Sustainable and Resilient Distribution Systems With Networked Microgrids

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Grid modernization calls for increasing requirements of electric grid operation with enhanced sustainability and resilience [1]. In particular, distribution grids serve as a critical venue to bridge bulk upstream transmission and generation systems and a large number of downstream end users on the customer side, playing a significant role in modern electric grids for multiple purposes (e.g., renewable energy integration, power flow distribution, and end-user power quality enhancement) [2]. Under a normal grid operation condition, the increasing penetration level of renewable energy sources imposes new challenges on conventional distribution grid infrastructure (e.g., protection malfunction [3] and voltage violation [4]); on the other hand, in an extreme grid operation scenario, it is urgently needed to restore grid services after severe power outages, such as those caused by natural disasters [5]. In particular, for critical infrastructures, an efficient grid service restoration strategy should be implemented to avoid further damage over an extended period of time.

To effectively manage diversified source and demand-side grid assets, an intuitive solution is to leverage local devices and controllers to replace conventional central control and management frameworks. Local controllable sources [e.g., photovoltaics (PVs), wind turbines, and energy storage] and demand-side assets (e.g., controllable loads) can be utilized to participate in grid control in a collaborative way. This type of local aggregated system is named as "microgrids," which have been extensively studied over the past years. As an interpretation of microgrids proposed by the U.S. Department of Energy (DOE), a microgrid is defined as

Digital Object Identifier 10.1109/JPROC.2019.2963605

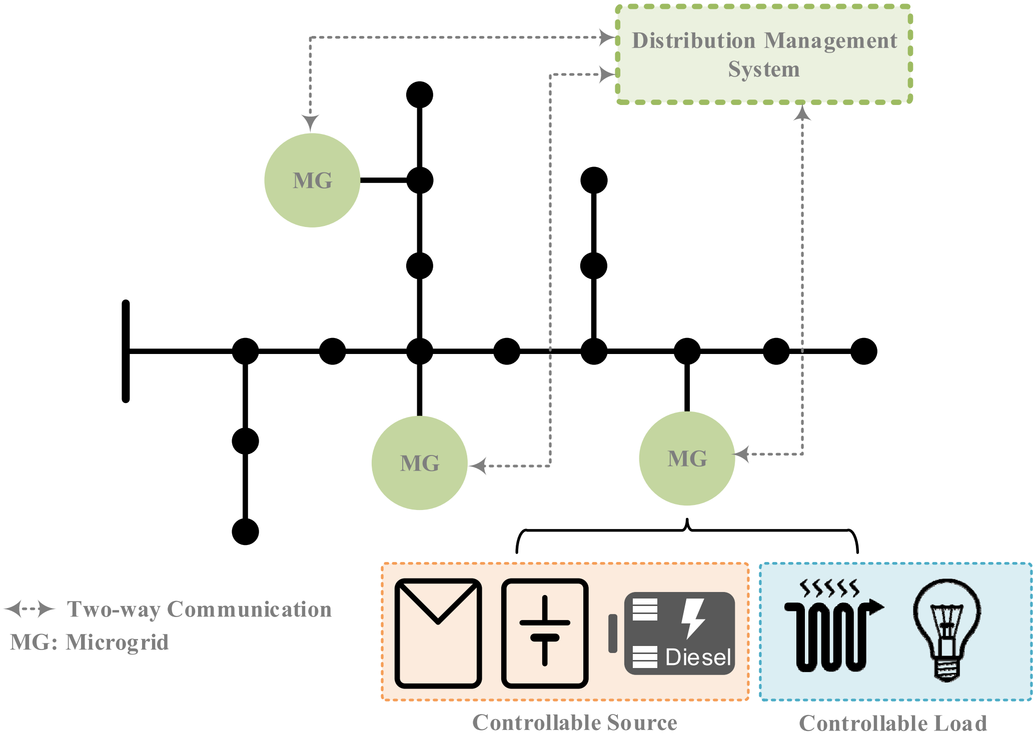

Fig. 1. ***Distribution grid architecture with networked microgrids.***

"a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid" [6], which indicates the integrity of control and communication network as well as physical circuits of a microgrid. Such a localized system offers improved energy supply reliability and resilience as it can island itself and avoid any power outage when the normally connected utility distribution grid is down.

I. DIFFERENCES BETWEEN MICROGRIDS AND CONVENTIONAL POWER SYSTEMS

As indicated in the definition of microgrids, it can be seen that microgrids are different compared to traditional power grids in terms of system configuration and control architecture. It should be noted that conventional power grids, especially distribution grids, are generally implemented based on a centralized grid architecture, i.e., downstream distribution feeders and customers therein solely rely on the power supply from upstream transmission grids. It is noticed that this grid architecture could be stressed out with insufficient resilience due to a single-point-of-failure at the substation, which is the interface between upstream power grids and downstream distribution feeders. However, given the integrity of controllability and sustainability of a single microgrid, distribution grids with one or more microgrids feature a revolutionary architecture with distributed grid assets integrated into conventional distribution feeders other than following a centralized structure [7]. In particular, considering renewable energy resources with increasing penetration levels, microgrids can be effectively used to integrate renewables and coordinate their operation with other controllable resources, e.g., energy storage units (ESUs) and demand response. Therefore, conventional centralized structures of distribution grids could be gradually replaced with distributed microgrids, enabling a paradigm shift toward greater grid resiliency with distributed grid assets and associated controls.

Note that deploying *a grid of microgrids* does not deviate from using the existing and predominant generation units. As the major venue of integrating microgrids, a distribution system still interconnects with upstream bulk power grids, which are dominated with large generation units, while in the meantime, downstream distributed energy resources (DERs) can also be integrated using localized microgrids. Therefore, multiple microgrids and traditional rotational generation units can coordinate with each other through collaborative control on transmission and distribution networks, rather than fighting with each other. Indeed, we stress that bulk power grids and microgrids should coexist to integrate resources of different sizes and locations.

II. DISTRIBUTION GRIDS WITH SINGLE OR NETWORKED MICROGRIDS

A microgrid, as a single controllable unit, should maintain source and load balance and achieve frequency and voltage stability within itself; meanwhile, it should also participate in various grid services and thereby improve modern distribution grid operation with respect to the enhanced resiliency and sustainability. Basically, a microgrid should be responsible for managing and coordinating the controllable sources and loads therein and respond to distribution grid commands for frequency and voltage regulation or active and reactive power support.

With the rapid development of microgrid technologies, an evolution of microgrid control and management is gradually moving toward a systematic and coordinated framework, i.e., *A Grid of Networked Microgrids*. Networked microgrids comprise multiple interconnected microgrids and nested within distribution systems. As depicted in Fig. 1, rather than focusing on a single microgrid, multiple microgrids can be interconnected and communicate with central distribution management systems simultaneously. Compared to the grid structure with a single microgrid, networked microgrids can further enhance grid operation flexibility and reduce control complexity with hierarchical architecture.

III. TECHNICAL CHALLENGES AND ASSOCIATED SOLUTIONS

Although there are tremendous advantages of microgrids with respect to grid resiliency and sustainability enhancement, there are still challenges that may slow the popularization of microgrid technologies.

A. Control Strategies With Stability Guarantees

In contrast to conventional distribution grids that are mainly implemented based on passive circuits and components, microgrids are structured and built upon active and controllable devices, requiring additional control designs to guarantee a sufficient stability margin. Furthermore, due to the physical nature of the sources and their associated controls in microgrids, a microgrid is usually a weak grid with inevitable grid impedance at the point of common coupling (PCC), and this grid impedance may trigger additional instabilities in microgrids that need to be carefully eliminated with fine-tuned advanced control diagrams [8].

B. Optimally Planned and Operated Grid Assets

In order to maximize the benefits of microgrids, the grid assets inside the microgrids should be optimally designed, leading to optimal planning and operation of microgrids [9], [10]. Particularly, microgrids should be well planned to determine the size and location of each grid asset. This is critical to ensure long-term functionality of microgrids; on the other hand, optimal dispatch should also be implemented considering different types of grid assets residing in microgrids. This is related to optimal scheduling and coordination to maximize the short-term cost-effectiveness of microgrid deployment.

C. Power Quality Management and Control

Since a variety of grid assets inside a microgrid are interfaced with power electronic converters, high-frequency switching in power electronic converters induces harmonic distortion and even high-frequency resonance, which can thereby trigger power quality issues. To mitigate such impacts on power quality, additional control loops (e.g., virtual impedance [11] and resonant control [12]) can be implemented in the control diagram of interface inverters. These control approaches are designed to alleviate the power quality distortions in an extended frequency range and tackle the corresponding stability problems.

D. Resilience Enhancement in Local and Regional Areas

Microgrids are designed to aggregate local sources and loads, and recently, with increasing requirements of grid resilience, microgrids also become a suitable candidate for resilience enhancement. However, the capacity and functionality of single microgrids are limited to achieve effective resilience improvement over the entire distribution grids. Therefore, networked microgrids can be implemented to enable additional mutual grid support among them. As reported, grid sectionalization with multiple microgrids can be implemented based on the optimal scheduling of grid assets and effective transient management [13]–[16].

According to the above discussion on various aspects of technical challenges and solutions associated with single and networked microgrids, it should be pointed out that although the technical maturity of enabling a grid of microgrids is still being advanced, there are remarkable and feasible solutions that can be utilized to tackle the technical barriers. Furthermore, cost reduction is also in good progress along with technical advances and mass production of relevant products designed for microgrid deployment. For example, as reported by Solar Energy Technologies Office (SETO) in the U.S. DOE [17], the cost targets of solar electricity by 2030 are \$0.05/kWh, \$0.04/kWh, and \$0.03/kWh for residential, commercial, and utility-scale PV applications, respectively, which can support greater solar energy affordability by lowering the costs by around 50% between 2020 and 2030. Such a dramatic cost reduction for DERs will facilitate the adoption of microgrids in modern electric grids.

IV. CONCLUSION: FUTURE TRENDS OF MICROGRIDS

With distribution grids evolving toward greater resilience and sustainability, microgrid technologies have been significantly advanced and are still being actively studied toward higher versatility. Among the technologies at the research frontier, research on networked microgrids is one of the emerging candidates for future advances.

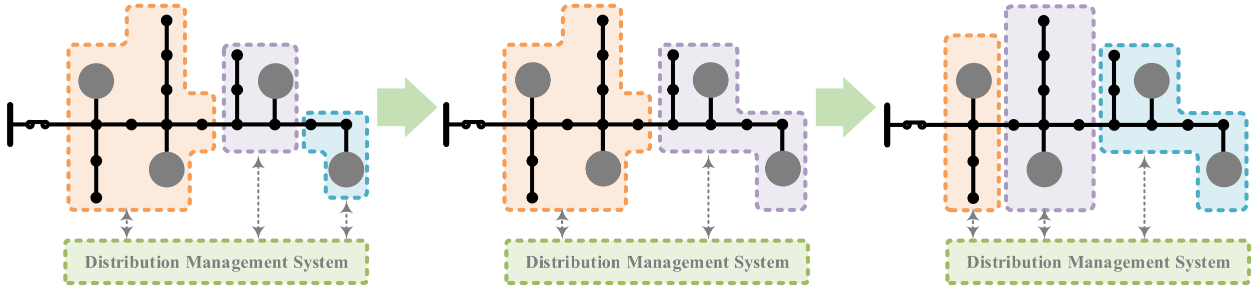

Fig. 2. ***Future networked microgrids with changeable boundaries.***

Networked microgrids exhibit remarkable advantages in distribution grid sectionalization, enabling efficient grid service restoration at critical infrastructures. Meanwhile, this type of networked microgrids can be further developed with *changeable boundaries* toward higher flexibility. Particularly, the boundary of each microgrid can be adjustable to better accommodate source and demand-side grid assets in real time; therefore, a distribution feeder can be divided into multiple *networked microgrids with changeable boundaries* [13]–[16], and a resilient and reconfigurable distribution architecture can be implemented, as depicted in Fig. 2.

From the industry perspective, to better popularize single and networked microgrids, some new business models should be developed to justify the cost and revenue of microgrid deployment. Furthermore, ownership of microgrids could also play a role in the future microgrid operation. Incentives should be designed to attract the interests and attention of different business entities. ■

REFERENCES

[1] *U.S. Department of Energy, Grid Modernization Initiative*. [Online]. Available: https://www.energy.gov/grid-modernization-initiative

[2] D. Apostolopoulou, S. Bahramirad, and A. Khodaei, "The interface of power: Moving toward distribution system operators," *IEEE Power Energy Mag.*, vol. 14, no. 3, pp. 46–51, May 2016.

[3] F. Katiraei, C. Sun, and B. Enayati, "No inverter left behind: Protection, controls, and testing for high penetrations of PV inverters on distribution systems," *IEEE Power Energy Mag.*, vol. 13, no. 2, pp. 43–49, Mar. 2015.

[4] S. Ghosh, S. Rahman, and M. Pipattanasomporn, "Distribution voltage regulation through active power curtailment with PV inverters and solar generation forecasts," *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 13–22, Jan. 2017.

[5] Y. Wang, C. Chen, J. Wang, and R. Baldick, "Research on resilience of power systems under natural disasters—A review," *IEEE Trans. Power Syst.*, vol. 31, no. 2, pp. 1604–1613, Mar. 2016.

[6] D. T. Ton and M. A. Smith, "The U.S. department of energy's microgrid initiative," *Electr. J.*, vol. 25, no. 8, pp. 84–94, Oct. 2012.

[7] R. H. Lasseter, "Smart distribution: Coupled microgrids," *Proc. IEEE*, vol. 99, no. 6, pp. 1074–1082, Jun. 2011.

[8] X. Wang, F. Blaabjerg, M. Liserre, Z. Chen, J. He, and Y. Li, "An active damper for stabilizing power-electronics-based AC systems," *IEEE Trans. Power Electron.*, vol. 29, no. 7, pp. 3318–3329, Jul. 2014.

[9] Z. Wang, B. Chen, J. Wang, J. Kim, and M. M. Begovic, "Robust optimization based optimal dg placement in microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2173–2182, Sep. 2014.

[10] Z. Wang, B. Chen, J. Wang, M. M. Begovic, and C. Chen, "Coordinated energy management of networked microgrids in distribution systems," *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 45–53, Jan. 2015.

[11] Y. Guo, X. Lu, L. Chen, T. Zheng, J. Wang, and S. Mei, "Functional-rotation-based active dampers in AC microgrids with multiple parallel interface inverters," *IEEE Trans. Ind. Appl.*, vol. 54, no. 5, pp. 5206–5215, Sep. 2018.

[12] R. Teodorescu, F. Blaabjerg, M. Liserre, and P. Loh, "Proportional-resonant controllers and filters for grid-connected voltage-source converters," *IEE Proc.—Electr. Power Appl.*, vol. 153, no. 5, pp. 750–762, 2006.

[13] C. Chen, J. Wang, F. Qiu, and D. Zhao, "Resilient distribution system by microgrids formation after natural disasters," *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 958–966, Mar. 2016.

[14] Y.-J. Kim, J. Wang, and X. Lu, "A framework for load service restoration using dynamic change in boundaries of advanced microgrids with synchronous–machine DGs," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3676–3690, Jul. 2018.

[15] Y. Du, X. Lu, J. Wang, and S. Lukic, "Distributed secondary control strategy for microgrid operation with dynamic boundaries," *IEEE Trans. Smart Grid*, vol. 10, no. 5, pp. 5269–5282, Sep. 2019.

[16] Y. Du, X. Lu, H. Tu, J. Wang, and S. Lukic, "Dynamic microgrids with self-organized grid-forming inverters in unbalanced distribution feeders," *IEEE J. Emerg. Sel. Topics Power Electron.*, to be published.

[17] *Goals of the Solar Energy Technologies Office*. [Online]. Available: https://www.energy.gov/eere/solar/goals-solar-energy-technologies-office