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Unified System-Level Modeling of Intermittent Renewables and Energy Storage in Power System Operation

Stephan Koch, *Student Member, IEEE*, Kai Heussen, *Student Member, IEEE*, Andreas Ulbig, *Student Member, IEEE,* and Göran Andersson, *Fellow, IEEE*

***Abstract*—The system-level consideration of intermittent renewable energy sources 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 % renewable energy 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 modeling framework presented and extended in this paper allows the modeling of a technologically diverse unit portfolio with a unified approach, whilst 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**

I. Introduction

ELECTRICITY generated from renewable energy sources is often not dispatchable and the forecast of its production over time is bound to uncertainty. Today, electricity generated from wind provides up to around 20 % of the electric energy demand in some countries, which means that wind power production at times exceeds local energy demand. Solar photovoltaic in Germany is exceeding 15 GW in installed capacity this year.Considering the ongoing large-scale deployment of intermittent renewable energy sources (RES) [1] and government plans for up to 100 % RES supply, the consideration of system operation and economic frameworks that are oriented towards the nature of intermittent renewables and energy storage become increasingly relevant.

Power systems require a continuous balance between supply and demand. To achieve this balance, anticipated energy needs and availability are procured in energy markets based on forecast, while the continuous power balance is maintained through an arrangement of automatic control schemes.

Traditionally and still in common practice, the dominant part of dispatchable power generation is based on energy stored in combustible fossil fuels. This process is mainly driven by spot market electricity prices and marginal electricity generation costs. In the case of intermittent renewable generation, available energy has to be absorbed by the system in the moment it becomes available. As the energy itself is free, costs to be recovered are predominantly for the investment into RES like wind turbines and solar PV installations which means that all available energy will be made available to the market[1]. 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 [2]. Thus, energy constraints – inherent to all kinds of energy storage – induce a different dispatch logic.

A fundamental problem in power system operation is the need for day-ahead planning and the unavoidable discrepancy between planned and actual power delivery in real-time. Especially in systems with intermittent sources, large prediction errors may have to be dealt with, and adequate control reserves have to be scheduled accordingly. Intra-day trading and rescheduling of generation allows to integrate shorter-term predictions with higher accuracy, reducing the need for control reserves balance the prediction error and unpredictable disturbances. In case that energy storage shall be utilized for dispatch and control tasks, this problem becomes particularly challenging since the energy constraints of the storages have to be accounted for.

A. Intermittent Renewable Energy

Intermittent power in-feeds from wind turbines and PV arrays are predictable to a certain extent [3]. Nowadays, information on the forecasted 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

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[1]In fact, current regulatory schemes often prioritize RES, which sometimes may induce negative energy prices.

unavoidable forecast errors are balanced via intra-day power 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 [4], [5], 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.

B. Energy Storage in Power Systems

All forms of energy storage, except for electromechanical energy storage inherent to AC power systems with rotating machines, entail energy conversion processes based on a wide range of technologies [6]. 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 amounts of electric vehicles connected to the power system [7], [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]–[11].

The economic value of energy storage is derived from its ability to be included in a market-oriented dispatch as well as by its flexibility when employed as a control resource in the framework of ancillary services. Especially in systems dominated by intermittent and/or inflexible generation capacity, flexibility is valuable [12]. 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 considered by system operators, while the electric energy required for control actions is not visible to the operator and is settled in post-operation. The impact of energy storage is particularly relevant for dispatch problems because of the storage dynamics and associated inter-temporal constraints. Here, the control methodology of (centralized or distributed) Model Predictive Control has been shown to be particularly suitable [13]–[15].

C. Objective of this Work

The additional degrees of freedom that energy storage and an increased controllability of intermittent power infeeds 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 [16], Cells [17], [18], or MicroGrids [19]. The comprehensive performance comparison of different operation and control approaches, however, constitutes a challenge in itself [20], [21].

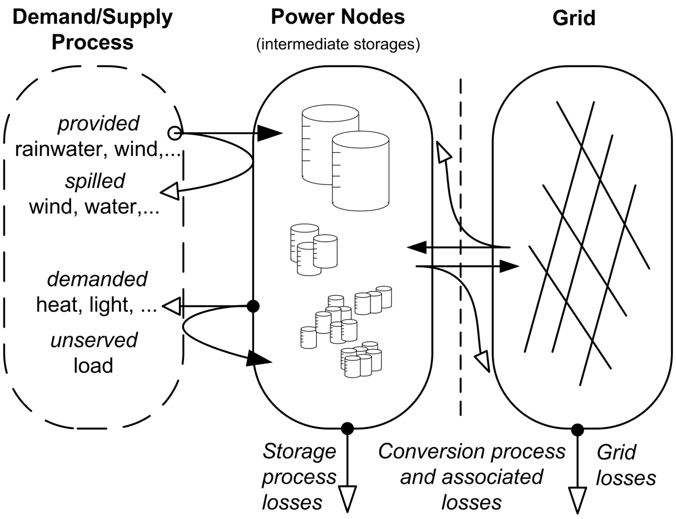


Fig. 1. Illustration of the three-domains concept. The Power Node- and Grid domains are model-internal domains and both are considered integral parts of the electric energy system. The domain of Demand/Supply processes is considered external, indicated by the dashed frame. Arrows indicate the energy (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.

This paper aims at developing an appropriate evaluation framework for addressing this challenge. The concept of "Power Nodes" is introduced as an extension to classical grid models, to represent a variety of unit types in a unified notation. This framework enables the assessment of operation strategies for power systems that integrate intermittent and controllable energy supply, energy storage as well as controllable loads.

The paper is structured as follows: The Power Nodes framework introduced in Section II, then Section III develops a multi-stage formulation of a power node, establishing the feasibility of energy storage representation in the common frameworks of system operation. The benefits of the developed concept are illustrated by a simple case-study 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

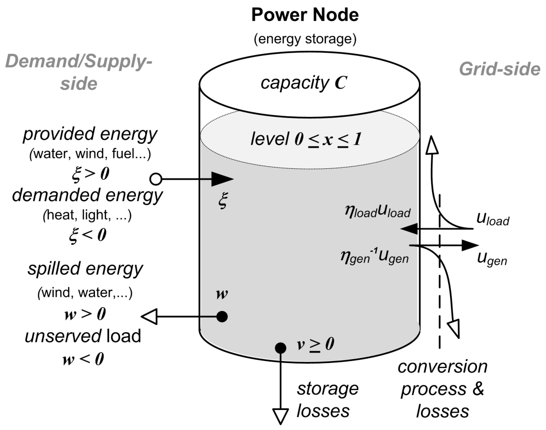


Fig. 2. Notation for a single power node.

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 use and supply processes consuming energy from and feeding energy into the Power Node domain. As indicated in the figure, these processes may be thought of as externally driven, such as intermittent renewable energy supply. However, this domain also accounts for controllable supply and demand, such as the supply of fuel for dispatchable generators.

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, balance terms as formulated in Section II-D 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 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 $\dot{u}_{\mathrm{gen},i}$ and $\dot{u}_{\mathrm{load},i}$, 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 II-E). 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-D.

2) Modeling 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 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

$$\xi_i - w_i = \eta_{\mathrm{gen},i}^{-1}\, u_{\mathrm{gen},i} - \eta_{\mathrm{load},i}\, u_{\mathrm{load},i} \quad . \tag{2}$$

This equation is able to describe both externally driven processes and controllable power generation.

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, 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 the controlled variables. ξ_i then accounts e.g. 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 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:

$$\begin{aligned} C_i\,\dot{x}_i \;\; = \;\; & \eta_{\mathrm{load},i}\, u_{\mathrm{load},i} - \eta_{\mathrm{gen},i}^{-1}\, u_{\mathrm{gen},i} + \xi_i - w_i \\ & -a_i\,(x_i - x_{\mathrm{ss},i}) \qquad , \end{aligned} \tag{3}$$

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 power grid composed of M busses denoted by $m, n \in \mathcal{M} = \{1, \ldots, M\}$ with a set of N power nodes $i \in \mathcal{N} = \{1, \ldots, N\}$ attached, representing a number of single or aggregated units. 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:

$$P_{\mathrm{netinj},m} = \sum_{i \in \mathcal{N}_m} u_{\mathrm{gen},i} - \sum_{i \in \mathcal{N}_m} u_{\mathrm{load},i} \quad . \tag{4}$$

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, such as DC or AC power flow, static of dynamic grid models, due to the clear separation from the electromechanical domain[2].

D. 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.

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 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 $i \in \{i | C_i = 0 \wedge \xi_i = \xi_{\mathrm{drv},i}(t) \geq 0 \wedge w_i = 0\} \subset \mathcal{N}$.

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: $\int_{t_1}^{t_2} P_{\mathrm{gen}}^{\mathrm{grid}}(t)\, dt$,

[2]In most cases it is appropriate to model the power-exchange $u_{\mathrm{gen/load}}$ as a power injection to the respective bus. In case of a dynamical grid model and the power node being a synchronous machine, the proper interface would be the *mechanical* power exerted on the its shaft.

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

- Primary energy supplied: $\int_{t_1}^{t_2} \xi^{\text{total}}_{\text{supply}}(t)\, dt$,
- Primary energy curtailed: $\int_{t_1}^{t_2} w^{+}(t)\, dt$,
- Energy conversion losses: $\int_{t_1}^{t_2} P_{\text{loss}}(t)\, dt$.

E. Characterization of Unit Properties

Specific unit characteristics can be modeled in the generic model by applying further restrictions on the power node variables. 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.

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:

- 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. It must then be further distinguished whether both conversions can happen at the same time (e.g. pumped hydro with independent turbine and pump), or not (e.g. inverter-connected battery).
- 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 accounts for supply ($\xi_i > 0$) or demand ($\xi_i < 0$) processes. For pure electricity storage (battery), $\xi_i = 0$ holds.
- Constraints on ξ_i and w_i indicate the controllability of the power exchange with an external process. If ξ_i is driven by an external signal $\xi_i = \xi_{\text{drv},i}(t)$, e.g. induced by an 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 fully controllable.
- 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, 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 powernodes framework.

III. FRAMING OF POWER NODE EQUATIONS FOR MULTI-STAGE OPERATION

This section presents a formulation of the power node equation for three different time horizons of system operation, starting with the day-ahead planning and ending with real-time operation. The formulation is based on a decomposition oriented towards the integration of prediction updates and control service provision with storage allocation. Unit commitment and long-term planning issues are not addressed here.

Given a representation of all grid-connected units as power nodes, the following three-stage operation and control framework is considered:

1) *Day-ahead dispatch*: multi-period optimization to establish an operating point trajectory for the controllable variables, based on operation cost and predictions for uncertain variables.
2) *Intra-day rescheduling*: receding horizon optimization on the grounds of updated predictions for uncertain variables and given the day-ahead baseline for instantaneous quantities and storage levels. Results in alteration of the working point trajectory.
3) *Real-time operation*: control actions on short time scales, e.g. Load Frequency Control, around the scheduled working point trajectory determined by the previous two stages. In the case of security-relevant control reserves requiring guaranteed availability, a control band has to be reserved around the working point trajectory, imposing additional constraints on the day-ahead dispatch and intra-day rescheduling.

In order to model the degrees of freedom related to each of the decision problems, the power node variables are decomposed into fractions, consisting of scheduled values (sch), schedule or prediction updates as deviations from the scheduled values (upd), and real-time deviations (rt) due to remaining prediction errors, unpredictable fluctuations, and automatic control actions:

$$\aleph = \aleph^{\text{sch}} + \Delta\aleph^{\text{upd}} + \Delta\aleph^{\text{rt}} \quad , \tag{5}$$

with $\aleph = \{u_{\text{gen}}, u_{\text{load}}, \xi, w\}$ being the instantaneous power node variables that may be subject to external dispatch and control commands. The physical storage loss term v has to be 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:

$$\begin{aligned} x &= x^{\mathrm{sch}} + \Delta x^{\mathrm{upd}} + \Delta x^{\mathrm{rt}} \quad \text{and} & (6)\\ \dot{x} &= \dot{x}^{\mathrm{sch}} + \Delta \dot{x}^{\mathrm{upd}} + \Delta \dot{x}^{\mathrm{rt}} \quad . & (7) \end{aligned}$$

The goal is to formulate separate power node equations for each of the fractions, such that in superposition they constitute the original power node equation. As a condition for the 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:

$$C_i\,\dot{\hat{x}}_i = \eta_{\mathrm{load},i}\,u_{\mathrm{load},i} - \eta_{\mathrm{gen},i}^{-1}\,u_{\mathrm{gen},i} + \xi_i - w_i - a_i\,\hat{x}_i \quad . \quad (8)$$

The power node equation is thus linear in $\hat{\cdot}$-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 $\Delta\hat{x}^{\mathrm{rt}} = \Delta x^{\mathrm{rt}}$. As a result, the original coordinates can be employed to denote the three related power node formulations.

1) Power node equation for the scheduling problem:

$$\begin{aligned} C_i\,\dot{x}_i^{\mathrm{sch}} &= \eta_{\mathrm{load},i}\,u_{\mathrm{load},i}^{\mathrm{sch}} - \eta_{\mathrm{gen},i}^{-1}\,u_{\mathrm{gen},i}^{\mathrm{sch}} & (9)\\ &\quad + \xi_i^{\mathrm{sch}} - w_i^{\mathrm{sch}} - a_i\,(x_i^{\mathrm{sch}} - x_{\mathrm{ss},i}) \quad , \end{aligned}$$

2) Update power node equation formulated as a schedule deviation:

$$\begin{aligned} C_i\,\Delta\dot{x}_i^{\mathrm{upd}} &= \eta_{\mathrm{load},i}\,\Delta u_{\mathrm{load},i}^{\mathrm{upd}} - \eta_{\mathrm{gen},i}^{-1}\,\Delta u_{\mathrm{gen},i}^{\mathrm{upd}} & (10)\\ &\quad + \Delta\xi_i^{\mathrm{upd}} - \Delta w_i^{\mathrm{upd}} - a_i\,\Delta x_i^{\mathrm{upd}} \quad . \end{aligned}$$

3) Real-time imbalance and control power node equation formulated as the difference between the actual realization $\aleph$ and the (updated) schedule $\aleph^{\mathrm{sch}} + \Delta\aleph^{\mathrm{upd}}$:

$$\begin{aligned} C_i\,\Delta\dot{x}_i^{\mathrm{rt}} &= \eta_{\mathrm{load},i}\,\Delta u_{\mathrm{load},i}^{\mathrm{rt}} - \eta_{\mathrm{gen},i}^{-1}\,\Delta u_{\mathrm{gen},i}^{\mathrm{rt}} & (11)\\ &\quad + \Delta\xi_i^{\mathrm{rt}} - \Delta w_i^{\mathrm{rt}} - a_i\,\Delta x_i^{\mathrm{rt}} \quad . \end{aligned}$$

The real-time imbalance is due to the mismatch between the forecasted power balance and the actual generation and consumption. A certain mismatch is unavoidable due to: continuous variation of load and intermittent generation, forecast errors, and unplanned outages of conventional generation. The continuous power balance is established by an arrangement of control structures activating controllable variables of the power nodes.

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. It is desirable that the multi-stage formulation exhibits both these physical limitations and a consistent relationship between the stages.

Resources for the real-time control of power systems, e.g. for Load Frequency Control provision, represent a reserved capacity that is ready for activation when imbalances occur:

$$\begin{aligned} -\Delta u_{\mathrm{gen}}^{\mathrm{rt,neg}} \le \Delta u_{\mathrm{gen}}^{\mathrm{rt}} \le \Delta u_{\mathrm{gen}}^{\mathrm{rt,pos}} \quad , & \quad (12)\\ -\Delta u_{\mathrm{load}}^{\mathrm{rt,pos}} \le \Delta u_{\mathrm{load}}^{\mathrm{rt}} \le \Delta u_{\mathrm{load}}^{\mathrm{rt,neg}} \quad , & \quad (13) \end{aligned}$$

where (rt,pos) and (rt,neg) indicate the constraints associated with the provision of positive and negative control reserve, respectively.

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 enough storage capacity to securely deliver the contracted control reserves without risk of depletion or overflow of their storage. This can be vastly different in the case of reserve provision by controllable thermal loads, small-scale combined-heat-and-power units, or plug-in hybrid electric vehicles, which have a significantly smaller capacity to store energy in proportion to their power capacity. In these cases, it may be necessary to also reserve a storage control band:

$$-\Delta x^{\mathrm{rt,pos}} \le \Delta x^{\mathrm{rt}} \le \Delta x^{\mathrm{rt,neg}} \quad . \quad (14)$$

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 *scheduling*-stage of the power node operation:

$$\begin{aligned} &\text{(a)} \quad \Delta x^{\mathrm{rt,pos}} \le x_i^{\mathrm{sch}} \le 1 - \Delta x^{\mathrm{rt,neg}} \quad , \\ &\text{(b)} \quad 0 \le u_{\mathrm{gen},i}^{\min} + \Delta u_{\mathrm{gen}}^{\mathrm{rt,neg}} \le u_{\mathrm{gen},i}^{\mathrm{sch}} \\ &\qquad \le u_{\mathrm{gen},i}^{\max} - \Delta u_{\mathrm{gen}}^{\mathrm{rt,pos}} \quad , \\ &\text{(c)} \quad 0 \le u_{\mathrm{load},i}^{\min} + \Delta u_{\mathrm{load}}^{\mathrm{rt,pos}} \le u_{\mathrm{load},i}^{\mathrm{sch}} \\ &\qquad \le u_{\mathrm{load},i}^{\max} - \Delta u_{\mathrm{load}}^{\mathrm{rt,neg}} \quad . \end{aligned}$$

For the *update* formulated as a schedule deviation, the absolute constraints of the scheduling problem are then relative to the planned trajectory:

$$\begin{array}{ll}\text{(a)} & \Delta x^{\text{rt,pos}} - x_i^{\text{sch}} \leq \Delta x_i^{\text{upd}} \leq 1 - \Delta x^{\text{rt,neg}} - x_i^{\text{sch}} \quad , \\ \text{(b)} & u_{\text{gen},i}^{\min} + u_{\text{gen}}^{\text{rt,neg}} - u_{\text{gen},i}^{\text{sch}} \leq \Delta u_{\text{gen},i}^{\text{upd}} \\ & \quad \leq u_{\text{gen},i}^{\max} - u_{\text{gen}}^{\text{rt,pos}} - u_{\text{gen},i}^{\text{sch}} \quad , \\ \text{(c)} & u_{\text{load},i}^{\min} + u_{\text{load}}^{\text{rt,pos}} - u_{\text{load},i}^{\text{sch}} \leq \Delta u_{\text{load},i}^{\text{upd}} \\ & \quad \leq u_{\text{load},i}^{\max} - u_{\text{load}}^{\text{rt,neg}} - u_{\text{load},i}^{\text{sch}} \quad . \end{array}$$

The constraints ensure that the 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 recast as a linear constraint because ξ is either always smaller or always greater than 0 for most processes. Additional ramping-constraints, constraints on the time-derivative of u_{load} and $u_{\text{gen},i}$ would be formulated entirely analog to the the above constraints.

C. Cost Functions

It is clear that all planning and operation activities should be aimed at utilizing the available resources in the best possible way, i.e. minimizing the cost of system operation. We take the perspective of a system operator here, considering economic dispatch as an idealized approximation of real market operations. In the case of considering DC power flow equations as additional constraints, the problem becomes a multi-period DC optimal power flow (OPF) problem. We consider the following cost function as a basis for both day-ahead dispatch and the update:

$$\begin{aligned} J \;=\; & \sum_{k=1}^{N} \left((\boldsymbol{x}_k - \boldsymbol{x}_k^{\text{ref}})^{\text{T}} \boldsymbol{Q} \, (\boldsymbol{x}_k - \boldsymbol{x}_k^{\text{ref}}) + \boldsymbol{q}^{\text{T}} (\boldsymbol{x}_k - \boldsymbol{x}_k^{\text{ref}}) \right) \\ + & \sum_{k=1}^{N} \left((\boldsymbol{u}_k - \boldsymbol{u}_k^{\text{ref}})^{\text{T}} \boldsymbol{R} \, (\boldsymbol{u}_k - \boldsymbol{u}_k^{\text{ref}}) + \boldsymbol{r}^{\text{T}} (\boldsymbol{u}_k - \boldsymbol{u}_k^{\text{ref}}) \right) \\ + & \sum_{k=1}^{N} \left(\boldsymbol{\delta u}_k^{\text{T}} \, \boldsymbol{\delta R} \, \boldsymbol{\delta u}_k \right) \quad , \end{aligned} \tag{15}$$

with the state and input variable vectors

$$\boldsymbol{x} = [x_1, \ldots, x_N]^{\text{T}} \quad , \tag{16}$$

$$\boldsymbol{u} = [\aleph_1, \ldots, \aleph_N]^{\text{T}} \quad , \tag{17}$$

$$\boldsymbol{\delta u}_k = \boldsymbol{u}_k - \boldsymbol{u}_{k-1} \quad , \tag{18}$$

and with $\boldsymbol{x}^{\text{ref}}$ and $\boldsymbol{u}^{\text{ref}}$ being reference values for state and input variable vectors. This cost function can be easily reformulated to a receding horizon problem for the dispatch update. Note that for both day-ahead dispatch and intraday rescheduling, the variables should be indexed with (sch) and (upd), respectively.

The individual terms in the cost function are explained 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 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.

Note that care has to be taken in the transformation of the cost function to a Δ-formulation, especially when non-zero targets are are considered. In this case, the linear term may have to be transformed to a penalization of the absolute value of the deviation since sign changes of the instantaneous variables can occur in a Δ-formulation.

IV. Simulation Case: Dispatch and Evaluation

A day-ahead dispatch including an intermittent power in-feed to the grid is considered in order to illustrate the management of a set of power nodes. The exemplary setup 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 (3) of the power node equation (1). As nodes 2, 3, and 5 contain no inherent storage, they are based on the reduced model (2). Thus, the set of power node equations for this problem is

$$C_1 \, \dot{x}_1 = \eta_{\text{load},1} \, u_{\text{load},1} - \eta_{\text{gen},1}^{-1} \, u_{\text{gen},1} \tag{19}$$

$$\xi_2 - w_2 = \eta_{\text{gen},2}^{-1} \, u_{\text{gen},2} \tag{20}$$

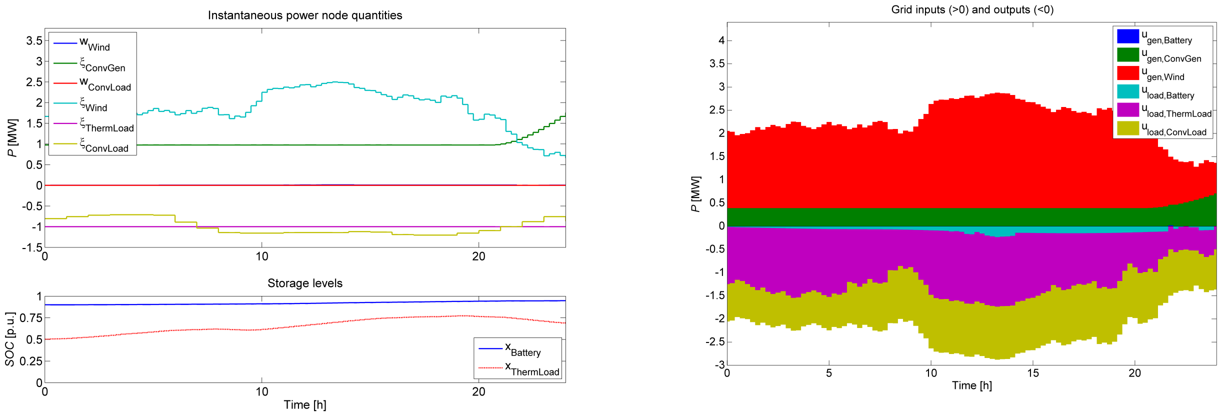
$$\xi_3 = \eta_{\text{gen},3}^{-1} \, u_{\text{gen},3} \tag{21}$$

$$C_4 \, \dot{x}_4 = \eta_{\text{load},4} \, u_{\text{load},4} + \xi_4 \tag{22}$$

$$\xi_5 - w_5 = -\eta_{\text{load},5} \, u_{\text{load},5} \quad . \tag{23}$$

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.

In accordance with the unit properties established in Section II-E, the additional constraints on these power



(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.

node equations are:

$$0 = u_{\text{gen},1}\, u_{\text{load},1} \quad (24)$$

$$\xi_2 = \xi_{\text{drv},2}(t) \geq 0 \quad (25)$$

$$\xi_4 = \xi_{\text{drv},4} = const < 0 \quad (26)$$

$$\xi_5 = \xi_{\text{drv},5}(t) \leq 0 \quad . \quad (27)$$

The power balance of the single bus system is

$$\sum_{i=\{1,2,3\}} u_{\text{gen},i} - \sum_{i=\{1,4,5\}} u_{\text{load},i} = 0 \quad . \quad (28)$$

The cost function parameters for the optimization are derived as follows: The cost term of the conventional generator is given by a linear approximation of generation cost per kWh. Furthermore, the conventional generator node is also subjected to a considerable ramping cost term, reflecting additional fuel costs and stresses on the plant when changing the plant's working point. For the wind feed-in a very small linear marginal cost term is used. This is realistic in the case of a wind farm, as fuel costs are non-existent and O&M costs per MWh wind in-feed produced are small as well. For the thermal load, a quadratic state penalization is used in order to consider a more-than-proportional loss of thermal comfort and increase in appliance switching actions for a certain deviation of the state from a neutral position of 0.5. The battery storage node's cost function is derived from a small cost term per cycling due to battery degradation, attributed to the discharging variable in order to allow for a non-penalized charging of the storage.

As a whole, the cost function represents the operation costs of the whole system, thus mimicking dispatch behavior of a standard economic dispatch optimization. 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

$$x = [x_1, x_2]^{\mathrm{T}} \quad , \quad (29)$$

$$u = [u_{\text{gen},1}, u_{\text{load},1}, u_{\text{gen},2}, w_2, u_{\text{gen},3}, \xi_3, \ldots \quad (30)$$
$$u_{\text{load},4}, u_{\text{load},5}, w_5, \xi_2, \xi_4, \xi_5]^{\mathrm{T}} \quad .$$

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 24 hours sampled in 15-minute intervals. 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 dispatch 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

TABLE III
SIMULATION PARAMETERS

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
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

TABLE IV
BALANCE TERMS FOR SIMULATION EXAMPLE

Balance term	Value [MWh]
Electricity consumed by loads	51.771
Electricity consumed by battery	2.378
Electricity supplied by conv. gen.	9.7273
Electricity supplied by wind turbine	44.4184
Electricity supplied by battery	0.0044
Prim. energy supplied by wind	44.5373
Prim. energy supplied by conv. gen.	9.7273
Use energy demanded by load	47.95
Wind energy curtailed	0.16454
Load demand not served	0

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. 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.

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.

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 linear 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. This formulation is particularly attractive when the provision of control services by energy-constrained units must be combined with scheduling requirements. One example is the case of an aggregated population of plug-in hybrid electric vehicles: the requirement to recharge the fleet during the night can be met by an adequate baseline scheduling leading to a continuous increase in the aggregated SOC. On top of this, contributions to frequency control can be made within a permissible deviation of e.g. $\Delta x^{\text{rt}} = \pm 10\%$ around that baseline, enabling to pursue both recharging and control service provision. However, a certain amount of knowledge concerning the statistical properties (e.g. autocorrelation) of the expected control signal is imperative in order to properly size the energy control band corresponding to a certain power control band. The scheduling of the units has to take into account the control band reservation by altering the power and energy constraints accordingly.

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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