Guest Editorial
Special Section on Power-Electronics-Enabled Smart Power Distribution Grid

I. Introduction

ECONOMIC and environmental constraints, as well as technological advancements, are reshaping the traditional view of power distribution systems. In a future distribution grid, as the number of inverter- and converter-based devices increases to more than hundreds of thousands, it is rather intuitive that the current state-of-the-art technical solutions and industry practices will no longer be effective. While tremendous progress has been made in advancing smart grid solutions, not much attention has been paid to bridging the gap between two traditionally disjointed research areas—power systems (especially distribution systems) and power electronics—that will ultimately facilitate the vision of 100% penetration of power-electronics-based distributed energy resources coming to fruition. There is a growing interest in the concepts of power electronics-enabled power systems around the world. This Special Section invites a broad spectrum of contributors (e.g., academics, researchers, engineers, consultants, market regulators and system operators, key policymakers) to define and develop the interdisciplinary technical approaches collectively. Although there are many technical challenges associated with making this vision a reality, policy, economic, and workforce issues also play a significant role. This Special Section hence concentrates on discussing various relevant topics associated with how to accommodate extremely high levels of power-electronics-based distributed energy resources to promote economic efficiency; improve social welfare; reduce energy cost; support plug-and-play of distributed renewable energy; and improve the capability, adaptability, scalability, resiliency, safety, security, and usability that our electric power distribution infrastructure can provide. The articles are authored by a diverse group of experts from academics, industry, and national laboratories around the world (**Fig. 1**). The guest editorial board received 120+ abstract submissions and invited 65 of them for full-paper submissions. After two-round rigorous reviews, 23 papers have been accepted for final publication. It is worth noting that this Special Section places an emphasis on addressing the mutual research interests of academics and industry. Hence, interdisciplinary research and real-world-problem-driven research topics are of particular relevance to this Special Section. The guest editorial board and IEEE PES leadership made tremendous efforts to attract authors from the industry. All the papers have gone through the same review criteria. Approximately 35% of the accepted papers are led or co-led by industry experts.

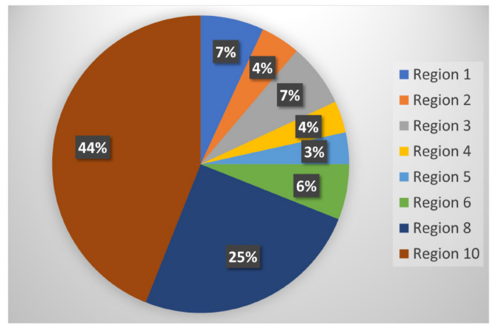

Fig. 1. The articles are authored by a diverse group of experts from academics, industry, and national laboratories around the world.

The scope of the presented articles covers a wide range of topics associated with power electronics-enabled smart power distribution grids:

- Emerging solid-state technologies for distribution-level applications
- Grid integration of grid-forming converters and inverters for active distribution networks or microgrids
- Distributed and decentralized control of power electronics for distribution-level applications
- Improving stability, reliability, and resilience of AC/DC microgrids with high penetration of power-electronics-based distributed energy resources
- Applications of cybersecurity and telecommunication technologies to power-electronics-enabled distribution networks
- Testbed, proof-of-concept demonstrations, pilot projects, and real-world implementation

II. Articles in the Special Issue

[A1] proposes an analytic quantifiable method to describe the power complementarity between AC/DC lines. A Gaussian mixture model is used to depict the temporal correlation and uncertainties. The complementarity is calculated by the conditional probability of the multi-dimensional joint probability density function of AC/DC hybrid lines. Accordingly, an optimal configuration method for a hybrid AC/DC distribution network is proposed considering the complementarity of power flows on AC/DC lines, in which the size and location of voltage source converters (VSCs) are optimized.

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[A2] deals with the short-circuit analysis of distribution systems dominated by voltage source converters (VSCs). A novel methodology is proposed in this paper for short-circuit calculation of power systems populated with VSCs where the control modes and potential current-saturated operation of power converters are considered. The studied distribution system has been modeled using an element-based steady-state formulation that includes the converter equations in both normal operation and fault scenarios. Then, equilibrium points of the studied distribution system are identified by solving the established systems of equations for different potential current-saturation states of the VSCs. The proposed methodology is applied to a specific case study of a distribution system penetrated with VSCs in both grid-forming and grid-following control.

[A3] investigates a full-view synchronized measurement system (SYMS) for the renewables, controls, loads, and waveforms of power-electronics-enabled power distribution grids. A general design method is proposed for the synchrophasor estimation of synchronized measurement devices (SMDs) in different scenarios by deducing phasor measurement error models. This is further applied in combination with the design of hardware and a communication protocol to develop SMDs for the measurement of the renewables, controls, loads, and waveforms of power-electronics-enabled power distribution grids.

[A4] develops a novel real-time parameter estimation algorithm for composite electronic ZIP load models (CEZLM) using synchrophasor data. An adaptive window selection algorithm is proposed to extract estimation windows with almost constant load-to-voltage sensitivity. Estimation window extraction is followed by mode-sensitive parameter estimation for the CEZLM. A data pre-processing method using ensemble-based anomalous-data filtering and mitigation in the measurement stream is developed. A cascade filter with a Kalman filter followed by a median filter is used to reduce the impact of noise. Two optimization algorithms: Constrained Least SQuares (CLSQ) and Sensitivity-Driven Constrained Optimization (SDCO) are proposed for tracking CEZLM parameters. CLSQ solves the constrained least squares problem for parameter estimation, and SDCO minimizes the L2 norm of a sensitivity-driven objective function with L1 norm regularization to estimate CEZLM parameters.

[A5] applies STRIDE-based threat modeling to analyze and identify multiple potential threats endured by the cyber-physical system of an extreme fast-charging station by using a weighted attack defense tree. Potential mitigation strategies are then suggested for the identified severe threats. In addition, this paper develops a stochastic probabilistic tool, the hidden Markov model, for modeling the security attacks for a given range of identified attack vectors and hence employing an appropriate defense strategy against the malicious hacker. Also, a weighted attack defense tree has been developed to generate various attack scenarios. In the end, the results of the proposed work will be substantiated and validated if it can considerably improve overall charging efficiency and cyber-physical security of the charging station network.

[A6] provides a point of reference and a background review for DC circuit breakers (DCCBs) from novel aspects, filling in absent parts in the literature. The elaborated subjects include current commutation circuitry, DCCBs trip-curves developments, and newly added functions in DCCBs, as well as marketing analysis. The advancements of DCCBs are surveyed and development needs are recognized. This paper aims to identify the future research needs of DCCBs for emerging DC power systems.

[A7] proposes a physics-data-based detection method to detect a variety of cyber-attacks in photovoltaic (PV) farms using power electronics-enabled harmonic state space (HSS) models, which, to our knowledge, is original. At the device level, HSS-based detection is developed to monitor harmonic vectors of individual PV converters with minimum sensor measurements, thus improving accuracy and robustness compared to Kalman filter-based detection. At the system level that involves multiple PV converters, a clustering approach is developed to investigate attack propagation and accurately locate attack sources within a PV farm. The proposed approach is one of the first attempts to address PV security through interaction between the device and the system, maximizing the accuracy and robustness at different levels.

[A8] demonstrates that forcing an EC to emulate a negative capacitance while connecting it in series with a passive capacitor leads to DC-DC converter rating reduction and the subsequent potential volume reduction and efficiency increase of a DC link. Such a device may replace the traditional bulk DC link capacitor present in power electronics-supported distributed energy resources in a plug-and-play manner. Simulations of and experiments on a common dual-stage AC/DC power conversion system employing the proposed active DC link validate the methodology.

[A9] presents a cascaded model predictive control (MPC) scheme for both the outer and inner loops of primary control, which improves frequency regulation capability with the advantage of satisfactory dynamic response and high tracking accuracy. In the outer loop, to enhance the dynamic frequency characteristics, the MPC-based virtual synchronous generator (VSG) method with two control objectives is proposed. According to the movement direction of the frequency under different load switching cases, the corresponding frequency response process speeded up or slowed down properly. In the inner loop, an improved finite-set double vector MPC (DV-MPV) is proposed to follow the output reference from the outer loop, which contributes to accurate frequency control by reducing tracking errors and by faster dynamic response as well.

[A10] proposes a transactive energy market in which the distributed generators act as independent suppliers. The market is formed in practice by the remote-control switches-enabled reconfiguration of the distribution network. The paper models this market as a cooperative Stackelberg game and studies the motivations and the dynamic interactions of various participants. Also, the paper designs a budget-balanced and individual rational market-clearing rule considering the power loss. The paper provides numerical studies based on an IEEE 33-bus and modified IEEE 123-bus distribution networks to demonstrate the performance of this market design.

[A11] proposes a novel converter-based moving target defense (CMTD) strategy by proactively perturbing the primary control gains to defend against deception attacks. First, the authors study the impact on the voltage stability in DC microgrids of perturbing the primary control gains and provide explicit conditions for the perturbation magnitude and frequency under which the voltage stability can be ensured. Then, the authors investigate the improved detectability against deception attacks under CMTD and present sufficient conditions under which these attacks can be detected. Finally, the authors conduct extensive MATLAB Simulink/PLECS-based simulations and systematic hardware-in-the-loop-based experiments to validate the effectiveness of CMTD.

[A12] aims toward developing a computationally tractable, scalable, and accurate phasor-based model for dynamic Volt/Var and Volt/Watt analyses of large distribution systems with high penetration of smart inverters. Case studies demonstrate that the proposed phasor-based model sufficiently captures the Volt/Var and Volt/Watt dynamics and is computationally faster by one order of magnitude compared to the average model and by two orders of magnitude compared to the detailed switching model. Case studies also demonstrate the efficacy and scalability of the proposed model in analyzing Volt/Var and Volt/Watt dynamics of large-scale power networks with hundreds of smart inverters.

[A13] presents a promising solution using an operator support system (OSS) to enable stable operation of a power system with up to 100% inverter-based resources (IBR) generation. The OSS consists of two components. First is dynamic security assessment to evaluate the system resiliency and to identify critical N-1 contingencies that could endanger the system. The second component, as the key technology behind the OSS, is dynamic security optimization (DSO). DSO optimizes the control parameters of generators and inverters to improve the stability of the system toward the identified N-1 contingencies. The paper shows through high-fidelity electromagnetic-transient (EMT) simulations of the future generation models of the Hawaii Island system with 100% IBR capacity that a system with 100% IBRs can be operated stably with the help of GFM inverters, and appropriate controller parameters can be found by DSO for the inverters.

[A14] proposes a novel decentralized operation strategy for a multi-terminal direct current (MTDC) link system to control the power flow between interconnected distribution networks. The proposed strategy is divided into two stages. First, by applying a curve-/surface-fitting technique to the network topology data, the formulas for the voltage and total line losses in the network are derived. Subsequently, the active/reactive power set-points of the MTDC link are optimized to minimize the network losses and balance the injected power from the upstream grid. The optimization model with a quadratically constrained quadratic problem is relaxed as a second-order constrained programming model using the proposed substitution process. The proposed strategy is implemented based solely on the information at the point of common coupling of the MTDC link and does not require the acquisition of any real-time data related to the distributed generator output and load demand.

[A15] proposes a high-order differentiator-based distributed secondary control. The proposed control can not only eliminate the chattering, but also improve the dynamics with shorter settling time. It is inherited from the conventional distributed control by requiring only neighboring communication to provide references for the primary-layer control in achieving bus voltage restorations, output current sharing, and output power sharing in power-electronics-based systems. Both simulation and experimental results have verified that the proposed control can compensate for different types of false data injection attacks and showcased its superior dynamic performance over that of a sliding mode observer without chattering.

[A16] presents an analysis of converter-side single-phase AC faults for a medium-voltage direct-current (MVDC) link based on the ANGLE-DC project from Scottish Power Energy Networks. It is shown that the capacitors of the converters will be overcharged without suitable protection in place. A protection strategy using a bypass thyristor-based branch is presented to relieve overvoltage issues following converter-side faults, and it is verified through simulations conducted in PSCAD/EMTDC. For completeness, case studies considering post-fault operation are also included.

[A17] proposes a novel interactive control scheme of a voltage source converter (VSC) connected to a weak grid. Firstly, a grid synchronization approach is performed using VSC side voltage transformed on a rotating reference frame with respect to grid voltage, which is carried out based on the lowest short circuit ratio (SCR) as approved by utilities such as the Australian Energy Market Operator's system strength report. The transformed voltage is then fed into the active power and reactive power control through PLL. Secondly, the grid synchronization approach through PLL is made interactive by adding virtual synchronous generator (VSG) control into the outer loop, which generates virtual inertia to mimic the synchronous generators of a power system. The design of the VSG control parameters is realized based on small signal stability analysis.

[A18] presents a robust mixed-integer convex model for the optimal scheduling of integrated ES-SOPs to ensure a zero probability of constraint violation. Losses of the subsystems comprising the ES-SOP are modeled using a proposed binary-polynomial model, enabling efficient scheduling of the energization state of subsystems to reduce no-load losses. The ES-SOP is considered in this paper to be owned by the network operator to (1) manage power flow constraints, (2) minimize cost of losses, and (3) maximize arbitrage profit.

[A19] discusses the implementation of inverter-dominated dynamic microgrids (MGs) in hybrid AC/DC distribution systems. A control framework is developed for hybrid AC/DC distribution systems. The entire feeder is sectionalized into multiple dynamic MGs that interact at varying points of interconnection (POIs). A set of distributed controllers is proposed to coordinate multiple inverter-interfaced distributed generators (DGs) and interlinking converters (ICs) across the hybrid AC/DC feeders under autonomous operation. Various control modes are developed for the system either to operate under static topology or to reconfigure as requested. Secondary regulations over the system operating frequency and voltage are enabled in both AC and DC sub-grids, along with proportional power sharing among DGs. Dedicated control efforts are developed to achieve seamless system topology transitions, and the operational stability of the proposed controllers is analyzed.

[A20] proposes a centralized control framework to achieve the collaborative operation of multiple energy storage devices (ES-1s) for frequency stabilization and economical power flow in microgrids. The proposed control framework exploits the power variations of the deferrable loads and enables the minimum reactive power flows in the microgrids, which leads to reduced storage requirements and minimum distribution loss. It is the first control framework to address the active and reactive power coupling issue of the ES-1-based smart loads, leading to the independent control of system frequency and optimal reactive power reallocation.

[A21] describes an electric vehicle (EV) charging station that provides ancillary services to the main AC grid. Due to the direct current (DC) nature of these loads and the easier integration of renewable energies, a DC microgrid is considered for powering the charging station. Targeting both DC grid voltage stability and the capability to support the main AC grid, nonlinear control laws based on Lyapunov theory and backstepping are developed for local and primary control levels (droop control). The proposed controllers are validated via MATLAB-Simulink simulations in a 25 kW DC microgrid with PV production, a vehicle-to-grid (V2G) mode of operation, fast and slow vehicle charging, ancillary services to the AC main grid, and islanded-mode operation.

[A22] presents an automatic secondary control scheme that fully coordinates the grid-forming (GFL) and grid-following (GFM) inverters to achieve frequency/voltage restoration, accurate power sharing, and circulating var mitigation in networked microgrids even without the support of any synchronous generators or the bulk power system. This paper uses a leader-follower consensus framework to develop the GFM-GFL coordinated secondary control in the absence of a centralized controller. The proposed coordination is effective under different disturbances and can work in a plug-and-play manner.

[A23] proposes a framework for the synchronous virtual power plant based on grid-forming inverter interfaced distributed energy resources. By coordinating the parameter settings of grid-forming inverters, the virtual power plant provides inertia support. Also, the authors design an online learning-based parameter-settings method that makes the inertia of the virtual power plant adjustable. A case study in an IEEE 34-nodes system illustrates the effectiveness of the proposed method.

[A24] discusses the advanced metering infrastructure (AMI) two-way communication and its recent industrial practice in the U.S., especially for applying the smart meter pinging functionality to monitor grid-edge devices and distributed energy resources (DERs). This paper develops the two-way communication model and the network calculus method to quantify the impact of two-way communication on the AMI network. In the end, the proposed method is validated with ns-3 simulation using the modified 13-node test feeder and 18 real-world feeder systems.

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APPENDIX: RELATED ARTICLES

[A1] L. Zhang, B. Tong, Z. Wang, W. Tang, and C. Shen, "Optimal configuration of hybrid AC/DC distribution network considering the temporal power flow complementarity on lines," *IEEE Trans. Smart Grid*, vol. 13, no. 5, pp. 3857–3866, Sep. 2022.

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