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Multi-commodity network flow models for dynamic energy management – Smart Grid applications

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Abstract

The strong interconnection between human activities, energy use and pollution reduction strategies in contemporary society has determined the necessity of collecting scientific knowledge from different fields to provide useful methods and models to foster the transition towards more sustainable energy systems. This is a challenging task in particular for contemporary communities where an increasing demand for services is combined with rapidly changing lifestyles and habits. The Smart Grid concept is the result of a confluence of issues and a convergence of objectives, which include national energy security, climate change, pollution reduction, grid reliability, etc. While thinking about a paradigm shift in energy systems, drivers, characteristics, market segments, applications and other interconnected aspects must be taken into account simultaneously. In this context, the use of multi-commodity network flow models for dynamic energy management aims at finding a compromise between model usefulness, accuracy, flexibility, solvability and scalability in Smart Grid applications.

*Keywords:*Dynamic energy management; Smart Grid; Multi-commodity network flow models

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1. Introduction

Energy planning and management for distributed energy resources [1,2] and mixed energy distribution systems [3,4] are receiving an increasing attention in recent years because of pressing economic, energy and environmental issues. The development of flexible energy systems, incorporating the efficient and

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combined conversion, distribution and storage of multiple energy vectors is a necessary step toward a more sustainable low carbon society.

Therefore, the essential energy infrastructures on which communities rely will need to be adapted and upgraded to meet increasing demands for energy efficiency, energy security, grid reliability and, at the same time, to face growing concerns related to climate change, pollution and resources depletion. The development of smart energy infrastructures is a fundamental step towards these goals. Conversion, distribution, storage and, more in general, efficient technologies must be controlled in a distributed way [5] by means of an enabling infrastructure. For these reasons, several visions are emerging with respect to the Smart Grid and Distributed Generation (DG) [1] that extend the reach of these new paradigms. At present, of course, the existing infrastructure and energy systems, such as electricity, gas, water, heat, transportation and waste are determining our impact, but in future systems, both “physical” and “virtual” infrastructures will contribute to lower the environmental impact and enhance sustainability.

The renovation process acts on different layers, from the physical power infrastructure layer, to the transmission and distribution operator layer, up to the applications and services layer. The long-range goal is sustainability but more focused and short-term goals, such as competitiveness, reliability, security, service quality, investments and job opportunities, can be fundamental driving factors.

However, the separation between levels of action is fuzzier than in the past and the concept of utility is evolving itself, with respect to the different possible visions. We cannot precisely foresee how utilities will look like in the future, but the transition towards a future paradigm seems more similar to a continuous evolution process than a revolution build upon break-through technologies. As a matter of fact, competing as well as complementary technologies are being developed, evaluated and deployed on a continuous base. As a consequence an increased level of systems thinking is needed to integrate the broad range of clean energy technologies in the renovation of the energy sector.

There are several possible strategies to put it into practice. One could be increasing the resources for regional-scale Smart Grid and DG projects. Another one could be moving forward for customers to have a real-time integrated view of energy consumption, production and informed decisions taken by dynamic energy management systems. Despite the presence of several possible applications, it is fundamental to avoid considering the emerging presence in the market of clean technologies alone [6] sufficient for a shift. Public and private-sector investments, using traditional business models aimed at fitting new technologies into existing systems cannot be considered a viable strategy, as many examples in the history of technological development indicate. Innovative projects in this field must contain four balanced components: enabling technological platform, effective business model, careful market adoption strategy and supportive government policy. The renovation of the energy sector is, in fact, a problem of vision and not merely of resources.

2. Overview of the dynamic energy management problem

The Smart Grid will change the way power is delivered, consumed and accounted for. Adding intelligence to the energy infrastructure would not be possible without an additional information and communication layer (communication protocols, open standards, interfaces, etc.) and all the positive effects that we expect from it rely on decentralized intelligent decisions and on the ability of the different nodes of communicating efficiently through the network. Up to now anyway, the recent advances in ICT have not determined a transformation of the power system and of the energy sector in general as extensive and pervasive as other high-tech industries.

In order to highlight the possible applications for dynamic energy management systems, it is necessary to introduce a logical subdivision. First, as a rough simplification we can identify three different layers in the Smart Grid: the physical one (generators, transmission and distribution lines), the communications and control one (transmission and distribution system operators) and the applications one (services and applications). Second, we can identify various types of end-users, subdivided by sector: residential, non residential, industry, transportation. Each sector has different demands and features. Finally, the end-users can be grouped together with different levels of aggregation, from individual buildings to homogeneous settlement and neighborhoods/districts. The presence of various possible actors, needs and levels of aggregation gives origin to a multi-time and multi-scale optimization problem. Dynamic energy management system will have to face this problem in the applications and services layer.

On the other hand, developing an energy infrastructure with an embedded intelligence at every node will contribute to ease the technical problems that a utility will have to face in a restructured power system and energy market with the help of distributed control. Obviously, it will be necessary to create a new utility regulatory model to foster and promote effectively energy-efficiency programs. In this sense, utilities' profits must be decoupled from the volume of energy sold, by selling other types of services or by sharing the economic benefits that the clients obtain by raising efficiency and reducing consumption.

3. Multi-commodity network flow models for dynamic energy management

Models have to capture the prominent features of a problem and neglect the irrelevant ones, thus being solvable with a reasonable computational effort to obtain valuable solutions. In optimization, several kind of problems can be solved using network models. Network flow programming models are derived from graph theory and represent a special case of linear programming models. Network flow models are used to solve problems such as the generalized network flow problem, the pure minimum cost flow problem, the transportation problem, the shortest path problem, the maximum flow problem and the assignment problem. The success of network models is primarily due to the following aspects:

- graphical representation, with the possibility to understand easily the underlying structure of the problem;
- simplicity and flexibility in modeling, with the possibility of constructing large-scale models with a compact notation and a moderate programming effort;
- computational efficiency and solvability, with the possibility of using both general purpose or tailored solution algorithms;
- scalability and generality, with the possibility of representing different but interconnected phenomena, which affects different scales and time intervals.

Beyond engineering applications, an emerging scientific discipline, network science, has demonstrated in recent years that it is possible to successfully investigate the properties, interconnections and the behavior of various types of large-scale complex networks such as engineered networks, information networks, biological networks, social networks, etc. [7].

3.1. Multi-commodity network flow models

Multi-commodity flow problems [8] are optimization problems with multiple commodities flowing through the network from sources to sink nodes. They have been successfully used in many fields but have not been used for optimizing the power flow in electrical networks because, while they respect Kirchhoff's current law, they don't respect Kirchhoff's voltage law. For this reason, specific models have been developed for optimal power flow. Further, electrical networks transport only a single commodity, electricity. Despite the first issue, network flow models can be used in integrated energy infrastructure operation planning, including electric system, if the arcs modelled are the ones in which flow can be directly controlled (e.g. control areas in the electric power system, flows are decision variables). With respect to the second issue, the increasing interdependencies among different energy infrastructures cannot be addressed by specific sector models. In particular, the evolution of the power paradigm towards distributed generation and the future stronger integration between transportation systems (trains, PHEV, PEV) and electric infrastructure claims for the development of reliable, flexible and scalable multi-commodity models.

3.2. Tasks for dynamic energy management systems

The general task for these systems is managing efficiently multiple energy commodities over arbitrary infrastructure topologies (networks), taking into account energy conversion, transport and storage in dynamic operating conditions. Several efficient models can be found in literature that addresses different issues related with DG techno-economic optimization, but they are, in general, tailored for specific applications and cannot be easily treated in a generalized and unified framework, thus complicating the construction of interoperable applications for Smart Grid. Anyway, the core assumptions and the main aspects contained constitute the knowledge basis for new implementations.

The choice of using network theory as the modeling framework is based on the features of this mathematical modeling technique, on the constitutive characteristics of the problem and on the future possible applications. Energy conversion, transport and storage, as wells as supply and demand of different energy commodities (fossil fuels, electricity, heating, cooling, etc.) and environmental impact (CO_2 and pollutant emissions) must be considered together in dynamic energy management. The goal is operating a general energy system with time varying properties at maximum efficiency (i.e. with a guaranteed global optimum) with a reasonable computational effort. Models have to be designed to work both online (real-time operation control and short-term planning) and offline (long-term planning and business evaluation) to perform the subsequent essential tasks:

- energy flows and system monitoring;
- real-time operation and short-term production planning;
- long-term production planning;
- business evaluation.

3.2.1. Energy flows and system monitoring

Monitoring of energy flows is a key component because it enables the correct control of performance and system status at different temporal intervals. If a accurate and logically structured data collection is performed, statistical and data mining techniques can be successfully employed to provide reliable forecasts about system's future states, long-term performance monitoring, performance feedback, diagnosis of fault detection. In a general sense, this task involves the concept of advanced monitoring with respect to the use of data analytics (machine learning, statistical analysis).

3.2.2. Real-time operation and short/medium-term production planning

Real-time operation and short/medium-term production planning (from twenty-four hour ahead to one week ahead) involves the definition of the operation of generation facilities to produce energy at the lowest cost to serve consumers, considering the operational constraints of technologies, demand and supply from non-controllable sources, emission factors, energy prices, load curtailment, load scheduling, load shifting and storage. Therefore, this function will act during systems' operation. The results obtained by the optimizer must be confronted at every time-step with actual conditions, evaluated through direct measurement and short-term forecasting. If significant differences are found, the optimization algorithm must be run again with the new input dataset. The production can be adjusted dynamically based on actual operating conditions and updated forecasts (actionable intelligence).

3.2.3. Long-term production planning

Long term production planning is performed offline. While in the case of short-term production planning the objective function to be minimized is the operational cost (subject to technical and environmental constraints), however in the case of long-term planning the problem can be reformulated in a multi-objective form, by incorporating investment cost, technical and environmental constraints together with operational costs in the objective function, via appropriate weighting coefficients (multipliers) or separately. The solution of a multi-objective optimization problem leads to a frontier of points (Pareto frontier) which represents the trade-offs between objectives. Long term production planning is necessary, in particular, for systems with high penetration of stochastic RES because of the evolving supply and demand conditions and the possible use of storage strategies. Similarly to the case of short-term planning, the model usefulness relies on accurate forecasting techniques and system behaviour knowledge. Further, within this task it is possible to automate the selection of system configuration (topologies, connections) and technologies (types, sizes) by introducing appropriate logical decision variables [9].

3.2.4. Business evaluation

Finally, the business evaluation task involves generally the comparison of financial indicators such as IRR (Internal Rate of Return), NPV (Net Present Value) and Discounted Payback Time. Further, environmental and energy performance indicators can be added, depending on the type of analysis to be performed. From a modelling point of view, in this case also the problem is formulated in a multi-objective form, obtaining trade-offs between objectives. The detailed metric for global evaluation are reported in the subsequent paragraph.

3.3. Metrics for global evaluation of projects

Long-term production planning and business evaluation affects the configuration of the energy system considered. Therefore, the global evaluation of a project involves the use of appropriate metrics able to provide a synthetic vision (indicators) of the problem. The proposed metrics are reported in Table 1. The indicators are calculated with a balance with respect to a boundary defined by demands, sectors and periods, summarized in Table 2.

Table 1. Proposed metrics (indicators)

Energy	Environment	Economy
Energy demand (end-use)	CO_2 emissions	Net present value (NPV)
Primary energy (fossil, renewable, total)	Pollutant emissions (NO_X, SO_2, PM, etc.)	Internal rate of return (IRR)
Peak power demand		Discounted payback period (DPP)
Exergy		
Embodied energy		

Table 2. Demands, periods and sectors for balance boundary definition

Demands	Periods	Sectors
Heating	Operation year	Residential
Cooling	Period of utilization	Non-residential
Lighting	Project lifetime/life cycle	Industry

Appliances	
Mobility	Transportation

4. Conclusion

The use of multi-commodity network flow models for dynamic energy management aims at finding a compromise between model usefulness, accuracy, flexibility, solvability and scalability. The possibility of constructing easily customized applications, based on a general modelling and programming framework, allows rapid prototyping and, due to the modelling flexibility, it is possible to implement interoperable applications with ongoing research in the field of optimal power flow control. Scalable applications that can work in a distributed way (agents) [10,11], without requiring the huge computational resource that a centralized system would require, are necessary for Smart Grid and DG applications. The wide use in the field of operations research and management science of several kinds of network models expands the possible user base, since the modelling techniques are not belonging only to the specific sector. The presence of a potential large user base can fosters the rapid development of applications, exploiting the recent improvements of predictive analytics and optimization techniques. On the other hand, data visualization techniques and graphical representation of system structure will help in end-user involvement, via a more efficient communication strategy. Finally, in a future perspective, it will be possible to study the properties and to obtain a deeper knowledge of the behavior of large-scale decentralized systems, using complex network modelling theory.

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