Energy management: flexibility, risk and optimization

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1. Introduction

The contributions in this theme issue of Philosophical Transactions of the Royal Society A address important global trends in energy management, both current and anticipated. Particularly in the context of electrical power systems, these trends will present complex scientific challenges in decision analysis and optimization, in the analysis and assessment of risk and in the modelling of flexibility, and will raise numerous computational issues. The articles herein aim to suggest new ways in which engineering and mathematics can combine to address them.

Significant challenges arise from the increasing connection of variable renewable energy generation. Despite their long-term benefits in terms of sustainability, renewable resources such as solar and wind power are both highly variable and partially unpredictable. They, therefore, present operational challenges in assessing and mitigating risk, including issues of imbalance between generation and demand and network constraints. Additionally, there is longer term uncertainty over the technology costs and environmental policies associated with renewable generation, among other factors. These uncertainties at various time scales may imply the need for significant investment in new, more flexible ‘smart grid’ technologies capable of adaptation to a range of future scenarios. As laid out in [1], examples are

— controllable distributed energy assets including storage;
— more flexible transmission systems;
— corrective control following network outages;
— wide area monitoring and control equipment and communications;
— controllable demand and the active participation of end users in, for example, system balancing and congestion management.

Particularly in the presence of uncertainty, such flexible technologies present a variety of new analytical challenges relating to short- and long-term decision-making. Owing to the scale and complexity of electrical power systems, models of their flexible operation under uncertainty may be both difficult to formulate and computationally expensive to evaluate. While on longer time scales, the issue of computational speed is less acute, new planning methods are required which account for both uncertainty and flexibility and can properly deal with the potential explosion of the size of the solution space to search.

This theme issue thus aims to contribute on a variety of levels including novel models and modelling frameworks, surveys of methodologies as yet largely untapped, opinion and outlook.

To date the main methodologies used to address uncertainty in the operation and planning of power systems have been stochastic programming and robust optimization [1]. The mathematical contributions herein draw from a wider range of approaches including the quickest detection of change in a noisily observed signal [2], approximate stochastic optimization over the large solution spaces encountered in planning problems [3], the conservative estimation of probabilities from small samples of data via Bayesian inference [4], exact solution methods for lower dimensional stochastic control problems via partial differential equations (PDEs) [5] and stochastic calculus [6,7], and a perspective on system-level constraints from the theory of games and teams [8].

Tindemans & Strbac [4] address the question of assigning probabilities to events based on small samples of data. Power systems are designed, operated and maintained in order to avoid certain high-impact events and in many power systems engineers have been successful in maintaining a low frequency or probability for these events. This success leads to the problem that a limited amount of data is available on failures, making statistical and probabilistic analyses challenging. However, many approaches to optimization under uncertainty require some notion of probability in order to balance cost against risk. In this context, a conservative approach to the estimation of probabilities is appropriate and the authors provide a methodology based on Bayesian statistics which infers ranges for probabilities of interest.

Where more extensive datasets exist, or where representative computer simulations can be performed, another feasible approach is to estimate the values of unknown probabilities. In the non-parametric approach, probabilities are not assumed to arise from any particular class of distributions and are inferred directly from data. A recent example is [9], where probabilistic neural networks are applied to learn relevant probabilities from simulated datasets. In the latter work, these probabilities are used to solve a problem of corrective control in the framework of optimal detection, to which Johnson et al. give an introductory overview [2]. This theory is concerned with the detection of a signal in the presence of noise, including the so-called online settings where the speed of decision-making is a key concern. It is hoped that Johnson et al. [2] will stimulate further applications of this promising, and widely applicable, probabilistic methodology to corrective control.

Alternatively, a parametric family of probability measures may be chosen and its parameters inferred from the data. This approach is particularly suited to the study of stochastic processes having random dynamics, where the non-parametric approach can become infeasible. In the energy context, relevant stochastic processes include noisily observed, repeated measurements and dynamic prices: a recent example is [10], where the stochastic optimal control of a combined heat and power plant is studied in the presence of real-time markets, and the real option value of thermal storage is derived. The parametric perspective is taken in two of this issue’s contributions [5,7] which both deal with the optimal operational control of energy storage under uncertainty. Utility-scale battery storage projects are becoming increasingly economically viable as the cost of battery storage continues to decline. Batteries have a range of physical
and economic applications including energy price arbitrage and power system balancing. The modelling of stochastic dynamics is particularly important in this operational context and stochastic differential equations (SDEs) offer a powerful mathematical approach. Szabó & Martyr [7] analyse a proposed new financial contract for the provision of balancing services using energy storage, studying its operational and economic implications. Taking a different perspective, Johnson et al. [5] aim to optimize revenues from wind generation coupled with storage by converting an SDE problem into a deterministic problem of PDEs. The PDE formulation is solved numerically and, as such, is able to take account of additional modelling detail such as a terminal time for the optimization or seasonality in the market price.

Johnson & El-Ghandour [6] address the question of the economic impact of storage when used for price arbitrage. This contribution aims to provide a practical bridge between the parametric and non-parametric approaches. Motivated by the desire to avoid risks associated with potentially incorrect inference of model parameters, a novel approach is provided which is based on SDEs but circumvents the user’s need to infer their parameters. Instead, the methodology works directly on the relevant observed data.

The article by Mijatović et al. [3] concerns the management of risks associated with network constraints at the distribution level. In the model, flexibility from demand response is procured from industrial and commercial customers local to a particular constrained network asset. The work provides another interesting perspective on the challenging issue of assigning probabilities in modelling. Relative to earlier work (e.g. [11]), the main novelty is to take account of uncertainty in the capability of customers to participate in a demand side response programme. They show that on one hand this changes the structure of the optimization problem, because the solution space can quickly become prohibitively large and a computationally efficient heuristic search is needed [12]. An interesting feature is that, given this structure and within limits, the results are relatively insensitive to the particular choice of probabilities, making the issue of their detailed specification less significant.

By contrast, Kulkarni [8] does not address the modelling or analysis of probabilistic uncertainty, instead focusing on the issues arising when optimization is performed by multiple agents. This review paper highlights the important issue of shared resources or constraints which arises commonly due to system level limitations in problems of energy management. In this setting, an introduction is provided to the theory of games, where the agents have differing objectives, and teams, where the agents have a common objective but may perform different roles. The issues addressed include concepts of equilibrium and the existence, uniqueness and efficiency of equilibria. The authors also discuss the important issue of the relationship between shared constraints and notions of price.

The contributions that are more focused on technical aspects of electrical power systems also cover a number of advanced analytical, simulation and optimization techniques for different applications, and are naturally aligned, in terms of methodologies and approaches, with the more mathematical papers discussed above. In particular, there are two ‘framework’ contributions that cover important general applications of stochastic and probabilistic modelling, namely smart grid and low-carbon power system planning [1], and system stability analysis [13]. Then, a number of papers deal with more specific and technical topics such as optimal location of advanced measurement devices in transmission networks [14], distribution network voltage control through multi-agent systems [15] and identification of analytical conditions for synchronous generators’ stability [16].

The already mentioned contribution by Moreno et al. [1] introduces, in the context of planning a renewables-rich power system, an optimization framework that deals with long-term uncertain scenarios, represents increased operational details, and is able to model the effects of multiple flexible, smart grid technologies. The importance of this novel framework is that, as demonstrated in the paper, proper modelling of uncertainty and operational constraints in planning is key to valuing operationally flexible solutions that can lead to optimal investment in a smart grid context. A review of the most used practices in power system planning under uncertainty is also presented, advocating the need for new and computationally effective optimization tools. These
tools are essential to properly value the benefits of flexible, smart grid solutions in planning and thus accelerate investment into the most appropriate portfolio of renewable energy sources and complementary enabling smart technologies.

Another key ‘framework’ contribution in this issue is [13]. Again in the context of a rapidly evolving power system with smart grid technologies and multiple temporal and spatial uncertainties, while Moreno et al. [1] deal with optimal investment under uncertainty, Milanović [13] highlights and discusses the importance of probabilistic approaches in a very technical topic such as power system stability analysis. In particular, the paper describes for the first time an integral framework for probabilistic stability analysis including small and large angular stability as well as frequency stability. The framework is demonstrated through a number of illustrative examples and recent results from probabilistic stability analysis in uncertain power systems, providing invaluable guidance for handling uncertainties in stability studies.

Gajare et al. [14] discuss a specific smart grid technology that can improve power system operation and stability (also see [13]) by decreasing the number of protection maloperations under stressed system conditions that may often lead to blackouts/large-scale disturbances. This technology is a wide area measurement system that allows real-time monitoring of the transmission system through the so-called phase measurement units. However, as part of investment optimization in new technologies [1], it is key to identify the strategic locations where PMUs should be installed and, at the same time, minimize their number. The work thus presents a method to decide the strategic locations for PMU placement, which can then be used for determining the minimum number of PMUs required.

Pullaguram et al. [15] introduce a coordinated control scheme aimed at reducing voltage unbalances in low-voltage distribution networks. The control approach considers single phases, as typical unsymmetrical line configurations as well as the rise of both new relatively large loads (e.g. electric vehicles and heat pumps) and embedded generators (e.g. solar PV supported by batteries) can exacerbate phase voltage unbalances. The proposed control methodology adopts a consensus-based coordination approach achieved using a multi-agent system, in which each agent makes their own estimate of the network voltage profile and uses it to modify the reference power of individual single phase injections/loads from PV and batteries. Reactive power is also locally controlled to further smoothen the network voltage profile. The contribution thus provides an interesting view on a very technical aspect of grid control performed via multi-agent optimization [8].

Schiffer et al. [16] deal with another classical power system application of mathematical concepts, namely, stability analysis of synchronous generators (see also [13]). Specifically, analytical conditions for almost global stability of an operating point of a synchronous generator connected to a strong network are derived under certain conditions. The methodology proposed adopts the recently proposed concept of input-to-state stability (ISS)-Leonov functions. This is an extension of the cell structure principle developed by Leonov and Noldus to the ISS framework, but also provides, as a key research contribution, an additional robustness guarantee.

Based on the above comments, it can be appreciated how the contributions discussed represent a complementary mix of modern power system and smart grid applications and advanced mathematical concepts and modelling techniques. We therefore believe that this issue of Philosophical Transactions of the Royal Society A can pave the way to new interdisciplinary research opportunities for addressing various mathematical and computational challenges that have recently arisen in low-carbon power systems and smart grids.

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