Power-Electronics-Enabled Autonomous Power Systems

POWER systems are going through a paradigm change from centralized generation to distributed generation and further onto smart grid. Millions of relatively small distributed energy resources (DER), including wind turbines, solar panels, electric vehicles and energy storage systems, and flexible loads are being integrated into power systems through power electronic converters. This imposes great challenges to the stability, scalability, reliability, security, and resiliency of future power systems. Field experiences in recent years have shown that large-scale deployment of DER affects the stability of power systems, which are dominated by synchronous machines (SMs). It is vital to develop appropriate control architecture and technologies so that these different players are able to take part in the regulation of future power systems in an autonomous and responsible way. During the last decade, significant developments have been made to operate power electronic converters to facilitate the integration of DER and flexible loads with the grid. This "Special Section on Power-Electronics-Enabled Autonomous Power Systems" of the IEEE Transactions on Industrial Electronics, consisting of 11 papers, joins the forces of the communities of control/systems theory, power electronics, and power systems to address various emerging issues of power-electronics-enabled autonomous power systems, paving the way for large-scale deployment of DERs and flexible loads.

In item 1) in the Appendix, it is shown that future power systems will be power electronics based, instead of electric machines based, with a huge number of incompatible players. Then, a lateral system architecture based on the synchronization mechanism of the SM is proposed to unify the integration and interaction of these players with the grid, by operating the power electronic converters involved to behave like a virtual SM (VSM). Moreover, two technical routes, one based on the synchronverter technology and the other based on the robust droop control technology, are proposed to implement the lateral system architecture for future power systems.

In item 2) in the Appendix, the feedforward of grid frequency and voltage magnitude through a synchronous reference frame phase-locked loop is proposed to mitigate the impact of grid fluctuations on power flow control for droop-controlled converters. Moreover, the voltage magnitude is controlled to enhance the accuracy of reactive power control and the droop control loops are modified to improve the system stability.

In item 3) in the Appendix, an extended droop control method is proposed to achieve dynamic current sharing autonomously during sudden load change and resource variations for energy storage systems having complementary characteristics, such as battery and supercapacitor (SC). The output voltage characteristics of the battery and the SC are regulated by a virtual resistance droop controller and a virtual capacitance droop controller, respectively, so that the SC compensates high frequency fluctuations during transient and the battery provides load power at the steady state.

In item 4) in the Appendix, it is demonstrated via extensive experiments on a microgrid in the megawatt-range that clock drifts may impair frequency synchronization in low-inertia power systems. Motivated by this, a model of an inverter-interfaced unit that incorporates the phenomenon of clock drifts is derived and validated experimentally. This model is then used to investigate the effects of clock drifts on the performance of droop-controlled grid-forming inverters with regard to frequency synchronization and active power sharing.

In item 5) in the Appendix, the small-signal dynamics of current-controlled VSMs with dynamic or quasi-stationary representation of the virtual stator impedance are compared. Detailed state-space models are developed for both VSM implementations, and eigenvalue analysis is utilized to assess their small-signal stability and parametric sensitivity. The presented models are verified by time-domain simulations and experimental results. The results demonstrate how VSMs with a dynamic model of the stator impedance require a high virtual resistance to avoid poorly damped oscillation. On the other hand, VSMs with quasi-stationary impedance representation can achieve good dynamic response also with a virtual resistance of zero, allowing for a better decoupling of the active and reactive power control.

In item 6) in the Appendix, a current-limiting droop controller is proposed for single-phase grid-connected inverters to maintain the inverter current below a given value at all times under both normal and faulty grid conditions, without using external limiters, additional switches, or monitoring devices. The controller introduces bounded nonlinear control dynamics and the current-limiting property of the inverter is analytically proven by using the nonlinear input-to-state stability theory.

In item 7) in the Appendix, a control method to achieve wide input voltage regulation along with high efficiency at partial power in galvanically isolated impedance-source dc–dc converters is proposed. The buck–boost dc voltage gain characteristic is achieved through a full-bridge topology reconfiguration into a single-switch topology in the buck mode, which results in reduced switching losses. The proposed method enables implementation of efficient photovoltaic microconverters with a ultra-wide range of the maximum power point tracking.

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In item 8) in the Appendix, a galvanically isolated power conditioning unit with only three stages is proposed for residential micro wind turbines with a low-voltage permanent-magnet synchronous generator (PMSG). A modular isolated dc–dc converter with a wide input voltage range is proposed as a standardized power electronic block to decrease the cost of the power electronic interface and to facilitate the adoption of residential PMSG-based micro wind turbines with a variety of voltage and power levels.

In item 9) in the Appendix, five modifications are proposed to the standard synchronverter algorithm to improve its stability and performance. The modifications are implemented in software and do not require any changes in the inverter hardware. Simulations and experiments show that these modifications increase the robustness of the synchronverter to faults, improve the synchronverter response to changes in grid frequency, voltage and to grid imbalance, and resolve the problem caused by drifts in the voltage sources of the inverter.

In item 10) in the Appendix, the idea of migrating the relatively mature VSM control strategy into the bidirectional grid-connected converters for improving the inertia of the dc microgrids is proposed. The virtual inertia control equation of the bidirectional grid-connected converters is obtained by following the concept of VSM. The proposed strategy reduces the dc-bus voltage fluctuations and enhances the stability of the dc microgrids.

In item 11) in the Appendix, a *d-q* impedance-based stability analysis method in the common synchronous *d-q* frame for three-phase inverter-based ac power systems is presented. Based on the component connection method and the generalized Nyquist stability criterion, the proposed method enables the stability analysis of complicated ac systems by using only the measurable impedances instead of the internal information of inverters.

The Guest Editors hope that the research topics covered in this Special Section will stimulate new ideas and enabling technologies to speed up the paradigm change of power systems into power-electronics-enabled autonomous power systems.

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APPENDIX
RELATED WORK

1) Q.-C. Zhong, "Power-electronics-enabled autonomous power systems: Architecture and technical routes," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5907–5918, Jul. 2017.
2) Y. Deng, Y. Tao, G. Chen, G. Li, and X. He, "Enhanced power flow control for grid-connected droop-controlled inverters with improved stability," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5919–5929, Jul. 2017.
3) Q. Xu *et al.*, "A decentralized dynamic power sharing strategy for hybrid energy storage system in autonomous DC microgrid," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5930–5941, Jul. 2017.
4) J. Schiffer, C. A. Hans, T. Kral, R. Ortega, and J. Raisch, "Modelling, analysis, and experimental validation of clock drift effects in low-inertia power systems," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5942–5951, Jul. 2017.
5) O. Mo, S. D'Arco, and J. A. Suul, "Evaluation of virtual synchronous machines with dynamic or quasi-stationary machine models," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5952–5962, Jul. 2017.
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7) A. Chub, D. Vinnikov, R. Kosenko, and E. Liivik, "Wide input voltage range photovoltaic microconverter with reconfigurable buck-boost switching stage," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5974–5983, Jul. 2017.
8) A. Chub, O. Husev, A. Blinov, and D. Vinnikov, "Novel isolated power conditioning unit for micro wind turbine applications," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5984–5993, Jul. 2017.
9) V. Natarajan and G. Weiss, "Synchronverters with better stability due to virtual inductors, virtual capacitors and anti-windup," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5994–6004, Jul. 2017.
10) W. Wu *et al.*, "A virtual inertia control strategy for DC microgrids analogized with virtual synchronous machines," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 6005–6016, Jul. 2017.
11) W. Cao, Y. Ma, L. Yang, F. Wang, and L. M. Tolbert, "*D-q* impedance based stability analysis and parameter design of three-phase inverter-based ac power systems," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 6017–6028, Jul. 2017.

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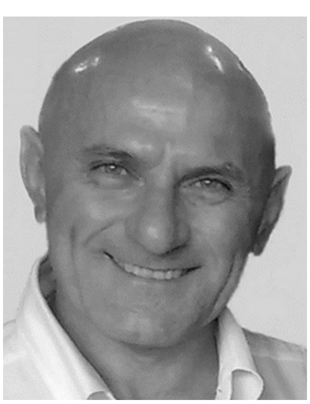

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