which holds for both externally driven processes and controllable power generation. The waste term w_i is particularly relevant for external supply and demand processes which are not directly controllable, while there is the option to curtail them. Examples are intermittent power generation ($\xi_{\mathrm{drv},i}(t) \geq 0$) and classical load ($\xi_{\mathrm{drv},i}(t) \leq 0$). For a fully controllable supply process such as a conventional generator, either the grid-related variables $u_{\mathrm{gen},i}$, $u_{\mathrm{load},i}$, or the power exchange with the environment through ξ_i can be considered controlled variables. ξ_i then accounts for example for primary energy usage.

3) Model-Specialization to Affine Model: Specializations and simplifications of the generic model are relevant for practical tasks such as controller design and implementation. Here we present the example of a simplified affine model which is suitable for describing a wide range of processes with state-dependent losses, such as heat storages that lose energy to the environment due to a difference between internal storage temperature and ambient temperature. For this purpose, a linear dependence of v_i on the storage state x_i is assumed, while the efficiencies η are assumed constant in order to eliminate non-linearities:

$$\begin{aligned} C_i \, \dot{x}_i \quad &= \quad \eta_{\mathrm{load},i} \, u_{\mathrm{load},i} - \eta_{\mathrm{gen},i}^{-1} \, u_{\mathrm{gen},i} + \xi_i - w_i \\ &\quad\; - a_i \, (x_i - x_{\mathrm{ss},i}) \qquad , \end{aligned} \tag{3}$$

subject to the same constraints as (1). The steady-state storage level $x_{\mathrm{ss},i}$ refers to the steady-state of the differential equation in the absence of inputs, e.g. the thermal equilibrium of a thermal storage with the ambiance, and a_i is a non-negative loss coefficient.

C. Mapping from Power Nodes to Grid Domain

Consider a grid composed of M busses denoted by $m, n \in \mathcal{M} = \{1, \ldots, M\}$ and a set of N power nodes $i \in \mathcal{N} = \{1, \ldots, N\}$, representing a number of single or aggregated units. A mapping can be formulated by index sets $\mathcal{N} \to \mathcal{M}$. The power node indices are divided into sets $\mathcal{N}_m \subseteq \mathcal{N}$ associated with one bus each; having the properties: $\mathcal{N}_m \cap \mathcal{N}_n = \emptyset$ for $m \neq n$, and $\bigcup_{m \in \mathcal{M}} \mathcal{N}_m = \mathcal{N}$.

The net power injection to a grid node $m \in \mathcal{M}$ is thus:

$$P_{\mathrm{netinj},m} = \sum_{i \in \mathcal{N}_m} u_{\mathrm{gen},i} - \sum_{i \in \mathcal{N}_m} u_{\mathrm{load},i} \quad . \tag{4}$$

The Power Systems literature offers many options for power system modeling, depending on the relevant study questions. In principle, the Power Nodes domain can be interfaced with many grid model types, such as DC or AC power flow, static or dynamic grid models, due to the clear separation from the electro-mechanical domain.

D. Characterization of Unit Properties

There is only a limited number of practical unit types. As discussed in Section II-A, the kinds of energy flows available in the generic power node model allow for a wide range of unit types. A given practical unit type is thus classified by its characteristic subset of the possible modes of energy flows. A “unit” in the power nodes framework is an arbitrary generation, load, or storage device, or a group of devices aggregated to behave as one unit. The type distinction is established via a set of constraints on the variables (energy-flow concepts) used in (1), i.e. $u_{\mathrm{load},i}$, $u_{\mathrm{gen},i}$, C_i, x_i, ξ_i, v_i, and w_i. These constraints hold in addition to the principal constraints (a) – (f) in (1), thus providing a classification of units with different properties.

TABLE I
UNIT PROPERTIES DEFINED BY POWER NODE EQUATION CONSTRAINTS

Variable(s)	Constraint(s)	Implication
$u_{\mathrm{gen},i}$,	$u_{\mathrm{gen},i} = 0$	Load
$u_{\mathrm{load},i}$	$u_{\mathrm{load},i} = 0$	Generator
	$u_{\mathrm{gen},i} \cdot u_{\mathrm{load},i} = 0$	One-conv.-unit storage
	–	Two-conv.-unit storage
C_i	$C_i = 0$	Non-buffered unit
	$C_i > 0$	Buffered unit
ξ_i	$\xi_i = 0$	No external process
	$\xi_i \geq 0$	Supply process
	$\xi_i \leq 0$	Demand process
ξ_i, w_i	$\xi_i = \xi_{\mathrm{drv},i}(t) \wedge w_i = 0$	Non-controllable
	$\xi_i = \xi_{\mathrm{drv},i}(t)$	Curtailable
	ξ_i arbitrary, $w_i = 0$	Controllable
v_i	$v_i = 0$	Lossless storage
	$v_i > 0$	Lossy storage
$\dot{u}_{\mathrm{gen},i}$	$\dot{u}^{\min}_{\mathrm{gen},i} \leq \dot{u}_{\mathrm{gen},i} \leq \dot{u}^{\max}_{\mathrm{gen},i}$	Ramp-rate-constr. gen.
$\dot{u}_{\mathrm{load},i}$	$\dot{u}^{\min}_{\mathrm{load},i} \leq \dot{u}_{\mathrm{load},i} \leq \dot{u}^{\max}_{\mathrm{load},i}$	Ramp-rate-constr. load

Table I establishes a set of basic properties defining the operational behavior of a unit modeled as a power node. The interpretation of constraints is given in the following:

- $\boldsymbol{u}_{\mathrm{load/gen},i}$: a pure generation process implies that $u_{\mathrm{load},i} = 0$ at all times; a pure load cannot inject power, expressed by $u_{\mathrm{gen},i} = 0$. In a bi-directional conversion system, both variables can assume non-zero values; both conversions can happen at the same time (e.g. pumped hydro with independent turbine and pump), or not (e.g. inverter-connected battery).
- $\boldsymbol{C}_i$: unit is modeled with ($C_i > 0$) or without energy storage capabilities ($C_i = 0$).
- $\boldsymbol{\xi}_i$: supply ($\xi_i > 0$) or demand ($\xi_i < 0$) processes. For pure electricity storage (battery), $\xi_i = 0$ holds.
- $\boldsymbol{\xi}_i, \boldsymbol{w}_i$: controllability of power exchange via an external process. If ξ_i is driven by an external signal $\xi_i = \xi_{\mathrm{drv},i}(t)$, e.g. induced by intermittent supply, it may either be curtailable (no further constraint on w_i) or non-controllable (no curtailment possible: $w_i = 0$). If ξ_i is not externally driven, the unit is controllable.
- $\boldsymbol{v}_i$: lossless if $v_i = 0$; lossy otherwise.
- $\dot{\boldsymbol{u}}_{\mathrm{load/gen},i}$: additional rate-constraints may be applied to the grid variables, to model physical limitations on the rate of change of a power conversion process.

Based on these properties, all unit types relevant for establishing the energy-balance in a power system can be classified and modeled inside the Power Nodes framework. A classification of unit types is included in [17]. Additional constraints may be considered for specific applications.

E. Performance Evaluation via System-Level Balances

The embedding of all energy units in the Power Nodes notation provides an energy-accounting framework. The performance of operation and control strategies can be evaluated on the basis of this framework: in form of *instantaneous quantities*, characterizing the current operational state of the system; or as *time-integrals*, serving to evaluate the system performance over a certain time span.

Examples for power balance terms indicating the current system state include:

- Power supplied to grid: $P^{\mathrm{grid}}_{\mathrm{gen}}(t) = \sum_{i \in \mathcal{N}} u_{\mathrm{gen},i}(t)$,
- Power consumed from grid: $P^{\mathrm{grid}}_{\mathrm{load}}(t) = \sum_{i \in \mathcal{N}} u_{\mathrm{load},i}(t)$,
- Currently stored energy: $E_{\mathrm{stored}}(t) = \sum_{i \in \mathcal{N}} C_i x_i(t)$,
- Power supply curtailed: $w^+(t) = \sum_{i \in \{i \mid w_i > 0\} \subset \mathcal{N}} w_i$,
- Power demand not served: $w^-(t) = \sum_{i \in \{i \mid w_i < 0\} \subset \mathcal{N}} w_i$,
- Power conversion loss: $P_{\mathrm{loss}}(t) = \sum_{i \in \mathcal{N}} \left(\frac{1 - \eta_{\mathrm{gen},i}(t)}{\eta_{\mathrm{gen},i}(t)} u_{\mathrm{gen},i}(t) + (1 - \eta_{\mathrm{load},i}(t))\, u_{\mathrm{load},i}(t) \right)$.

All of the above quantities can be restricted to certain unit types by placing restrictions on the index i. For example, the consideration of all non-controllable non-buffered generation units would require a summation over the index $i \in \{i \mid C_i = 0 \wedge \xi_i = \xi_{\mathrm{drv},i}(t) \geq 0 \wedge w_i = 0\} \subset \mathcal{N}$.

Energy balance terms can be derived by integration over power balance terms in the time interval $[t_1, t_2]$, such as

- Electric energy supplied to grid: $\int_{t_1}^{t_2} P^{\mathrm{grid}}_{\mathrm{gen}}(t)\, dt$,
- Primary energy supplied: $\int_{t_1}^{t_2} \xi^{\mathrm{total}}_{\mathrm{supply}}(t)\, dt$,
- Primary energy curtailed: $\int_{t_1}^{t_2} w^+(t)\, dt$,
- Energy conversion losses: $\int_{t_1}^{t_2} P_{\mathrm{loss}}(t)\, dt$.

The calculated power and energy quantities can be combined with time-specific cost, or energy- and fuel-specific emissions information, characterizing the scenario in this important larger context.

III. DECOMPOSITION OF POWER NODE EQUATIONS FOR MULTI-STAGE OPERATION

This section presents a decomposition of the affine power node equation (Section II-B3) for consideration of the contributions of different planning and operation stages: day-ahead planning, intra-day re-scheduling and real-time operation. Unit commitment and long-term planning issues are not addressed here. Given a representation of units as power nodes, the following three stages are considered:

1) *Day-ahead dispatch*: an operating point schedule for the controllable variables; established once a day, on the basis of operation cost and predictions for uncertain variables.
2) *Intra-day rescheduling*: alteration of the operating point schedule; several updates a day.
3) *Real-time operation*: realization of continuous system behavior; formulated as relative changes to the operating point schedules determined in previous stages.

The degrees of freedom related to each of the decision and control problems shall be modeled separately. The actual power node model variables are therefore decomposed into three fractions, consisting of scheduled values (sch), schedule updates as deviations from the scheduled values (upd), thus formulating the real-time (rt) behavior as a deviation from the planned baseline:

$$\aleph = \aleph^{\mathrm{sch}} + \Delta\aleph^{\mathrm{upd}} + \Delta\aleph^{\mathrm{rt}} \quad , \tag{5}$$

with $\aleph = \{u_{\mathrm{gen}}, u_{\mathrm{load}}, \xi, w\}$ as the actual power node variables. Physical storage loss (v) is dealt with separately.

A. Decomposition of Power Node Equation

The decomposition of the power node equation and constraints is based on the analogous decomposition of the storage state variable:

$$x = x^{\mathrm{sch}} + \Delta x^{\mathrm{upd}} + \Delta x^{\mathrm{rt}} \quad \text{and} \tag{6}$$

$$\dot{x} = \dot{x}^{\mathrm{sch}} + \Delta \dot{x}^{\mathrm{upd}} + \Delta \dot{x}^{\mathrm{rt}} \quad . \tag{7}$$

The goal is to formulate separate power node dynamics for each of the fractions, such that in superposition they constitute the original power node equation. As condition for superposition, the differential equation has to be linear. This decomposition is thus not applicable for the general case (1), but it can be shown to hold for the affine case (3). If a coordinate translation $\hat{x} = x - x_{\mathrm{ss}}$ is applied to the affine model (3), the result is:

$$C_i\,\dot{\hat{x}}_i = \eta_{\mathrm{load},i}\,u_{\mathrm{load},i} - \eta_{\mathrm{gen},i}^{-1}\,u_{\mathrm{gen},i} + \xi_i - w_i - a_i\,\hat{x}_i \quad . \tag{8}$$

The power node equation is linear in $\hat{\square}$-coordinates, enabling the application of the superposition principle. For the decomposition of $\hat{x}$, the offset x_{ss} can be associated with any of the fractions of x in (6). We choose $\hat{x}^{\mathrm{sch}} = x^{\mathrm{sch}} - x_{\mathrm{ss}}$, and consequently $\Delta\hat{x}^{\mathrm{upd}} = \Delta x^{\mathrm{upd}}$ and $\Delta\hat{x}^{\mathrm{rt}} = \Delta x^{\mathrm{rt}}$. The original coordinates can thus be employed to denote the three related power node formulations:

1) Power node equation for the scheduling problem:

$$\begin{aligned} C_i\,\dot{x}_i^{\mathrm{sch}} = {} & \eta_{\mathrm{load},i}\,u_{\mathrm{load},i}^{\mathrm{sch}} - \eta_{\mathrm{gen},i}^{-1}\,u_{\mathrm{gen},i}^{\mathrm{sch}} \\ & + \xi_i^{\mathrm{sch}} - w_i^{\mathrm{sch}} - a_i\,(x_i^{\mathrm{sch}} - x_{\mathrm{ss},i}) \quad , \end{aligned} \tag{9}$$

2) Schedule update equation, formulated as a deviation:

$$\begin{aligned} C_i\,\Delta\dot{x}_i^{\mathrm{upd}} = {} & \eta_{\mathrm{load},i}\,\Delta u_{\mathrm{load},i}^{\mathrm{upd}} - \eta_{\mathrm{gen},i}^{-1}\,\Delta u_{\mathrm{gen},i}^{\mathrm{upd}} \\ & + \Delta\xi_i^{\mathrm{upd}} - \Delta w_i^{\mathrm{upd}} - a_i\,\Delta x_i^{\mathrm{upd}} \quad . \end{aligned} \tag{10}$$

3) Real-time balancing and control (power node) dynamics, formulated as the difference between realization and schedule: $\Delta\aleph^{\mathrm{rt}} = \aleph(t) - (\aleph^{\mathrm{sch}} + \Delta\aleph^{\mathrm{upd}})$:

$$\begin{aligned} C_i\,\Delta\dot{x}_i^{\mathrm{rt}} = {} & \eta_{\mathrm{load},i}\,\Delta u_{\mathrm{load},i}^{\mathrm{rt}} - \eta_{\mathrm{gen},i}^{-1}\,\Delta u_{\mathrm{gen},i}^{\mathrm{rt}} \\ & + \Delta\xi_i^{\mathrm{rt}} - \Delta w_i^{\mathrm{rt}} - a_i\,\Delta x_i^{\mathrm{rt}} \quad . \end{aligned} \tag{11}$$

The continuous power balance in the grid is established by an arrangement of reactive control structures and operator interventions. Real-time imbalances are caused by continuous variation of load and intermittent generation, forecast errors, and unplanned outages of conventional generation, but also by uncoordinated ramping between scheduled operating points. For a given operation strategy, the $\Delta\aleph^{\mathrm{rt}}$-formulation may provide feedback about the quality of schedules established by the planning stages [15].

TABLE II

Directionality of control reserve provision

	Positive Reserve	Negative Reserve
Generation	$\Delta u_{\mathrm{gen},i}^{\mathrm{rt}} \nearrow \Rightarrow \Delta x_i^{\mathrm{rt}} \searrow$	$\Delta u_{\mathrm{gen},i}^{\mathrm{rt}} \searrow \Rightarrow \Delta x_i^{\mathrm{rt}} \nearrow$
Load	$\Delta u_{\mathrm{load},i}^{\mathrm{rt}} \searrow \Rightarrow \Delta x_i^{\mathrm{rt}} \searrow$	$\Delta u_{\mathrm{load},i}^{\mathrm{rt}} \nearrow \Rightarrow \Delta x_i^{\mathrm{rt}} \nearrow$

B. Constraints Coordination and Reserve Allocation

The power node constraints (1) (a) – (f) have been formulated as 'physical' limitations of the unit operation ranges. The multi-stage formulation requires a coordination of constraints between the stages that is compliant with those original power node constraints. For the real-time control of power systems, e.g. for Load Frequency Control provision, power capacity is reserved for activation when imbalances occur[2]:

$$-\Delta u_{\mathrm{gen}}^{\mathrm{rt,neg}} \le \Delta u_{\mathrm{gen}}^{\mathrm{rt}} \le \Delta u_{\mathrm{gen}}^{\mathrm{rt,pos}} \quad , \tag{12}$$

$$-\Delta u_{\mathrm{load}}^{\mathrm{rt,pos}} \le \Delta u_{\mathrm{load}}^{\mathrm{rt}} \le \Delta u_{\mathrm{load}}^{\mathrm{rt,neg}} \quad , \tag{13}$$

where (rt,pos) and (rt,neg) indicate constraints associated with the provision of positive/negative control reserves.

Nowadays it is not common in power system operation to deliver control reserves through units with energy constraints relevant on the time-scale of the reserve provision. Pumped hydro power plants, which are naturally energy-constrained by their water reservoir, usually have sufficient storage capacity to securely deliver the contracted control reserves without risk of depletion or overflow of their storage. This is different in the case of reserve provision by controllable thermal loads, small-scale combined-heat-and-power (CHP) units, or plug-in hybrid electric vehicles (PHEVs), which have a significantly smaller capacity to store energy in proportion to their power capacity. Here, it may be necessary to also reserve a storage control band:

$$-\Delta x^{\mathrm{rt,pos}} \le \Delta x^{\mathrm{rt}} \le \Delta x^{\mathrm{rt,neg}} \quad . \tag{14}$$

The nomenclature of $\Delta x^{\mathrm{rt,pos}}$ for the lower and $\Delta x^{\mathrm{rt,neg}}$ for the upper bound is due to positive and negative reserves being formulated from a grid perspective, whereas x is from a power node perspective. The implications of reserve provision by energy-constrained generation and load units are summarized in Table II.

Control reserves are security-critical and are typically procured with considerable lead-time. This requirement of availability calls for the reservation of a control band to be taken into account in the day-ahead-*scheduling* stage of the power node operation:

$$\Delta x^{\mathrm{rt,pos}} \le x^{\mathrm{sch}} \le 1 - \Delta x^{\mathrm{rt,neg}} \quad ,$$

$$0 \le u_{\mathrm{gen}}^{\mathrm{min}} + \Delta u_{\mathrm{gen}}^{\mathrm{rt,neg}} \le u_{\mathrm{gen}}^{\mathrm{sch}} \le u_{\mathrm{gen}}^{\mathrm{max}} - \Delta u_{\mathrm{gen}}^{\mathrm{rt,pos}} \quad ,$$

$$0 \le u_{\mathrm{load}}^{\mathrm{min}} + \Delta u_{\mathrm{load}}^{\mathrm{rt,pos}} \le u_{\mathrm{load}}^{\mathrm{sch}} \le u_{\mathrm{load}}^{\mathrm{max}} - \Delta u_{\mathrm{load}}^{\mathrm{rt,neg}} \quad .$$

For the schedule-*update*, the above absolute constraints are then formulated relative to the pre-planned trajectory:

$$\Delta x^{\mathrm{rt,pos}} - x^{\mathrm{sch}} \le \Delta x^{\mathrm{upd}} \le 1 - \Delta x^{\mathrm{rt,neg}} - x^{\mathrm{sch}} \quad ,$$

$$u_{\mathrm{gen}}^{\mathrm{min}} + u_{\mathrm{gen}}^{\mathrm{rt,neg}} - u_{\mathrm{gen}}^{\mathrm{sch}} \le \Delta u_{\mathrm{gen}}^{\mathrm{upd}} \le u_{\mathrm{gen}}^{\mathrm{max}} - u_{\mathrm{gen}}^{\mathrm{rt,pos}} - u_{\mathrm{gen}}^{\mathrm{sch}} \quad ,$$

$$u_{\mathrm{load}}^{\mathrm{min}} + u_{\mathrm{load}}^{\mathrm{rt,pos}} - u_{\mathrm{load}}^{\mathrm{sch}} \le \Delta u_{\mathrm{load}}^{\mathrm{upd}} \le u_{\mathrm{load}}^{\mathrm{max}} - u_{\mathrm{load}}^{\mathrm{rt,neg}} - u_{\mathrm{load}}^{\mathrm{sch}} \quad .$$

[2]In the following, the sub-index i is dropped for compact notation.

The constraints ensure that trajectories scheduled in one stage do not influence the feasibility of trajectories formulated in another stage with respect to the original power node constraints. All other constraints of (1) (d) – (f) can be transformed accordingly. Note that the nonlinear constraint (d) can be easily recasted as a linear constraint, as $\xi(t) \neq 0 \ \forall t$ for most processes. Additional ramping-constraints can be formulated entirely analogously.

IV. Dispatch and Real-time Simulation Environment

Planning activities are aimed at establishing the best possible use of available resources. This objective can be formulated as minimizing the cost of system operation, while maintaining power system security constraints. In real-time operation, these schedules define the baseline of expectations for the actual events. Here the primary objective is to maintain a secure operating state in spite of unexpected variations and events – optimality becomes a secondary objective. Today, the schedules for operation planning are usually an outcome of market operations, facilitating the coordination of multiple actors. In the perspective of a system operator, an economic dispatch approximates the outcome of market operations [34].

A perfect dispatch would require perfect information about the actual operating conditions, which is not available in advance. In particular, uncertainty in the prediction of load or wind power induces a mismatch between scheduled and actual energy turnover. In analogy to the multi-stage formulation of the power node equation, the simulation environment is composed of three stages:

1) *Day-ahead dispatch*: daily multi-period optimization for a complete day, with optimization horizon of several days; generates the baseline operating point schedule for the controllable variables and storage states, utilizing predictions of the uncertain variables with a time-lag of half a day; the optimization result can be interpreted to reflect a market outcome.
2) *Intra-day rescheduling*: receding horizon optimization, executed regularly e.g. hourly, utilizing predictions with a short time-lag as well as the day-ahead baseline controllable variables and storage levels; results in a new operating point schedule for controllable variables; the result reflects the intra-day market outcome.
3) *Real-time operation*: simulation of continuous system behavior with high time-resolution; utilizes the operating point schedule for the controllable variables and actual values of uncertain variables, enhanced by characteristic power fluctuations; here, power system operation structures are modeled.

The implementation used here consists of two parts: a dispatch strategy based on in-feed and load predictions utilized in an MPC approach, and a simulation of the actual load and in-feed realizations including power system frequency dynamics and control. Both parts are combined in the case study in Section V. The flow diagram in Figure 3 illustrates the structure of the simulation environment.

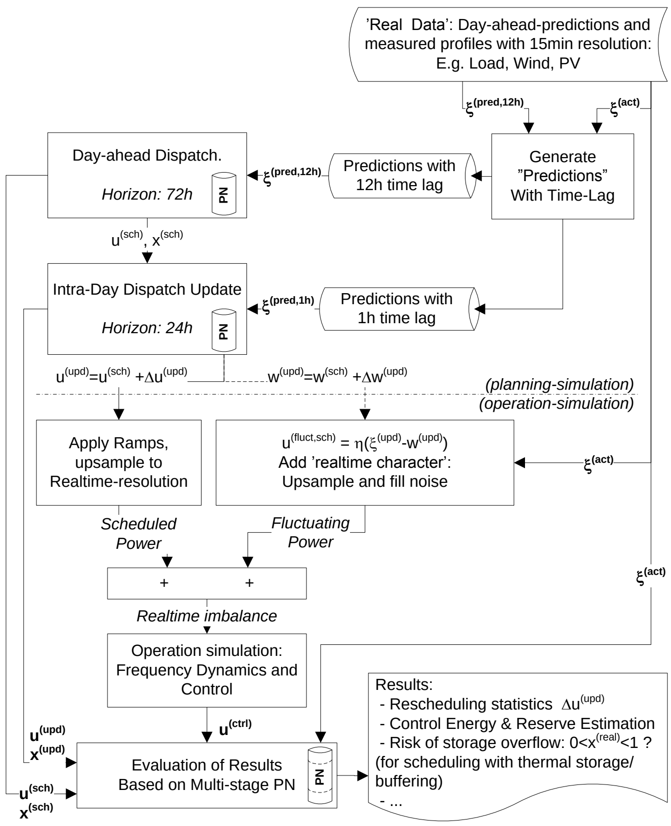

Fig. 3. Flow diagram of the simulation environment. The (PN) symbols indicates that the respective internal model and data formatting are based on the PowerNode formalization.

A. MPC-based Planning

A multi-period-optimization is required in the presence of inter-temporal constraints. In particular the presence of energy storage requires the explicit consideration of dynamic states in the planning environment. MPC-based optimization provides these features. MPC combines a receding horizon optimization with a periodic observation of actual state variables of the plant. This emulates a closed-loop-like behavior, which enables the controller to deal with unanticipated disturbances. Within the Power Nodes approach, the state of the "plant" is the set of State-of-Charge (SOC) variables $\boldsymbol{x}_i$ of the storages, and external predictions for in-feeds and loads are considered up to the optimization horizon[3].

The main simulation parameters of the two stages for day-ahead scheduling and update are:

1) The optimization frequency, e.g. daily, hourly, ...,
2) The sampling time and the look-ahead horizon,
3) Available predictions at the time of carrying out the optimization, e.g. 24-hour ahead wind forecast with 15-minute time resolution,
4) The time lag between the execution of the optimization and the realization, in liberalized settings given by the gate closure time of the energy exchange.

[3]Although the nature of the given problem is stochastic, a deterministic dispatch based on the available predictions is chosen here for simplicity. This can be extended in order to better represent the stochasticity of the underlying processes by 1) a stochastic programming approach or 2) a Monte-Carlo scenario-based optimization.

The details of the multi-stage optimization are given as:

1) Cost functions: For compact cost function formulation, we define the state and input variable vectors

$$
\begin{aligned}
\boldsymbol{x} &= [x_1, \ldots, x_n]^{\mathrm{T}} \quad , & (15)\\
\boldsymbol{u} &= [u_{\mathrm{gen},1}, \ldots, u_{\mathrm{gen},N}, u_{\mathrm{load},1}, \ldots, u_{\mathrm{load},N}, & (16)\\
&\quad \xi_1, \ldots, \xi_N, w_1, \ldots w_N]^{\mathrm{T}} \quad , \\
\boldsymbol{\delta u}_k &= \boldsymbol{u}_k - \boldsymbol{u}_{k-1} \quad , & (17)
\end{aligned}
$$

where $\boldsymbol{x}^{\mathrm{ref}}$ and $\boldsymbol{u}^{\mathrm{ref}}$ are reference values for state and input variable vectors. We consider the following cost function for the day-ahead dispatch:

$$
\begin{aligned}
J_k = &\sum_{l=k}^{k+N_{\mathrm{opt}}-1} \left((\boldsymbol{x}_l - \boldsymbol{x}_l^{\mathrm{ref}})^{\mathrm{T}} \boldsymbol{Q} \, (\boldsymbol{x}_l - \boldsymbol{x}_l^{\mathrm{ref}}) + \boldsymbol{q}^{\mathrm{T}} (\boldsymbol{x}_l - \boldsymbol{x}_l^{\mathrm{ref}}) \right) \\
+ &\sum_{l=k}^{k+N_{\mathrm{opt}}-1} \left((\boldsymbol{u}_l - \boldsymbol{u}_l^{\mathrm{ref}})^{\mathrm{T}} \boldsymbol{R} \, (\boldsymbol{u}_l - \boldsymbol{u}_l^{\mathrm{ref}}) + \boldsymbol{r}^{\mathrm{T}} (\boldsymbol{u}_l - \boldsymbol{u}_l^{\mathrm{ref}}) \right) \\
+ &\sum_{l=k}^{k+N_{\mathrm{opt}}-1} \left(\boldsymbol{\delta u}_l^{\mathrm{T}} \, \boldsymbol{\delta R} \, \boldsymbol{\delta u}_l \right) \quad , \qquad (18)
\end{aligned}
$$

The individual terms in the cost function are as follows: The first line penalizes a deviation of the state from a desired target value. Penalizing state deviation is only meaningful in cases when actual financial costs are incurred by the deviation, or when the state shall be kept in the vicinity of a certain level, e.g. in order to reduce the risk of a storage depletion or overflow. The second line penalizes all instantaneous quantities except for the physical loss term v. This includes mainly generator cost functions (linear and/or quadratic terms) for fuel cost and operation and maintenance (O&M), and penalties for curtailments of load and generation (the latter is only relevant when actual compensation payments have to be made e.g. for RES curtailments). The last line represents ramping costs incurred by working point changes. This is particularly relevant for thermal generation processes where thermal stress is an important factor for unit lifetime.

The cost function can be reformulated to also accommodate a receding horizon problem for the dispatch update. Note that the variables for day-ahead dispatch and intra-day update are indexed with (sch) and (upd), respectively.

2) Day-ahead dispatch:

a) Available predictions and timing: The day-ahead dispatch is usually settled around noon of the day preceding actual operation. One day in advance, predictions of the load and fluctuating RES in-feed are still rather inaccurate. Due to the time lag between execution of the prediction and implementation, the full length of the available prediction, e.g. 72 hours, cannot be exploited. The effectively available prediction is shortened by this.

b) Cost function: The penalization used for the day-ahead dispatch should normally be based on the marginal cost that is incurred by system operation, provided that the goal of the dispatch is least-cost operation.

3) Intra-day Update:

a) Available predictions and timing: Intra-day predictions are usually more accurate and have a shorter forecast horizon, e.g. 4–12 hours. Due to the market gate-closure, there is also a time lag between prediction and execution, e.g. of one hour. This leads to a reduction in accuracy of the forecast because it is already one hour old when it is executed, and a current measurement of the real values cannot be employed directly for the upcoming period.

b) Cost function: For the intra-day update, the penalization should also include the marginal cost of system operation. Additionally, terms can be included which penalize the deviation from the original schedule. The main reasons for this are transaction costs for intra-day rescheduling, as well as costs due to the deviation from the scheduled storage operation, which was determined to be optimal by a longer-term optimization.

B. Operation Simulation

The two planning stages result in a schedule for the dispatchable generation, formulated on the basis of expectations of fluctuating consumption and power generation. Simulating the realization of schedules in real-time means that additional information has to be added to the available signals. In operation-time, schedules for dispatchable generation are realized in form of ramping between the schedule-levels. But fluctuating power does not follow the prediction. Given a realization of the fluctuating power with a low time resolution, the energy content will be correct for that resolution, but the continuous fluctuation of the signal needs to be added. The system dynamics and control structures then react to the deviations between scheduled and actual values in continuous time.

1) Upsampling: For the simulation of realtime-operation, the scheduled and recorded power profiles with a low time resolution (Δt_{disp}) are upsampled to a higher resolution (Δt_{rt}). Here the ramping and fluctuating character of different processes is emulated.

a) Ramping of Scheduled Power.: According to [4], the transition between schedule levels shall occur with a 10-min. long ramp, starting 5 min. before and ending 5 min. after the schedule time. In the present model, this is realized on the basis of 15-minute schedules.

b) Emulation of Wind Power and Load Behavior.: Wind power fluctuation and load behavior in real-time are best understood as stochastic processes. The recorded profiles present the energy content for a 15 min. resolution. The fluctuation module emulates the real-time fluctuation by a) spline-interpolation through interval midpoints, b) adding a combination of white noise with time-lag filters and c) rescaling the resulting signal to the energy content given by the profiles. The parameters of white noise and time-lag filters have been tuned heuristically to match the fluctuation width for an estimated average wind farm size using data from [35]. The noise is then scaled by a factor of $1/\sqrt{N}$, e.g. [36], modeling the smoothing of uncorrelated power fluctuations from wind farms at different sites. The load noise is modeled as white noise and scaled roughly according to literature values [37].

2) Frequency Control Simulation: The present real-time module emulates the behavior of a secondary (area) controller in the ENTSO-E Regional Group Continental Europe. Primary (droop) frequency control in the face of instantaneous fluctuations is performed by the whole synchronous region. As a result, only slower fluctuations are visible in the control actions of the individual area controller. At present, no tertiary control actions and operator interventions are modeled. Other types of control structures may be embedded in this block by simply exchanging the real-time simulation module.

C. Evaluation of Multi-Stage Signals

The present simulation environment translates a scenario definition and a control structure into virtual operation data. The operation data includes time series of all control variables and allows the evaluation of the given control scenario. This data serves as a basis to define measures for evaluating the performance of the respective control and operation structures: Are incentives given by power markets and grid codes aligned with control needs? Are control actions effective or are control resources wasted? What is the energy content of control actions?

The data generated allows the study of a) different control structures under same parameterizations of the dispatch framework and b) alterations of the dispatch parameters, e.g. gate closures, with a fixed control structure, and c) the study of varying energy scenarios and with load and generation mixes. In addition to the energy accounting functions introduced in [17] and Section II-E, the present multi-stage formulation allows indicators for evaluating control performance characteristics, for example:

- Control energy requirements per time-scale,
- Reserve requirements estimation,
- Rescheduling statistics $\Delta u^{(\mathrm{upd})}$.

Data generated from multi-stage evaluation allows the study of other operation-relevant features than the dispatch simulation alone. If the operation stages are well-modeled, this data reproduces the characteristic behavior of actual system operation. Evaluation can be performed by comparison to actual operation data. However, within the scope of this paper, only a simple case is presented.

V. Exemplary Study Case

As a study case, a simulation of a hypothetical control area within the ENTSO-E Regional Group Continental Europe is studied. The exemplary setup consists of four power nodes connected to a single grid bus:

1) A conventional load without buffer, not curtailable ($\xi_1 = \xi_{\mathrm{drv},1}(t) < 0$),
2) An intermittent generation unit that can be curtailed, here the aggregated wind of a region ($C_2 = 0$, $\xi_2 = \xi_{\mathrm{drv},2}(t) \geq 0$),
3) Conventional generation aggregated in one unit ($C_3 = 0$, ξ_3 controllable, $w_3 = 0$),
4) A storage unit with capacity C_4 and without external process ($\xi_4 = 0$) emulating the pumped hydro capacity in that region.

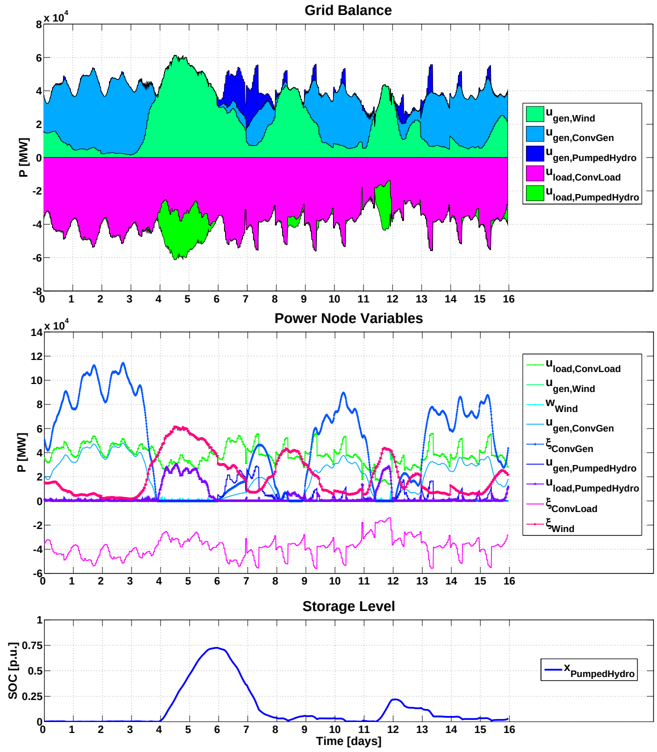

Fig. 4. Dispatch based on day-ahead predictions.

The set of power node equations given here is based on Eq. (1). As power nodes 1–3 contain no inherent storage, they use the reduced model (2). The problem set is thus

$$\xi_1 = -\eta_{\mathrm{load},1}\, u_{\mathrm{load},1} \quad , \tag{19}$$

$$\xi_2 - w_2 = \eta_{\mathrm{gen},2}^{-1}\, u_{\mathrm{gen},2} \quad , \tag{20}$$

$$\xi_3 = \eta_{\mathrm{gen},3}^{-1}\, u_{\mathrm{gen},3} \quad , \tag{21}$$

$$C_4\, \dot{x}_4 = \eta_{\mathrm{load},4}\, u_{\mathrm{load},4} - \eta_{\mathrm{gen},4}^{-1}\, u_{\mathrm{gen},4} \quad . \tag{22}$$

The numerical values of the scenario parameters and power node constraints are summarized in Table III.

The setup is tested for the case of one year, sampled in 15-minute intervals, with a wind energy contribution of up to 40% of the total load. Figure 4 illustrates the result of a day-ahead dispatch for an excerpt of 16 days. The result of the corresponding intra-day redispatch exhibits some differences, notably the significant curtailment of wind power in-feed around the 5th day, as shown in Figure 5. The internal evaluation of the predictive dispatch is given in Table IV. Note that the actual performance of the dispatch will deviate strongly, given that it is subject to large forecast errors. A 14-hour excerpt of the real-time simulation is provided in Figure 6, showing trajectories of

TABLE III
Simulation Parameters

Storage capacities			
C_1,C_2,C_3	0 GWh	C_4	480 GWh
Power ratings			
$P_{\mathrm{rated},1}$	60.2 GW	$P_{\mathrm{rated},2}$	90 GW
$P_{\mathrm{rated},3}$	60.2 GW	$P_{\mathrm{rated},4}$	60 GW
Grid variable constraints			
Efficiencies			
$\eta_{\mathrm{gen},3}$	0.45		
$\eta_{\mathrm{gen},4}$	0.9	$\eta_{\mathrm{load},4}$	0.85

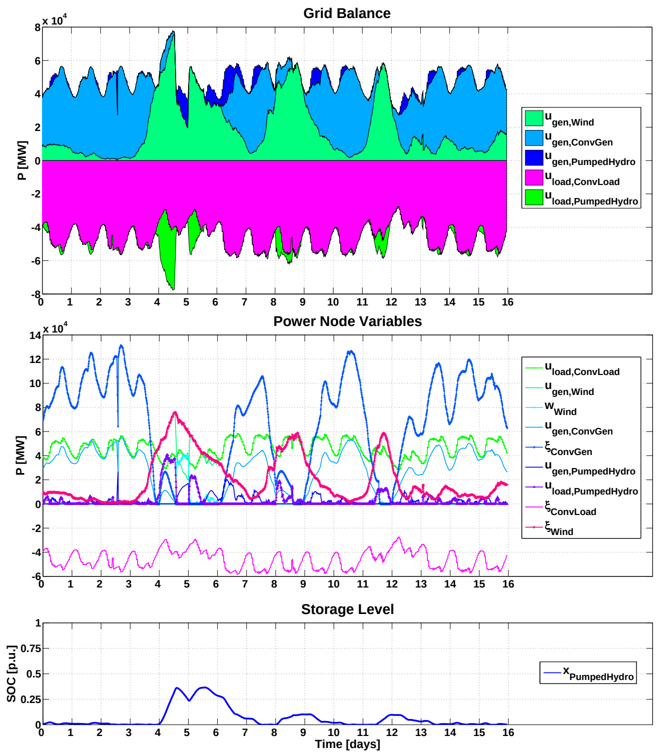

Fig. 5. Re-dispatch based on intra-day prediction updates.

fluctuating and dispatched power (lower plot), as well as control signals and balancing power (upper plot). The real-time imbalance results from summing up dispatched and fluctuating power. Here dispatched power is the sum of conventional plus hydro storage schedules with 10-minute ramps applied, and fluctuating power is load minus wind power. The resulting imbalance is the disturbance signal for the grid frequency dynamics and frequency control cascade. The continuous decrease in scheduled generation, observable in the lower plot from 4h onward, is a result of increasing wind power generation. Significant imbalances can be observed with an hourly pattern, which results from the hourly resolution of energy markets and load forecasting. The secondary control power (black line in upper plot) follows minute-to-minute fluctuations, hourly trends are clearly visible.

An important aspect in the evaluation of energy storage for power system operation is that the time sequence of control signals matters more than in conventional power systems. The present framework generates these time series with a high time-resolution. This data can be utilized to generate statistics characterizing the resource utilization for a given resource mix and control framework. Figure 7 suggests exemplary graphs evaluating the present study case. The topmost plot presents a power histogram which is a classical method for the study of control reserve needs (the relative frequency in this 'historic' data corresponds to a likelihood for the given power value). As observed from this plot, the modeled fluctuations and prediction errors induce significant utilization of the secondary reserve, even though plant outages have not been included in this simulation. The histogram shows a

TABLE IV
BALANCE TERMS FOR SIMULATION EXAMPLE

Balance term [TWh]	Int. Dispatch	Int. Update
Energy consumed by load	355.87	361.53
Energy supplied by conv. gen.	207.71	224.79
Energy supplied by wind power	151.64	141.15
Energy supplied by hydro storage	13.42	18.24
Energy consumed by hydro storage	16.90	22.64
Wind energy curtailed	0.53	3.90
Load demand not served	0	0

minor positive bias for small fluctuations. The other two diagrams serve the investigation of energy volumes in the time-sequence. The distributions presented in the middle plot show a likelihood distribution for how much energy reserve units provide/consume offering secondary reserve for a given time period (15 min., 1 h, 3 h, 6 h, 12 h). The energy values have been computed as time integrals for the given time horizons, with varying initial times. The somewhat expected results indicate that for the 15-min. horizon less than ±50 MWh and for the 1 h horizon less than ±100 MWh of energy are required. It can be seen that after 12 h, the energy-values become quite uncertain, just indicating the slight positive bias seen already in the power histogram. The second energy diagram evaluates the data strategically from an energy-storage perspective: For how long could a given energy storage(-level) provide a specific (either positive or negative) regulating power service? Given the available power signal, the time for which the service could be provided has been computed for each initial energy level. By computing the time for varying initial times, a distribution of service-time could be calculated for each energy level. The plot provides mean and standard deviation for the charging/discharging time (assuming a Gaussian distribution of the statistic) of the various energy levels. As a decision-support, this diagram may be read the other way around: charging a cluster of batteries with 200 MWh by continuously providing 10% of the total negative reserve will take about 5±1 hours.

The generated data can then be used to feed investigations of control requirements that result from these scenarios. In addition to this identification of quantitative requirements, also the effect of different regulation services can be estimated in this framework.

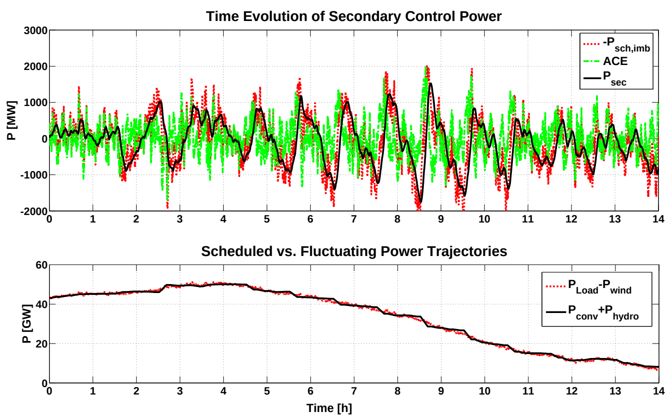

Fig. 6. Excerpt of real-time simulation of control areas.

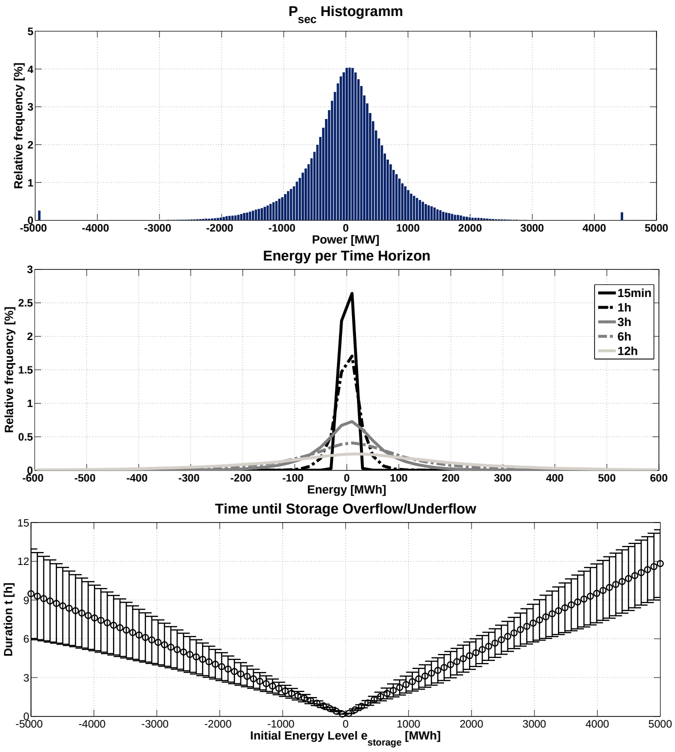

Fig. 7. Three analyses of the secondary control power signal.

VI. Conclusion & Outlook

A flexible and comprehensive modeling framework for generic energy storage and different degrees of dispatchability in power systems has been presented. The model architecture is designed such that it can integrate with existing power system analysis tools such as power flow computations and dynamic frequency simulations.

It has been shown how the power node equation can be decomposed into a baseline scheduling model, a schedule update model, and a real-time control model, which in superposition account for the entire affine power node dynamics. While the baseline model accounts for the basic dispatch, e.g. in day-ahead planning, the update model is a valuable tool to consider updated predictions of intermittent units closer to real-time operation. The balance terms associated with the power node equations can be used to evaluate the effect of updated predictions on unit and reserve utilization. The real-time model accounts for disturbances and control actions at the time of realization, e.g. the provision of load frequency control around a baseline trajectory. In contrast to (computationally less expensive) implicit approaches, the explicit modeling allows the synthesis of system-behavior: by integration of knowledge about characteristic real-time behavior, e.g. of load, wind or PV, it enables parametric scaling. Future energy scenarios are typically computed on a highly aggregated level, which makes it difficult to anticipate the implications for power system operation. With the presented modeling environment, operation-data can be generated out of relatively simple scenario specifications. This formulation is particularly attractive when the introduction of new ancillary services in a changing external environment is to be studied. The multi-stage formulation is also useful to analyze how provision of control services by energy-constrained units should be combined with scheduling requirements. Some examples for the evaluation criteria of real-time control structures have been presented.

The formulation of concrete power node equations for common units in power systems, such as different types of generation units, storage technologies and clusters of thermostatically controlled loads will broaden the support for applications. Ongoing research addresses the formulation of representations for control structures enabling flexible reconfiguration and experimentation with alternative control strategies and architectures. Further analysis of both existing and newly proposed power system operation concepts will support the adaptation of power system operation to the challenges ahead, such as the challenge of power systems with 100% RES.

In traditional operation concepts, intermittent generation is seen predominantly as a disturbance. The presented framework is aimed at facilitating the shift from the traditional operation paradigm of controllable generation and fluctuating demand towards an understanding of operation that integrates conventional, as well as non-controllable and partially controllable intermittent generation, flexible demand and energy storage.

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