Modeling, Control, and Integration of Energy Storage Systems in E-Transportation and Smart Grid

RESEARCH in energy storage systems (ESSs), such as batteries, ultracapacitors, and flywheels, is essential to foster the use of renewable energy sources (RESs) and the future development of electric transportation (E-transportation). RESs are characterized by intermittences and they cannot be dispatched as conventional energy resources. ESSs are the key technology to solve this problem, thus increasing the penetration of RESs in the utility grid. ESSs are also essential components to improve the performance of microgrids and are an enabling technology for smart grid operation. Major challenges are the design of high-performance and cost-effective ESSs, which can safely meet the energy and power demand throughout the expected lifetime. This "Special Section on Modeling, Control, and Integration of Energy Storage Systems in E-Transportation and Smart Grid" of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS collects 24 research papers, discussing innovative solutions for the design and management of ESSs, as well as the required power electronics interface and control systems for their effective integration into utility grids and E-transportation.

The 24 papers can be grouped into three main areas. Papers from item 1) in the Appendix to item 6) in the Appendix deal with modeling, control, and management of Li-ion batteries. A new method to improve the accuracy and robustness of the estimation of the residual energy stored in a Li-ion battery is proposed in item 1) in the Appendix. The method combines an electrical battery model with an analytic one to consider the effects of the battery initial state of charge (SOC), load current rate and direction, operating temperature, and ageing. In item 2) in the Appendix, the application of a machine learning technique, based on a recurrent neural network with long short-term memory, to the accurate estimation of the battery SOC is investigated. In item 3) in the Appendix, a control-oriented electrochemical-thermal model to predict the battery dynamics is introduced and applied in a linear time-varying model predictive control algorithm to develop a health-aware fast charging strategy.

The other papers in the first area focus on the equalization of a high-voltage battery consisting of many series-connected cells, which is a crucial objective to extend the battery lifetime. For instance, a nondissipative equalization scheme, based on a two-stage bidirectional equalization circuit with energy transferring inductors and fuzzy logic control, is presented in item 4) in the Appendix. A different nondissipative equalization approach, simultaneously achieving the balancing of the high-voltage battery and the charging of an auxiliary low-voltage (LV) battery, is presented in item 5) in the Appendix. The application of a multilevel converter to achieve the balancing of a modular battery, consisting of modules with different degradation levels, is presented in item 6) in the Appendix. The proposed control method is based on the estimation of the state of health of each battery module.

Papers from item 7) in the Appendix to item 19) in the Appendix cover various aspects of the design, sizing, control, and integration of ESSs into the utility grid. The design of a novel utility-scale shaftless, hubless flywheel, together with the integrated coreless permanent-magnet motor/generator, is presented in item 7) in the Appendix. Papers from item 8) in the Appendix to item 12) in the Appendix focus on the control of ESSs to optimize battery sizing and the exploitation of renewable energy sources. In particular, a predictive controller, based on updated forecast data, is developed in item 8) in the Appendix. It manages a sodium–sulfur battery and fulfills a production commitment by reducing the error between the scheduled generation and the actual wind farm output. A new filter design method, based on metaheuristic optimization algorithms, able to minimize the energy capacity and power rating of the ESS while smoothing the fluctuation of the wind farm output sufficiently, is presented in item 9) in the Appendix. In item 10) in the Appendix, a proportional-integral controller is introduced to interface a solar photovoltaic (PV) array, combined with a battery ESS (BESS), to a single-phase grid providing a wide range of services, such as power and load leveling, harmonics mitigation along with reactive power compensation, and resynchronization of the grid during reconnection of the grid after the mitigation of a failure. A novel management of multiple types of batteries in a microgrid with PV and diesel power generation is presented in item 11) in the Appendix. An ESS-equipped energy-sharing provider is proposed in item 12) in the Appendix to facilitate the energy sharing of multiple PV prosumers.

An adaptive cutoff frequency high-pass filter is proposed in item 13) in the Appendix to achieve autonomous control of multiple ESS with reasonable power sharing and SOC balancing. In item 14) in the Appendix, a novel distributed algorithm is presented for the optimal resource management in a microgrid under various operating conditions. The application of neural networks to the control of a hybrid ESS (HESS) for an improved

Digital Object Identifier 10.1109/TIE.2018.2810658

and optimized operation of load-frequency control applications is instead investigated in item 15) in the Appendix.

The last four papers of this second area present some innovative solutions to interfacing ESSs to the utility grid, in particular, in item 16) in the Appendix, a novel dominant dynamic elimination control for three-phase voltage-controlled microgrid inverters is discussed. The designed compact control structure for the inverter-layer control in the microgrid hierarchical control includes separated static state feedback and feedforward terms. An improved dc transformer based on switched capacitor with reduced switches for the integration of low-voltage dc energy storage systems and medium-voltage (MV) dc power distribution grid is proposed in item 17) in the Appendix. In item 18) in the Appendix and item 19) in the Appendix, the application of a smart transformer (ST), i.e., a solid-state transformer with control and communication functionalities, is presented. In particular, a control strategy for an medium voltage (MV)/low voltage (LV) smart transformer with integrated storage is proposed in item 18) in the Appendix. It allows the full decoupling of the reactive power flows between the MV and the LV networks. Item 19) in the Appendix provides a detail procedure for selecting the different power converters of the ST while considering the peak load power demand and the maximum SOC availability of the BESS.

Finally, papers from item 20) in the Appendix to item 24) in the Appendix focus on the control and integration of ESSs in E-transportation. In item 20) in the Appendix, the integration and management of a battery-ultracapacitor HESS and a dual three-phase permanent magnet synchronous machine is presented. Item 20) in the Appendix instead proposes a novel power distribution algorithm between the battery and ultracapacitor components of a HESS based on the prediction of their state available power. An online energy management strategy, based on a novel fractional-order extremum seeking method, which can improve both the fuel cell efficiency and durability during the hybrid electric vehicle operation is presented in item 22) in the Appendix.

The last two papers of this special section study the use of ultracapacitor ESS in urban railway systems to achieve an energy-saving effect by storing the regenerative braking energy. In particular, a hierarchical control strategy, which consists of an energy management layer and a converter control layer, is proposed in item 23) in the Appendix. On the other hand, a brake voltage following energy management strategy of the ESS is developed in item 24) in the Appendix to adjust the charging and discharging threshold voltage based on the analysis of the train operation states.

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Acknowledgment

The guest editors would like to thank the authors for submitting their contributions, the reviewers for their dedicated effort in providing valuable comments/suggestions on each paper, and Prof. L. Franquelo and S. Jacobs, respectively, Editor-in-Chief and Administrator of the IEEE Transactions on Industrial Electronics, for their professional advice and guidance.

Appendix
Related Works

1) K. Li, F. Wei, K. J. Tseng, and B.-H. Soong, “A practical lithium-ion battery model for state of energy and voltage responses prediction incorporating temperature and ageing effects,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 8, pp. 6696–6708, Aug. 2018.
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5) M. Preindl, “A battery balancing auxiliary power module with predictive control for electrified transportation,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 8, pp. 6552–6559, Aug. 2018.
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14) T. Zhao and Z. Ding, "Distributed finite-time optimal resource management for microgrids based on multi-agent framework," *IEEE Trans. Ind. Electron.*, vol. 65, no. 8, pp. 6571–6580, Aug. 2018.
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