Guest Editorial
The Theory of Complex Systems With Applications to Smart Grid Operations

The existing power grids, being recognized as one of the significant engineering accomplishments, work exceptionally well for the purposes they have been designed to achieve. Enabled by the advances in sensing, communication, computation, and actuation, smart power are rapidly growing in scale, inter-connectivity, and complexity. Major paradigm shifts in power grids include departing producercontrolled structures and transforming to more decentralized and consumer-interactive ones, being more distributed in electricity generation, enhancing the coupling between the physical and cyber layers, and operating in more variable and stochastic conditions. Driven by these emerging needs, power grids are anticipated to be complex and smart networked platforms in which large volume of high-dimensional and complex data is routinely generated, exchanged, and processed for various monitoring, control, and scheduling purposes.

This special issue covers some of the recent research in the theory of complex systems with applications to power grid operations, which present novel research contributions in all aspects of complex and large-scale systems of relevance and significance in power grids. The papers in this special issue can be broadly organized into four categories addressing issues pertinent to (I) analyzing cascading failures, (II) security measures for resilient operation, (III) scheduling, resource management, power flow optimization, and (IV) grid monitoring and control.

I. Analyzing Cascading Failures

As the smart grid generation, loads, and transmission networks are transformed and become more complicated, there is no guarantee that the reliability that is essential to society will be maintained. In particular, rare but high-impact large cascading blackouts pose a significant risk that must be managed. The special issue papers cover a range of approaches to analyzing these blackouts. “Cascading Failure Analysis for Indian Power Grid” simulates and analyzes the unstable modes of one of the largest blackouts ever recorded. To forestall blackouts due to transient instability, it is necessary to respond quickly to multiple outages, and “Transient Instability Mitigation For Complex Contingencies With Computationally Constrained Cost-Based Control” shows how to efficiently select controls to do this using synchrophasor measurements. In a more theoretical vein, “Impact of Topology on the Propagation of Cascading Failure in Power Grid” studies how network connectivity characteristics used in complex network theory affect the average propagation of cascading outages determined using branching process models. Voltage collapse is a form of blackout in which voltages progressively decline due to a combination of dynamical instability and cascading events. “Distributed Monitoring of Voltage Collapse Sensitivity Indices” shows how to coordinate synchrophasor measurements in a distributed way to monitor the proximity to slower voltage collapses, and “A New Dynamic Performance Model of Motor Stalling and FIDVR for Smart Grid Monitoring/Planning” applies energy methods to model and analyze the cascading stall of induction motors that can cause a fast version of voltage collapse. Finally, “Cascading Failures in Interdependent Infrastructures: An Interdependent Markov-Chain Approach” provides a stochastic model that enables tracing and analyzing the propagation of failures in interconnected infrastructures.

II. Cyber Security

The distributed and highly connected nature of power grids can be a source of security vulnerability. Especially, as the physical and cyber operations become more strongly coupled, any malicious intrusion can potentially cause severe disruptions in energy generation, transmission, and distribution. Thus, modernizing the aging grids will be truly effective if they are also protected against cyber and physical attacks. Hence, the issue of cyber-physical security against malicious adversarial attacks will be critical. Novel threat mitigation methods that ensure the resilience of critical functional blocks and are able to cope with the large-scale distributed nature of the system need to be developed. This special issue contributes to the timely topic of security analysis and threat mitigation methodologies with a view achieving resilience in the context of critical applications such as monitoring and state estimation. The special issue papers cover a range of approaches that aim to enhance the resiliency of grid operations against data injection attacks. “Maximum Distortion Attacks in Electricity Grids” analyzes the stochastic interplay between the effectiveness and detectability of decentralized attacks. “Physical System Consequences of Unobservable State-and-Topology Cyber-Physical Attacks” considers an attack that both physically trips a line and injects data into the measurements. The goal of the attack is to increase the power flow on a target line. “A Bayesian Algorithm to Enhance the Resilience

Date of current version June 17, 2016.
Digital Object Identifier 10.1109/TSG.2016.2575418

of WAMS Applications Against Cyber Attacks" proposes a Bayesian-based approximated filter to extract oscillatory parameters from the manipulated measurements in some malicious disturbances. "Data Injection Attacks on Smart Grids with Multiple Adversaries: A Game-Theoretic Perspective" focuses on data injection attacks launched by multiple non-cooperating adversaries and analyzes the effectiveness of the attacks in a game-theoretic framework.

III. Optimization and Scheduling

The 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. On a fast time scale, control theory aims to provide stability and robustness margins for the entire system in the presence of uncertainty and stochasticity and offer some optimality guarantee on the real-time behavior. Since centralized controllers often suffer from serious computation, communication, and robustness issues for power systems with many controllable devices, distributed control is perhaps the only viable strategy for such systems. The special issue covers a range of power flow optimization and scheduling issues under different physical settings and constraints. "Preserving Privacy of AC Optimal Power Flow Models in Multi-Party Electric Grids" presents a method for solving a multi-party optimal power flow on a cloud computing platform while preserving the privacy of the parties. "Scalable Optimization Methods for Distribution Networks with High PV Integration" considers the problem of coordinated active power curtailment and reactive power compensation in a power distribution grid in which it is shown that the optimal power flow can be cast as a convex problem. "Probabilistic Decision Making for the Bulk Power System Optimal Topology Control" proposes an approach for optimal transmission switching in which probabilistic models for wind generation and load are taken into the consideration. "Extended Second Price Auctions with Elastic Supply for PEV Charging in the Smart Grid" provides a game-theoretic framework for electric vehicle charging at the distribution network. "A Fast Distributed Algorithm for Large-Scale Demand Response Aggregation" presents a fast distributed gradient algorithm applied to a double smoothed dual function for home energy management. "Cooperation of Storage Operation in a Power Network with Renewable Generation" investigates the problem of coordinating intermittent sources and storage units in to minimize the use of conventional power generation source.

IV. Monitoring and Control

Future grids will be equipped with many more sensors streaming data to the operation centers. This large scale and complex data from synchrophasors provides both opportunities and challenges to real-time system operation. Such data can provide extremely useful inference and information about system states as well as classification of events, and their localization. "ADMM Optimization Strategies for Wide-Area Oscillation Monitoring in Power Systems under Asynchronous Communication Delays" investigates the effect of communication delays between PDCs on a decentralized algorithm for performing wide-area oscillation monitoring. "Managing Contingencies In Smart Grids via the Internet of Things" deals with the emergency situations arising due to transmission line contingencies by optimally curtailing smart appliances. "Non-Disruptive Load-Side Control for Frequency Regulation in Power Systems" investigates non-disruptive load-side control for the provision of secondary frequency control and presents an approach for integrating controllable load units into existing frequency control schemes. "A Restorative Self-Healing Algorithm for Transmission Systems Based on Complex Network Theory" presents an electrical betweenness approach for performing restorative network reconfiguration.

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