Resurgence of Grid-Forming Inverter Technology

By Xiongfei Wang

THE EMERGENCE OF GRID-FORMING INVERTERS DATES to the early 2000s, following the advent of inverter-based microgrids and distributed energy resources. The "grid-forming" concept was introduced, mainly as a control paradigm for inverter-based resources, to assure the stability of microgrids. Since then, a wide variety of control strategies have been developed for grid-forming inverters, yet their applications are primarily in microgrids or small islands. In recent years, with the rapid growth of inverter-based resources in bulk power systems, there has been a resurgence of interest in grid-forming inverters from power system operators. However, a wide-scale adoption of grid-forming technology is still not ready since it requires updates to codes, standards, and guidelines, along with further developments of models and tools for system planning and operations. This issue of *IEEE Electrification Magazine* delivers five feature articles and two columns that share the prospects and challenges of grid-forming inverter technology. In addition, an article about e-bikes is included.

In the "Technology Leaders" column, we present "Grid-Forming Technologies Enabling a Decarbonized Power System," by Guohui Yuan. The author conveys the necessity of grid-forming technology by describing the ongoing transformations of electric power systems and then presents the grid-forming technology ecosystem established in United States, which is represented by the Universal Interoperability of Grid-Forming Inverters consortium, funded by the Department of Energy. The author also emphasizes that a decarbonized power system will depend on the interoperability of grid-forming and grid-following inverters.

The first feature, "Pathways to the Next-Generation Power System With Inverter-Based Resources," was contributed by Yashen Lin, Joseph H. Eto, Brian B. Johnson, Jack D. Flicker, Robert H. Lasseter, Hugo N. Villegas Pico, Gab-Su Seo, Brian J. Pierre, Abraham Ellis, Jeremiah Miller, and Guohui Yuan. It begins with an overview of

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grid-following and grid-forming control paradigms and their functional characteristics. Then, open research questions concerning inverter control are organized into four categories: 1) frequency control, 2) voltage control, 3) system protection, and 4) fault ride-through capability and power system voltage recovery, which are followed by a summary of challenges to modeling and simulation approaches for inverter-based systems. Next, a road map for developing and deploying grid-forming inverters is introduced, and the importance of establishing an environment of technical standards is emphasized.

The second article, "Collaborative Autonomous Grid-Connected Inverters—Flexible Grid-Forming Inverter Control for the Future Grid," is by Joseph Benzaquen, Mohammadreza Miranbeigi, Prasad Kandula, and Deepak Divan. The authors provide a historical review of the evolution of power grids and predict that a universal set of rules for grid-connected inverters to collaborate with one another is needed and will be the foundation for building the future grid. They also discuss a universal control strategy for grid-forming inverters, where a phase jump algorithm is proposed and added to the power synchronization control loop.

In "Islanding Detection of Grid-Forming Inverters: Mechanism, Methods, and Challenges," Teng Liu, Xiongfei Wang, Fangcheng Liu, Kai Xin, and Yunfeng Liu provide a systematic discussion of the difficulties with the islanding detection of grid-forming inverters. The authors compare islanding detection mechanisms, i.e., the dependencies of physical variables, for grid-following and grid-forming inverters and identify differences resulting from the grid-forming control paradigm. The prior art of islanding detection for grid-forming inverters is then reviewed. This is followed by an outline of challenges, where the need to update grid codes and standards, the conflict between grid forming and islanding detection, the clash between fault ride-through and islanding detection, and the islanding detection of multiple inverters are highlighted.

Next, "Grid-Forming Inverters for Grid-Connected Microgrids," by Andrew Tuckey and Simon Round, shares two practical examples of megawatt-level grid-forming battery energy storage systems (BESSs) deployed in commercial grid-connected microgrids. Grid-forming BESSs are demonstrated in a rate-of-change-of-frequency event and for seamless islanding operation. The authors also elaborate on the full range of inverter control levels and give a comparison of grid-following and grid-forming inverters with respect to their capabilities. They highlight the fact that stiff voltage sources are not preferred for inverters.

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The fifth feature is "Grid-Forming Wind: Getting Ready for Prime Time, With or Without Inverters" by Vahan Gevorgian, Shahil Shah, Weihang Yan, and Geoff Henderson. It introduces three types of grid-forming wind turbines, including two inverter-based (type 3 and type 4) and one synchronous generator-based (type 5) wind turbines, and it compares them with respect to grid integration challenges. The stability of type 3 wind turbines equipped with grid-following and grid-forming controls is compared through impedance-based analysis. The frequency-stabilizing effect of type 4 grid-forming wind turbines is also demonstrated. Electromechanical interaction issues with type 4 grid-forming wind turbines and prevention measures are discussed.

In the "Viewpoint" column, Nicholas W. Miller contributes "From the High Plains and Deserts—A New Look at Getting Renewable Energy From Remote Sources to Load Centers." He shares another challenge to be faced in the immediate future: the long-distance bulk power transfer from remote, large-scale wind and solar power plants to load centers. Power–angle and power–voltage ("nose") curves are used to indicate the physical limits of the energy transfer, regardless of grid-following and grid-forming inverters. The author also indicates that the dynamic behaviors of power systems will be fundamentally altered by inverter control, although the physical laws of power transfer will not change.

Finally, the article "Indonesian Electric Motorcycle Development" is from Yuniarto et al. The authors discuss lessons from innovation-based concept implementation for designing and producing the first Indonesian electric motorcycle.

Enjoy the Issue

We hope you enjoy the diverse and comprehensive views in this issue. The guest associate editor would like to thank Lingling Fan, editor-in-chief, for her tireless support throughout the final and time-demanding stages of this special issue. Finally, we would like to thank Randi E. Scholnick-Philippidis, senior publications administrator of the IEEE Power and Energy Society, for providing indispensable support. If you would like to submit an article or to have a topic addressed in future issues, please contact the editorial board at electrification@ieee.org.