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Technical Challenges of the Smart Grid: From a Signal Processing Perspective

We are at a historic point where countries throughout the world are charting new ways to produce, distribute, deliver, and use electricity. Whereas current electricity systems are based on a one-way flow of energy and information from the source to the end user, the future smart grid system will provide a two-way flow of energy and information throughout the system. The results will herald a potential paradigm shift from current economies driven by hydrocarbon energy to the ones driven by a variety of energy sources, including a significant portion of wind, solar, and other renewable energies. Of particular interest is the role of signal processing in data representation and forecasting to track renewable energy generation, load demand, and the rapid monitoring and detection of infrastructure attacks, both in cyber- and physical infrastructures. Therefore, the main emphasis of this special issue is on the technical challenges of the smart grid from a signal processing perspective.

The selected articles in this special issue aim at articulating signal processing methodologies critical to the design and operation of the future smart grid. For example, the deployment of plug-in hybrid electric vehicles (PHEVs) and plug-in electric vehicles (PEVs) involves researching not only the vehicles themselves, but also the new challenges for electrical power generation and distribution grid infrastructures that support them. Addressing these challenges for the smart grid requires technology that leverages a number of emerging signal processing techniques. Andres Kwasinski and Alexis Kwasinski present an overview of PHEVs, EVs, and smart grid characteristics in their article, "Signal Processing in the Electrification of Vehicular Transportation." This is followed by a discussion of signal processing techniques used to model and forecast the impact of EVs on the electric power grid and vehicle charging management.

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A tenet of the smart grid is to enable a more interactive and intelligent power grid. This is the theme of the second article by Top et al., "Observing the Power Grid." The article begins with the history and operation of the power grid before detailing the signal processing and technologies necessary for collecting and processing the data. It also provides a series of examples from actual data and demonstrates simple signal processing techniques for acquiring, analyzing, and applying data extracted from a common wall outlet.

The future grid will be expected to provide real-time system-wide state awareness. Advances in state estimation (SE) via enhanced measurement systems will play an important role in attaining this goal. The article "State Estimation in Electric Power Grids" by Huang et al. surveys evolution in SE research over the last four decades and explores signal processing research for pushing frontiers, discussing concepts like forecast-aided SE as well as distributed estimation for multiarea SE from a signal processing perspective. The article highlights the idea of event-triggered approaches to SE, which has the potential to reduce the future grid's data processing and communications infrastructure requirements. It also surveys algorithms and applications for SE at the distribution-system level.

In the smart grid, frequency drifts occur due to frequent switching between the main grid and microgrids, together with generation-consumption mismatch, harmonics, and voltage sags. In "Adaptive Frequency Estimation in Smart Grid Applications," Xia et al. examine the inherent problems associated with these phenomena. The article describes the theoretically optimal minimum variance unbiased estimators for frequency drift that can provide estimates in as little as a quarter of a frequency cycle as well as frequency estimation methods for three-phase power systems that work in both balanced and unbalanced system conditions.

One of the most important missions of the smart grid is to facilitate public participation in controlling energy consumption and cost. Two articles are dedicated to this topic. The article "Demand-Side Management in the Smart Grid," by Alizadeh et al. surveys the different options to make the electrical load responsive and critically analyzes the challenges that lie ahead with the implementation of direct load control or real-time pricing, which include managing a capillary information telemetry infrastructure to implement the control as well as overcoming the uncertainty in the load response in real time and its potential repercussions on the safe operation of the grid. One of the key technologies in

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the demand response domain that is attracting considerable attention is having real-time pricing of electricity delivered to consumers. The second article in the area of demand response by Chan et al. is "Load/Price Forecasting and Managing of Demand Response for Smart Grids." It is specifically devoted to analyzing methodologies for load/price forecasting. The article showcases advances in signal processing techniques that will find concrete applications in the price prediction for demand-response management.

Using game theory for modeling, smart grids present promising potential due to the heterogeneous and large-scale nature of the smart grid, which is expected to integrate advanced power, communications, control, and computing technologies. This is covered in the article "Game-Theoretic Methods for the Smart Grid" by Saad et al. The article constitutes a unified reference that gathers state-of-the-art contributions on the topic and providing insights to future opportunities for adopting game theoretic methods for smart grid design and analysis.

One article in our collection is dedicated to the critical issue of communication security in smart grid networks. The article "Coordinated Data-Injection Attack and Detection in the Smart Grid" by Cui et al. surveys the theoretical framework to study malicious data injection attacks in power grid sensors systems. Its focus is on the distributed implementation of attack detection schemes and explores the tradeoff between detection speed and reliability.

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Another important area advancing in conjunction with the smart grid architecture is the physical layer design of power line communication (PLC) systems, which have an attractive complementary role with respect to wireless technologies, in the deployment of advanced metering infrastructure. Specifically, narrowband PLC (NB-PLC) systems operating in the 3–500 kHz band are a viable candidate to provide a two-way communication link between smart meters and the local utility. The article "Local Utility Power Line Communications in the 3–500 kHz Band" by Nassar et al. covers the salient features of NB-PLC physical layer communications and addresses challenges on how to overcome distortion and noise. In their article, the authors review signal processing approaches to model channel impairments and impulsive noise and mitigate their effects in NB-PLC systems. They examine ways to improve the communication performance based on current and emerging standards by focusing on the feasibility of PLC deployment and field trial data.

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