Guest Editorial: Special Issue on Communications and Data Analytics in the Smart Grid

The Smart Grid represents an unprecedented opportunity to move the electric grid into a new era of reliability, availability, and efficiency. It uses two-way communications, digital technologies, advanced sensing and computing infrastructure, and software abilities to provide improved monitoring, protection and optimization of all the grids' components, including generation, transmission, distribution and consumers.

Communication infrastructures are critical for the successful operation of modern smart grids. Numerous dedicated solutions, such as power line communications, RF mesh, modified long term evolution (LTE), CDMA at sub GHz bands, dedicated fiber along high voltage lines, etc. have been investigated and deployed in modern power systems. Additionally, future 5G networks promise to provide the QoS of dedicated networks through a multi-purpose infrastructure by network slicing. 5G will greatly support distributed Smart Grid deployments, as well as ultra-reliable low latency communications, for automation and protection mechanisms. Given the wide choice of communication and network technologies, intensive research efforts are needed to compare options and optimize solutions for Smart Grids.

Ongoing digitalization, e.g. deployment of advanced metering infrastructures (AMI) and phasor measurement units (PMUs), as well as intelligent automation systems, is drastically increasing the amount, quality, and variety of data that utilities and grid operators are collecting on supply, transmission, distribution, and demand. Big data analytics in Smart Grids transform the large volume of data into meaningful inputs that help to predict and understand end-customer behavior, improve network resilience and faults, enhance security and monitoring, and optimize resource management and future planning. To this end, cross-disciplinary research efforts in machine learning, deep learning, statistics, and optimization are needed.

With the above vision, a Call for Papers for a Special Issue (SI) on Communications and Data Analytics in Smart Grid, IEEE Journal on Selected Areas in Communications, was published in February, 2019. The SI attracted 56 high quality submissions from authors distributed over 19 countries. All papers received at least three reviews and the accepted papers went through at least one revision round. We eventually accepted 19 technical papers covering various aspects of communications and data analytics in Smart Grids. The contributions of the papers are categorized as follows.

Demand Response, Energy Market and Transactive Energy

The paper "Posted-Price Retailing of Transactive Energy: An Optimal Online Mechanism without Prediction" proposes a theoretic framework to study a general transactive energy retailing problem in smart grid. The authors consider the setting where the customer arrival information is unknown and focus on maximizing the social welfare of the transactive energy system through a posted-price mechanism that runs in an online manner with causal information only. Considering a competitive analysis framework, it is shown that the proposed method is optimal in the sense that no other online mechanism can achieve a better competitive ratio. A vehicle charging case is used to evaluate and validate the theoretical results.

The paper "Peer-to-Peer Energy Trading in DC Packetized Power Microgrids" proposes a power packet trading protocol in DC power grids. The authors formulate the P2P trading problem as an auction game, where the energy subscribers submit bids to compete for power packets, and a controller decides the energy allocation and power packet scheduling. The convergence and complexity of the auction scheme have been analyzed.

The paper "Storage or No Storage: Duopoly Competition Between Renewable Energy Suppliers in a Local Energy Market" studies the market competition between renewable energy suppliers with or without energy storage in a local energy market. The authors formulate the interactions between renewable energy suppliers and consumers as a three-stage game-theoretic model, based on which characterize a price-quantity competition equilibrium in the local energy market, and further characterize a storage-investment equilibrium. Several counterintuitive findings are discussed based on the framework and the simulation studies.

The paper "Relaying-Assisted Communications for Demand Response in Smart Grid: Cost Modeling, Game Strategies, and Algorithms" describes a relay-based communication system for Smart Grids: while so-called data aggregator units (DAUs) are deployed and operated by the utility, the relaying base stations are operated by telecommunication companies. The authors formulate the interactions between the utilities and the telecom operators as Stackelberg game to reduce the cost of the utilities and increase the profit of the telecom operators. A distributed algorithm based on the backward induction method, taking into account the admission control, is proposed to search for the equilibrium. The results of an in-depth analysis show that the proposed relaying mechanism can be of benefit to both players.

Estimation and Prediction in Smart Grids

The paper "Residential Customer Baseline Load Estimation Using Stacked Autoencoder with Pseudo-load Selection" proposes an unsupervised machine learning-based solution for residential customer baseline load (CBL) estimation. The stacked autoencoder (SAE) is used to generate pseudo-load pool and reconstruct residential CBL, and a support vector machine (SVM) classifier is self-trained to conduct the pseudo-load selection. Test results show that the accuracy of the residential CBL reconstruction significantly improves as compared to existing methods.

The paper "PMU Placement Optimization for Efficient State Estimation in Smart Grid" develops algorithms to determine optimal placement of phasor measurement units. The algorithms aim to find the minimal number of PMUs and their location so that the mean-square error or the mutual information of the estimated phase angles is within a given bound. The proposed algorithms rely on iterative convex optimization and on an iterative greedy path optimization. These algorithms are applied to reference grids of sizes up to more than 2000 buses in order to exemplarily show the behavior of the optimization metrics and the execution times.

The paper "Scenario Forecasting of Residential Load Profiles" proposes a scenario forecasting approach for residential load using flow-based conditional generative models. In particular, the flow-based approach utilizes a flow of reversible transformations to maximize the value of conditional density function of future load given the past observations. The approach can generate scenarios that are both diverse and follow the true pattern of the load.

The paper "Probabilistic Forecasting of Battery Energy Storage State-of-Charge under Primary Frequency Control" utilizes a multi-attention recurrent neural network (MARNN) to forecast the state of charge (SoC) of battery energy storage systems (BESSs) under primary frequency control. The framework is also extended to a variational MARNN for providing a robust probabilistic forecast. The performance of the proposed approaches is validated in three European synchronous areas with different droop curve characteristics of primary frequency control.

The paper titled "Sequential Generative Adversarial Network Based Scenario Generation for Microgrid Day-Ahead Scheduling with High Wind Penetration" addresses the challenging problem of forecasting regenerative energy production based on wind power to derive appropriate scheduling of energy production/consumption in microgrids. The authors propose a new sequential generative adversarial networks (SeqGAN) approach and validate the approach with real-life data sets and simulations. The results clearly demonstrate the performance advantages of the proposed SeqGAN solution compared to baseline approaches, such as Gaussian distribution and KDE (kernel density estimation) methods.

Cyber Security and Resilience for the Smart Grids

The paper "Fault Location in Power Distribution Systems via Deep Graph Convolutional Networks" develops a new graph convolutional network (GCN) framework in order to identify the location of faults in power distribution networks. The proposed approach incorporates the measurements from different buses in a flexible manner, especially when the losses of data are taken into consideration. It also takes into account the system topology. The effectiveness of the GCN model is corroborated by the IEEE 123 bus benchmark system. Simulation results show that the GCN model significantly outperforms other widely-used machine learning schemes with very high fault location accuracy. In addition, the proposed approach is robust to measurement noise and data loss errors. Data visualization results of two competing neural networks are presented to explore the mechanism of GCNs superior performance. A data augmentation procedure is proposed to increase the robustness of the model under various levels of noise and data loss errors. Finally, the model can adapt to topology changes of distribution networks and perform well with a limited number of measured buses.

Smart grid systems are potentially vulnerable to network server attacks as data collector knowledge heavily relies on real-time consumer usage data. The paper entitled "An Efficient Signcryption Protocol for Hop-by-Hop Data Aggregations in Smart Grids" proposes an efficient scheme to secure collection of data from smart meters using aggregation trees. The proposed scheme includes homomorphic encryption and aggregate signature. The paper also provides detailed security proofs, as well as comparisons to state-of-the-art schemes highlighting its superior performance.

The paper "Assessing and Mitigating Impact of Time Delay Attack: Case Studies for Power Grid Controls" investigates smart grid control scenarios in which an attacker maliciously adds delay to the actuator communication. The paper introduces an approach to assess the joint impact of such attacks on stability and safety (here in the meaning of bounded system state) utilizing a Machine Learning model trained by offline simulations. The approach is applied to generation control based on grid frequency measurements and to control of a thermal power plant in order to demonstrate the benefits on accuracy and performance of the joint stability and safety assessment. An attack mitigation approach is proposed that uses a variant of the Machine Learning Model to search for suitable controller gain settings.

The paper "A Dependency Analysis Model for Resilient Wide Area Measurement Systems in Smart Grid" develops an algorithm for deployment of wide-area measurement systems (WAMS) in smart grids, aiming at finding optimal trade-offs between cost and resilience. The proposed solution is based on minimization of the impact of dependencies among the components of the WAMS system. Algorithms are developed both for the case where the WAMS system is under design, and for the case where it already exists and needs to be equipped with some form of redundancy to enhance resilience of the smart grid. The methodology is based on a dependency analysis approach that calculates the degree of dependency in a graph-based representation of the WAMS infrastructure where nodes are buses, PMUs or communication links. The simulation results show that the proposed method is able to suggest sub-optimal WAMS topologies that combine robustness and redundancy.

The paper "Model-based and Data-driven Detectors for Time Synchronization Attacks against PMUs" addresses the important class of cyberattacks, namely, the time synchronization attacks (TSAs) against Phasor Measurement Units (PMUs). These attacks pose a severe threat to smart grid security. In this paper, the authors present an approach for detecting TSAs based on the interaction between the time synchronization system and the power system. The methodology is built based on a phasor measurement model which is used to derive an accurate closed-form expression for the correlation between the frequency adjustments made by the PMU clock and the resulting change in the measured phase angle, without an attack. One model-based and three data-driven TSA detectors are then proposed that can exploit the change in correlation due to a TSA. Using simulations, the authors evaluate the proposed detectors under different strategies for implementing TSAs, and show that the proposed detectors are superior to state-of-the-art clock frequency anomaly detection, especially for unstable clocks.

The paper "Phasor Measurement Units Optimal Placement and Performance Limits for Fault Localization" investigates the performance limits of identifying the location of faults in power systems using synchrophasor data. The focus is on a non-trivial operating regime where the number of PMUs is insufficient to have full observability of the grid state. The proposed analysis uses the Kullback Leibler (KL) divergence between different fault location hypotheses, which are associated with the observation model. This analysis shows that the most likely locations are concentrated in clusters of buses more tightly connected to the actual fault site akin to graph communities. Consequently, a PMU placement strategy is derived that achieves a near-optimal resolution for localizing faults for a given number of sensors. The problem is also analyzed from the perspective of sampling a graph signal, and how the placement of the PMUs i.e. the spatial sampling pattern and the topological characteristic of the grid affect the ability to successfully localize faults is studied. The detection of cyber-physical attacks is also examined where PMU data and relevant Supervisory Control and Data Acquisition (SCADA) network traffic information are compared to determine if a network breach has affected the integrity of the system information and/or operations.

To defend against malicious cyber attacks and ensure a secure routing in communication network for smart grid, the paper entitled "A Cross-Layer Trust Evaluation Protocol for Secured Routing in Communication Network of Smart Grid" proposes a novel trust evaluation framework with Bayesian Inference to calculate direct trust, Dempster-Shafer to compute indirect trust, Analytical Hierarchy Process to evaluate the creditability trust using cross-layer metric, and Fuzzy theory to compute the link-layer trust to find secured and reliable link. Simulation results validate the effectiveness of the proposed solution in defending against various attacks thereby ensures secured routing.

The paper "A Statistical Framework for Detecting Electricity Theft Activities in Smart Grid Distribution Networks" presents and evaluates detection methods for energy theft scenarios within one LV grid area, during which an attacker reduces its own smart meter value and increases other smart meter values to keep the total sum constant. The methods in the paper use the covariance structure between smart meter readings under the assumption of specific stochastic model for the smart meter values. Evaluation results on synthetically generated data from uniform and gamma distributions and on one set of measurements from 19 buildings show good detection performance.

Electric Vehicles

The revolution of communications and data analytics in smart grid has opened possibilities for Electric Vehicle (EV) charging scheduling problems. In the paper entitled "Smart and Resilient EV Charging in SDN-Enhanced Vehicular Edge Computing Networks," by leveraging vehicular edge computing enhanced by software defined networking, the authors investigate a joint problem of fast charging and EV route planning. Their main objective, from the user's perspective, is to minimize the total overhead, including time and charging fares that consider charging availability and electricity price fluctuation. A solution that is based on deep reinforcement learning is then proposed to achieve an optimal charging scheduling policy for all EVs in need. The authors further develop a resilient EV charging that is based on incremental updates of each EV charging within a certain time period.

The next paper on the topic of EV charging and scheduling is entitled "Decentralized PEV Power Allocation with Power Distribution and Transportation Constraints". The paper proposes a spatio-temporal scheduling algorithm for the electric vehicle rechargeable problem where multiple charging stations are located within a small geographical area. A centralized optimization model is first considered, which takes into consideration the power constraint induced by the underlying electrical grid infrastructure. The authors then present a decentralized PEV power allocation scheme for temporal-spatial scheduling when considering power distribution and transportation constraints. The authors then present a decentralized version, which allows for the computation of the optimal solution in a distributed fashion. Finally, the authors propose an estimated methodology for the characterization of future charging demands. The proposed framework is then evaluated using a thorough numerical performance analysis.

Guest editors:
Ying-Jun Angela Zhang, Department of Information Engineering, The Chinese University of Hong Kong
Hans-Peter Schwefel, GridData GmbH, Germany & Aalborg University, Denmark
Hamed Mohsenian-Rad, University of California at Riverside, USA
Christian Wietfeld, TU Dortmund, Germany
Chen Chen, Xi'an Jiaotong University, China
Hamid Gharavi, National Institute of Standards and Technology, USA