# Guest Editorial
# Distributed Control and Efficient Optimization Methods for Smart Grid

SMART grid proactively uses the state-of-the-art technologies in communications, computing, and control to improve efficiency, reliability, sustainability, and stability of the electrical grid. In particular, distribution networks are expected to undergo dramatic changes by incorporating a large number of sensors and thousands of controllable devices such as distributed generators, batteries and flexible loads. To be able to efficiently operate such complex large-scale systems, new sets of control and optimization tools should be developed. On a slow time scale, optimization theory plays a major role in solving various large-scale decision-making problems for future power transmission and distribution systems. One major challenge is the design of computational methods for handling fairly detailed power system models that often include continuous and discrete nonlinearities. It is also important to develop distributed computation techniques to shift the computation from a centralized platform to many computing devices.

On a fast time scale, control theory could be used to provide stability and robustness margins for the entire system in presence of uncertainty and stochasticity, and yet offer some optimality guarantee on the real-time behavior. Since centralized controllers often suffer from computation, communication and robustness issues for power systems with many controllable devices, distributed control is perhaps the only viable strategy for such systems. However, there are several challenges regarding the design of optimal distributed controllers for different parts of the grid, the co-design of the underlying communication network of the distributed controller, the development of mechanisms for the coordination of different distributed controllers used in the system, and the replacement of time-consuming offline optimization algorithms with real-time distributed controllers in order to accelerate computations and improve the robustness of the closed-loop system.

This special issue brings together 17 papers addressing several problems on optimization and control techniques for power systems. A short description of each paper is provided below.

Some of the papers in this issue that study advanced optimization techniques are as follows. The paper "A Survey of Distributed Optimization and Control Algorithms for Electric Power Systems" by D. K. Molzahn *et al.* reviews recent progress in applying distributed optimization and control techniques to problems relevant to electric power systems. After providing background material on various power flow representations and distributed optimization and control techniques, this survey summarizes applications of distributed algorithms to optimal power flow (both in offline and online settings), optimal frequency control, optimal voltage control, and optimal wide-area control for oscillation damping. "Real-time Optimal Power Flow" by Y. Tang *et al.* proposes an online optimization approach to optimal power flow. The developed algorithmic approach relies on a quasi-Newton method to track the critical points of the optimal power flow problem when interconnected to a power system via real-time measurements and actuation. The results are validated with detailed simulation studies. "Optimal Power Flow of Radial Networks and its Variations: A Sequential Convex Optimization Approach" by W. Wei *et al.* proposes a sequential convex optimization method to solve different types of optimal power flow problems over radial networks. The non-convex branch power flow equation is decomposed as a second-order cone inequality and a non-convex constraint involving the difference of two convex functions. Provided with an initial solution offered by an inexact second-order cone programming relaxation model, this approach solves a sequence of convexified penalization problems and recovers a feasible power flow solution that usually appears to be close to a global optimum. In order to improve the computational tractability of convex relaxations for optimal power flow solution algorithms, "Hybrid Methods in Solving Alternating-Current Optimal Power Flows" by J. Marecek *et al.* proposes an approach that switches from the first-order methods commonly used in distributed optimization algorithms to second-order methods that have faster convergence characteristics when near a solution. In order to determine how close the current iterate is to the solution, the proposed approach applies techniques developed using Smale's theory. Case studies demonstrate superior numerical characteristics compared to the separate application of both first- and second-order methods.

Some of the papers in this issue that study distributed control problems are as follows. The paper "Distributed and Decentralized Voltage Control of Smart Distribution Networks: Models, Methods, and Future Research" by K. E. Antoniadou-Plytaria *et al.* surveys the literature of distributed and decentralized voltage control algorithms and discusses future research needs. The survey classifies the literature based on communicated scheme, control model, and solution methodology. "Distributed Optimal Dispatch of Distributed Energy Resources over Lossy Communication Networks" by J. Wu *et al.* proposes a distributed algorithm for optimally dispatching distributed energy resources that communicate over a lossy network. It shows that, as long as the communication network is strongly connected with a positive probability and the random packet drops are independent and identically distributed, the proposed algorithm converges to an optimal dispatch. "A Distributed Framework for Stability Evaluation and Enhancement of Inverter-Based Microgrids" by Y. Song *et al.* considers the small-signal

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stability problem for microgrids by analyzing the associated system Jacobian matrix in a distributed fashion. It develops algorithms that rely on distributed communication and exploits the structural properties of the Jacobian matrix in order to compute the full Jacobian and eventually enhance the system stability. The paper demonstrates that power dispatch and power sharing schemes are preserved under their distributed control approach. "A Distributed Control Approach for Enhancing Smart Grid Transient Stability and Resilience" by M. Ayar *et al.* proposes a distributed nonlinear robust controller to improve the transient stability margins of Synchronous Generators (SG) in the presence of excessive communication delay and cyber-physical disturbances. The proposed controller uses phasor measurement units to receive real-time measurements and actuates distributed storage systems to inject or absorb power in order to accelerate stabilization of frequency oscillations of SG following a disturbance. The controller is designed for robustness to delay and additive disturbances.

Some of the papers in this issue that study optimal control and model predictive control are as follows. The paper "Low-Complexity Distributed Predictive Automatic Generation Control with Guaranteed Properties" by P. R. B. Monasterios and P. Trodden presents an automatic generation control for multi-area power systems based on distributed model predictive control (MPC), where local area controllers solve nested MPC problems to regulate states to steady values and reject disturbances. The proposed scheme guarantees constraint satisfaction and stability. "Model Predictive Control of Distributed Air-Conditioning Loads to Compensate Fluctuations in Solar Power" by N. Mahdavi *et al.* proposes a strategy to coordinate air-conditioning to respond to the rapid fluctuations of photovoltaics at the minute-by-minute timescale. A second-order model of air-conditioner dynamics is used in conjunction with model predictive control to compensate for photovoltaic variation. A case study based on modeling 1000 air conditioning units demonstrates ability to compensate for fluctuations despite many uncertainties. "Cooperative MPC-Based Energy Management for Networked Microgrids," by A. Parisio *et al.* considers the scheduling of energy, both electrical and thermal, over the 10 minutes and longer timescale. A model predictive control approach is taken to scheduling and a case study with 15 coordinated microgrids is presented, showing savings over uncoordinated operation. "A Macroscopic View of Demand-Side Grid Regulation Through Fluid Queueing Models and $H_2$ Control" by F. Bliman *et al.* considers a demand aggregator handling a large number of deferrable loads through a simple interface. The loads must align their overall consumption with an operator-provided reference. A macroscopic model of the load aggregate is developed as a two-state stochastic differential equation, with a scalar input controlling deferred service, where deadlines are enforced. The solution yields a distributed implementation with mild communication requirements and it is tested in a simulation environment using real-world grid frequency regulation signals, achieving a high performance with the relevant industry metric.

The following papers address a diverse set of topics related to the control and optimization of power systems. The paper "Privacy-Protecting Energy Management Unit Through Model-Distribution Predictive Control" by J. X. Chin *et al.* designs an energy management method based on energy storage and local generation in order to minimize mutual information between a consumer's energy consumption and the net demand seen by the grid. It is shown that the method is effective in reducing information leakage at the expense of increased energy cost. "Optimal Placement of Energy Storage in Distribution Networks" by Y. Tang *et al.* studies the storage placement problem in a spatially continuous and homogeneous setting, where all loads take the same shape. It shows that the optimal storage allocation is near the leaves of a radial network, and demonstrates insightful monotonicity properties on the optimal capacity as well as on the locational marginal value. The results are developed in a continuous setting and validated in a detailed discrete model. "Price-Based Schemes for Distributed Coordination of Flexible Demand in the Electricity Market" by A. De Paola *et al.* applies Lyapunov-based techniques in a game theoretic framework to develop an iterative control algorithm for coordinating price-response appliances that are programmed with individual customer preferences. Simulations demonstrate the proposed algorithm in future scenarios of the Great Britain power system with high penetrations of flexible demand. "Voltage Stability Prediction Using Active Machine Learning" by V. Malbasa *et al.* proposes an active learning technique for monitoring the voltage stability in transmission systems. It identifies operating points where machine learning predictions based on power system measurements contradict with actual system conditions. Its experiments show a significant advantage in relation to the training time, prediction time and number of measurements that need to be queried to achieve high prediction accuracy. "Distributed Optimal Power Management via Negawatt Trading in Real-time Electricity Market" by Y. Okawa and T. Namerikawa proposes a scheme to allow customers to change their demands to receive monetary rewards through a mechanism called negawatt trading. It uses a distributed market algorithm to adjust customer demand to compensate for imbalances in generation. Storage elements are also considered in this algorithm. A case study based on an IEEE network is used to demonstrate the effectiveness of the mechanism over traditional methods.

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