Guest Editorial: Theory and Application of PMUs in Power Distribution Systems

OPERATIONAL practices of power distribution systems are impacted by the increasing connection of renewable energy resources, electric vehicles, energy storage systems and deployment of demand-response mechanisms. The synchronized, low-latency, and high-resolution measurements that are provided by distribution-level phasor measurement units (D-PMUs) can enable the better operation of power distribution systems. However, data availability is only a necessary step to build an enhanced operational intelligence that is required by the future distribution grid. Data must be furnished with useful analytics to translate said data into actionable information.

This special section, aims at addressing the challenges in the theory and application of D-PMUs. A total of 113 concept papers were initially received; out of which 65 resulted in submitting full papers. Through a careful review process, 18 papers were selected for publication in this special section. Two papers were published in the November 2019 issue. The remaining 16 papers were published in the January 2020 issue.

Based on the various aspects of the contributions, these papers are categorized into five groups, as we summarize next.

I. Time Synchronization and Computational Infrastructure

In a paper entitled "The White Rabbit Time Synchronization Protocol for Synchrophasor Networks", Derviskadic, *et al.* proposed a new time synchronization approach for distribution synchrophasors, as an alternative to using GPS signals. Within the context of time dissemination techniques for power systems applications, the paper discusses the use of the White Rabbit (WR) protocol for synchrophasor networks. Specifically, the paper presents a D-PMU integrating the WR technology and its experimental validation with a focus on the synchrophasor phase estimation in steady state conditions, by using a D-PMU calibrator generating the reference signals. We further compare the accuracy of the developed D-PMU with other state-of-the-art time synchronization technologies for D-PMUs, i.e., GPS and Precision Time Protocol (PTP), demonstrating applicability of WR for D-PMU networks.

In a paper entitled "UPS: Unified PMU-Data Storage System to Enhance T+D PMU Data Usability", Huang, *et al.* focused on D-PMU data processing and storage. To overcome the existing limitations on high-performance, flexibility, and scalability, they proposed a unified PMU-data storage system (UPS). A unified I/O interface between storage servers and computing jobs is developed to reduce the overhead of managing various computing jobs and data analytics over multiple storage infrastructures. It is demonstrated that UPS achieves high performance on fast and big data processing and data storage, and efficiently increases the flexibility and scalability of D-PMU data management systems.

II. Situational Awareness and Cyber-Security

In a paper entitled "Situational Awareness in Distribution Grid Using Micro-PMU Data: A Machine Learning Approach", Shahsavari, *et al.* proposed a framework and a set of algorithms to transform the large amount of data that is generated by D-PMUs to actionable information. First, a novel data-driven event detection technique is introduced to extract events from the extremely large collection of raw D-PMU data. Subsequently, a data-driven event classifier is developed to effectively classify power quality events. Field expert knowledge and utility records are used to conduct an extensive data-driven event labeling. A multi-class support vector machine classifier is trained and tested over 15 days of real-world data from two D-PMUs on a distribution feeder in Riverside, CA, USA. A total of 1.2 billion measurement points and 10,700 events are analyzed. Two real-world use-cases are presented for the proposed data analytics tools, including remote asset monitoring and distribution-level oscillation analysis.

In a paper entitled "Learning Behavior of Distribution System Discrete Control Devices for Cyber-Physical Security", Roberts, *et al.* proposed a method for cyber-security intrusion detection to monitor network traffic for malicious activity and indications. The approach discussed here expands the idea of a traditional intrusion detection system within electrical power systems, specifically power distribution networks, by monitoring the physical behavior of the grid. This is achieved through the use of high-rate D-PMUs, alongside SCADA packets analysis, for the purpose of monitoring the behavior of discrete control devices. A set of algorithms are proposed to passively learning the control logic of voltage regulators and switched capacitor banks. Upon detection of an abnormal operation, the operator is alerted for further action.

In a paper entitled "Attack Identification and Correction for PMU GPS Spoofing in Unbalanced Distribution Systems", by Wang, *et al.* proposed an algorithm to identify GPS spoofing attacks (GSAs) against D-PMUs, which introduce phase shifts into true phase angle measurements. A sensitivity analysis of state estimation residuals on a single GSA phase angle is implemented. An identification algorithm using a probing technique is proposed to determine the locations of spoofed D-PMUs and the ranges of GSA phase shifts. Based on the identification results, these GSA phase shifts are determined via an estimation algorithm that minimizes the mismatch between measurements and system states.

III. Analysis of Faults and Outage Management

In a paper entitled "Location of Single Phase to Ground Faults in Distribution Networks based on Synchronous Transient Energy", Shi, *et al.* proposed using a new fault location identification method based on the analysis of the energy of the transient zero-sequence current in the selected frequency band (SFB). The equivalent impedance of the distribution network with lateral branches is studied with an equivalent network, and the phase-frequency characteristics of the equivalent impedance are analyzed. The SFB, within which the transient energy of the faulty line section is larger than that of the healthy line sections is determined. A combined fault-section location criterion is proposed and the implementation scheme is illustrated with the distribution level phasor measurement units. Numerical simulations of the IEEE 34 node system and the field experiments of a 10kV distribution network validate the feasibility and effectiveness of the proposed method.

In a paper entitled "Multi-Task Logistic Low-Ranked Dirty Model for Fault Detection in Power Distribution System", Gilanfar, *et al.* proposed a Multi-task Logistic Low-Ranked Dirty Model (MT-LLRDM) for fault detection in power distribution networks by using the D-PMU data. The MT-LLRDM improves the fault detection accuracy by utilizing the similarities in the fault data streams among multiple locations across a power distribution network. The captured similarities supplement the information to the task of fault detection at a location of interest, creating a multi-task learning framework and thereby improving the learning accuracy. The algorithm is validated with real-time PMU streams from a hardware-in-the-loop testbed that emulates real field communication and monitoring conditions in distribution networks. The results showed that the MT-LLRDM outperforms other state-of-the-art classification methods using actual synchrophasor data achieved from a power hardware-in-the-loop testbed.

In a paper entitled "Enhance High Impedance Fault Detection and Location Accuracy via Micro-PMUs", Weng, *et al.* proposed a stochastic High Impedance Fault (HIF) monitoring and location scheme using high-resolution time-synchronized data in D-PMUs for distribution network protection. A process was designed based on feature selections, semi-supervised learning (SSL), and probabilistic learning for fault detection and location. A wrapper method is proposed to leverage output data in feature selection to avoid over-fitting and reduce communication demand. To utilize unlabeled data and quantify uncertainties, an SSL-based information theoretic method is proposed for fault detection. For location, a probabilistic analysis is proposed via moving window total least square based on the probability distribution of the fault impedance. An experiment platform was set up based on a real-time simulator, to show the enhanced HIF detection and location performance, when compared to the traditional methods.

In a paper entitled "Measurement-Based Network Clustering for Active Distribution Systems", Monadi, *et al.* presented a network clustering (NC) method for active distribution networks (ADNs). Following the outage of a section of an ADN, the method forms an optimum cluster of microgrids within the section. The optimum cluster is determined from a set of candidate microgrid clusters by estimating the following metrics: total power loss, voltage deviations, and minimum load shedding. To compute these metrics, equivalent circuits of the clusters are estimated using measured data provided by D-PMUs. Hence, the proposed NC method determines the optimum microgrid cluster without requiring information about the network's topology and its components.

IV. State and Parameter Estimation

In a paper entitled "Decentralized Robust State Estimation of Active Distribution Grids Incorporating Microgrids Based on PMU Measurements", Wu, *et al.* proposed a decentralized D-PMU-based robust state estimation of active distribution grids incorporating microgrids. The D-PMU-based robust state estimation is formulated as a quadratic programming problem and solved in a decentralized manner to accommodate the autonomous operation mode among microgrids, as well as to preserve information privacy between different operators. During each iteration of the decentralized method, each microgrid evaluates its bad measurements and sends its local optimization objective with respect to boundary states to the utility grid for a unified optimization.

In a paper entitled "Dynamic Distribution State Estimation Using Synchrophasor Data", Zhu, *et al.* explored the development of a fast algorithmic framework by casting the distribution system state estimation (DSSE) task within the time-varying optimization realm. The time-varying formulation involves a time-varying robustified least-squares approach, and it naturally models optimal trajectories for the estimated states under streaming of measurements. The formulation is based on a linear surrogate of the AC power-flow equations, and it is robust against measurement outliers. The paper then leverages a first-order prediction-correction method to achieve simple online updates that can provably track the state variables from heterogeneous measurements. This online algorithm is computationally efficient as it relies on the Hessian of the cost function without computing matrix-inverse. Convergence and bounds on the estimation errors are established analytically.

In a paper entitled "Bayesian Learning-Based Harmonic State Estimation in Distribution Systems with Smart Meter and D-PMU Data", Zhou, *et al.* proposed an approach for harmonic state estimation utilizing two types of measurements from smart meters and D-PMUs. It involves regression analysis for power flow calculation, prediction of demands using recurrent neural networks, and sparse Bayesian learning for state estimation. The proposed approach requires fewer DPMUs than nodes, making it more applicable to existing distribution grids. The effectiveness of the proposed estimator is shown through extensive numerical simulations. The impact of the increased penetration of distributed energy resources is investigated on the performance of our state estimator.

In a paper entitled "Unsupervised Impedance and Topology Estimation of Distribution Networks–Limitations and Tools", Moffat, *et al.* proposed a noise-robust technique for estimating effective impedances via the reduced Laplacian form of the Kron reduced admittance matrix, termed the "subKron" form. An algorithm was presented to reconstruct radial networks from effective impedances. Evaluations of estimation and reconstruction accuracy with decreasing signal to noise ratio highlight fundamental tradeoffs in unsupervised network estimation performance from noisy measurements.

V. Control and Stability Analysis

In a paper entitled "D-PMU Based Secondary Frequency Control for Islanded Microgrids", by Rodrigues, *et al.* proposed a secondary frequency control approach for distributed energy resources (DERs) in networks operating in stand-alone mode. The proposed approach uses D-PMUs data to iteratively adjust the generators contribution, so as to improve the dynamics of the islanded microgrid frequency regulation. These adjustments are performed using a novel adaptive time-variable droop characteristic capable of speeding-up the secondary frequency regulation, mitigating oscillations and reducing the frequency nadir. The proposed secondary frequency control can be held after the stabilization of the primary control, or simultaneously with the primary frequency regulation.

In a paper entitled "Monitoring Long Term Voltage Instability due to Distribution Transmission Interaction using Unbalanced micro-PMU and PMU Measurements", by Ramapuram Matavalam, *et al.* extended the idea of the Thevenin equivalent into unbalanced 3-phase circuits and proposed a 3-phase long-term voltage stability indicator (VSI), that can identify critical loads. In order to identify whether the voltage stability limit is due to the transmission network or a distribution network, a transmission-distribution distinguishing index (TDDI) is proposed. A convex optimization formulation is proposed to estimate the 3-phase Thevenin equivalent using PMU and D-PMU measurements, making it possible to calculate VSI and TDDI in an online model-free manner. Multiple case studies demonstrate the importance of D-PMU measurements in identifying the regions causing long term voltage instability.

In a paper entitled "Model-Free Optimal Voltage Phasor Regulation in Unbalanced Distribution Systems", by Sankar, *et al.* the use of D-PMUs to optimally control line power flows without explicit measurements of these quantities and without a priori knowledge of the underlying distribution system topology. To do so, a two-dimensional Extremum Seeking (2D-ES) control paradigm is extended to simultaneously manage DER active and reactive power contributions in unbalanced distribution systems. Simulation results show the ability of the proposed approach to virtually island different portions of a 3-phase unbalanced the network using DER injections while maintaining voltage magnitudes in the rest of the network.

In a paper entitled "A Fast Load Control System Based on Mobile Distribution-Level Phasor Measurement Unit", by Yao, *et al.* proposed a method to use D-PMU data for disturbance event detection, power mismatch estimation and fast load control. First, the systematic design of the MDPMU introduced. Second, the distribution-level measurement is utilized for the Rate Of Change Of Frequency (ROCOF) calculation. Upon detection of a power system frequency event, power mismatch is estimated at the early stage of the event. With the proposed control system, residential load responses can be controlled coordinately based on load availability and compensation prices offered by customers, providing adaptive frequency regulation service after large resource contingencies.

In a paper entitled "Microgrid Dynamic Modeling and Islanding Control with Synchrophasor Data", by Valibeygi, *et al.* investigated the application of D-PMU data to formulate reduced order dynamic models and use these models to design control algorithms that allow automated islanding and grid reconnection of a microgrid. The dynamics of the phasors at the point of common coupling (PCC) excited by the controllable assets in the microgrid are captured in reduced order models estimated from phasor data. The controllable assets are taken to be a hybrid set of DERs with different operational constraints and dynamics. In turn, the reduced order models are used to design a self-tuning feedback control algorithm to control the phasors at the PCC to allow seamless islanding and reconnection of the microgrid.

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Hamed Mohsenian-Rad *Guest Editor-in-Chief*
Department of Electrical and Computer Engineering
University of California
Riverside, CA, USA
(e-mail: hamed@ece.ucr.edu)

Mario Paolone
Distributed Electrical Systems Laboratory
École Polytechnique Fédérale de Lausanne
Lausanne, Switzerland

Vassilis Kekatos
Department of Electrical and Computer Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA, USA

Omid Ardakanian
Department of Computing Science
University of Alberta
Edmonton, AB, Canada

Yan Xu
School of Electrical Electronic Engineering
Nanyang Technological University
Singapore, Singapore

Di Shi
GEIRI North America
San Jose, CA, USA

Reza Arghandeh
Department of Computer Science, Electrical Engineering, and Mathematical Sciences
Western Norway University of Applied Sciences
Bergen, Norway