iEnergy

REVIEW

https://doi.org/10.23919/IEN.2022.0035

An overview of the operation architectures and energy management system for multiple microgrid clusters

Yajuan Guan[1], Baoze Wei[1], Josep M. Guerrero[1], Juan C. Vasquez[1] and Yonghao Gui[2] ✉

ABSTRACT

The emerging novel energy infrastructures, such as energy communities, smart building-based microgrids, electric vehicles enabled mobile energy storage units raise the requirements for a more interconnective and interoperable energy system. It leads to a transition from simple and isolated microgrids to relatively large-scale and complex interconnected microgrid systems named multi-microgrid clusters. In order to efficiently, optimally, and flexibly control multi-microgrid clusters, cross-disciplinary technologies such as power electronics, control theory, optimization algorithms, information and communication technologies, cyber-physical, and big-data analysis are needed. This paper introduces an overview of the relevant aspects for multi-microgrids, including the outstanding features, architectures, typical applications, existing control mechanisms, as well as the challenges.

KEYWORDS

Renewable energy resource, multi-microgrid cluster, power electronics, control theory, optimization algorithms, information and communication technologies, big-data analysis.

By the U.S. Department of Energy, the microgrid is defined as a standalone electric entity that consists of distributed energy resources and a group of loads, as well as local controllers, which offers the availability of both islanded and grid-connected operation modes[1]. Regarding the definition, a microgrid can be basically understood as a small-scale energy generation system that connects distributed generators (DGs) into distribution networks with the ability of self-supply and grid supporting, which will manage energy generation, distribution, and regulation[2–4]. A Microgrid sometime is considered or understood as a backup power supply, however, in fact it is much more than that. The backup generator is widely used to provide temporary power supply to the loads during utility grid faults or interruptions. Compared to the concept of a backup generator, the microgrid offers significant benefits, such as more reliable, flexible, and sustainable[5]. Microgrid is an attractive solution to match a growing demand for higher energy efficiency, reduced carbon emission, utilization of less costly renewable DGs, economic operation, and improved power quality and reliability[6,7].

As a summary of the significant benefits that endowed by microgrids: it offers an opportunity to integrate various clean renewable energy sources thereby reducing green house gas emission; improve power quality and system dynamic performance by optimal control; flexible operation transition between islanded and grid-connected modes; lower the cost of power distribution and transmission for remote communities; and improve the system reliability by self-healing capability[5]. Due to these advantages, AC microgrids, DC microgrids, and hybrid microgrids have been proposed and investigated in the past decade in various applications[8].

1 Multi-microgrids cluster

As aforementioned, in the past, microgrids were appearing as simple and small isolated electrical grids in remote areas and their control has basically been dominated by conventional techniques and management systems conceived for fixed and small electrical islanded structures, and major part of them validated in a two, or three-unit systems, often faraway from real-world power grids. Recently, microgrids are becoming relatively large and complex interconnected systems with interactions among different technologies like power electronics, control systems, and communications, providing reliable energy support to the end-users, while taking into account efficiency and high rates of renewable energy penetration. The multiple microgrids clusters could be implemented in various applications, such as renewable energy communities and smart houses-based energy systems.

By clustering a microgrid with a number of other electrically adjacent microgrids, a series of benefits can be obtained:

- Facilitate the decentralization of the power system;
- Improved high rates of renewable energy penetration;
- Optimized power flows and reduced energy losses as well as reduced operation costs in local energy network;
- Reliable and efficient energy support to the end-users;
- Extensive deployment and interconnection capability;
- More sustainable and resilient within the microgrid cluster.

Among many research and projects that have investigated microgrids, SAMES project studied a three-microgrid cluster that is geographically separated naval bases in San Diego to maximize energy security and efficiency with the lowest operation cost[9]; In Bronzeville, the US, the electric utility-ComEd that serves 4 million customers in Chicago and Northern Illinois, is connecting the Chicago's Bronzeville Community Microgrid to a microgrid already serving the nearby campus of Illinois Tech, with the aim to install America's first utility-operated microgrid cluster based on the MISST (https://www.energy.gov/eere/solar/project-profile-commonwealth-edison-company-shines project).

Figure 1 shows a hierarchical control structure of a multi-

[1]Center for Research on Microgrids (CROM), AAU Energy, Aalborg University, 9220 Aalborg, Denmark; [2]The Electrification and Energy Infrastructures Division, Oak Ridge National Laboratory, United States
Address correspondence to Yonghao Gui, guiy@ornl.gov

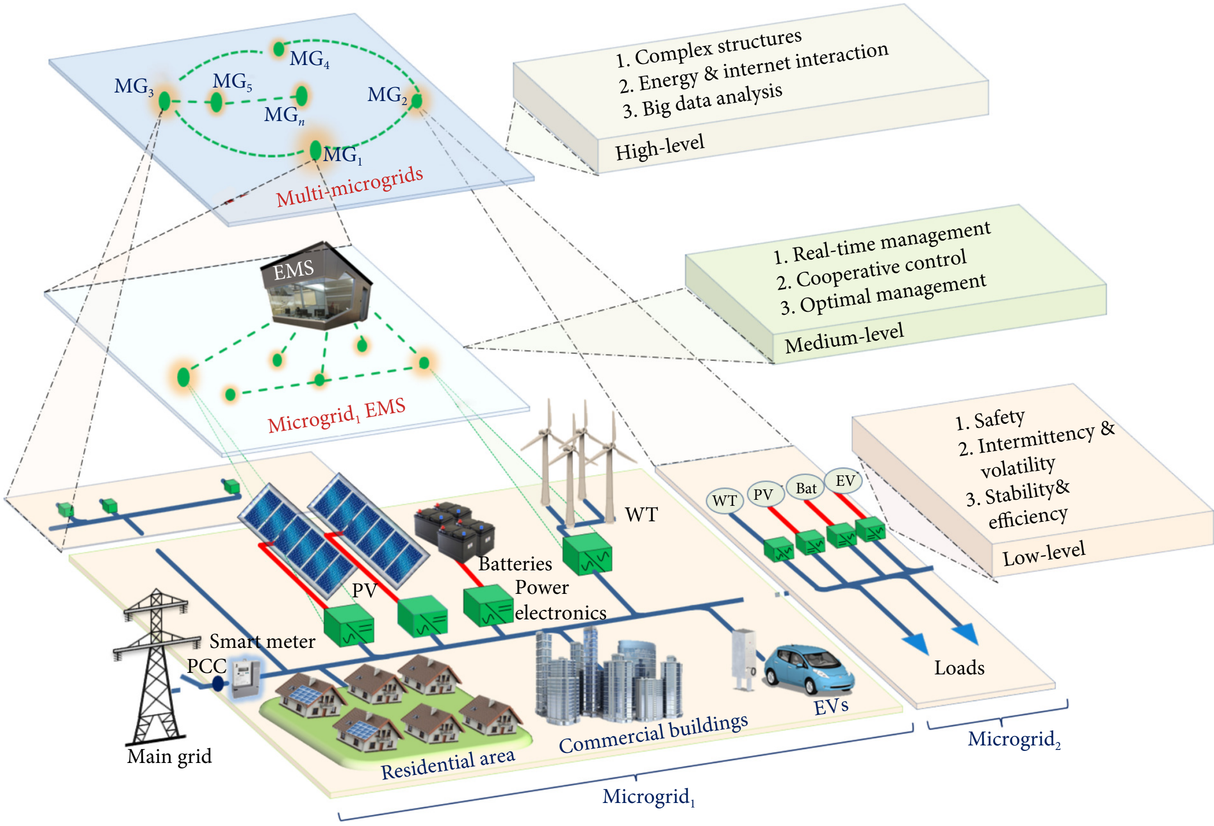

Fig. 1 The general architecture of multi-microgrids.

microgrid cluster, which consists three levels of framework: low-level, medium-level, and high-level. The low-level deals with the inner control among DG units, energy storage system (ESS), residential and commercial loads, and EVs. The objectives are to maintain voltage and frequency stability, energy efficiency, compensate for the intermittent nature of renewable energy. The medium-level aims to achieve cooperative control for the different generation units, prosumers and local loads, as well as the real-time optimized management within one microgrid. The high-level control deals with the complex and complicated multi-microgrid interconnections. It is responsible for handling the interactions among microgrids, energy and information flow management, economical optimization, efficient improvement, as well as protection at a cluster level. As observed in Figure 2, various knowledge such as power electronics, control theory, optimization algorithms, information and communication technologies, cyber-physical, and big-data analysis are involved in the development of multi-microgrid clusters.

- The large-scale complex multi-microgrid clusters are spatially distributed and interconnected, where fully distributed control and modeling methods having good compatibility with the spatial distribution of electric power systems are required[10–12].
- Since the flexible energy demand and living quality requirements are ever-growing and there are multiple sources of energy and various types of smart sensors, smart devices, actuators, and smart appliances, the need for a decentralized comprehensive asset management system has arisen. Distributed multi-microgrid cluster control architectures inherently contain the cyber and physical layers; therefore, the networked information systems are the core components of microgrid clusters[13].
- A completely decentralized solution stands for massive data inputs, big-data analysis, various control strategies, and complex decision-making algorithms resulting in higher complexity and interdependency in the architecture of future distribution networks composed of microgrid clusters. Interconnection of multi-microgrid within a neighbourhood can allow them to negotiate as a group with their potential forecasted energy flexibility (both consumption and distributed generation) and load scheduling as well as within a smart energy neighbourhood ecosystem by means of the Internet of things (IoT) that allow the realisation of collective dynamic optimized management and demand response strategies[14]. Blockchain and edge computing technologies can help to achieve a secure and fully decentralized comprehensive resource management system.

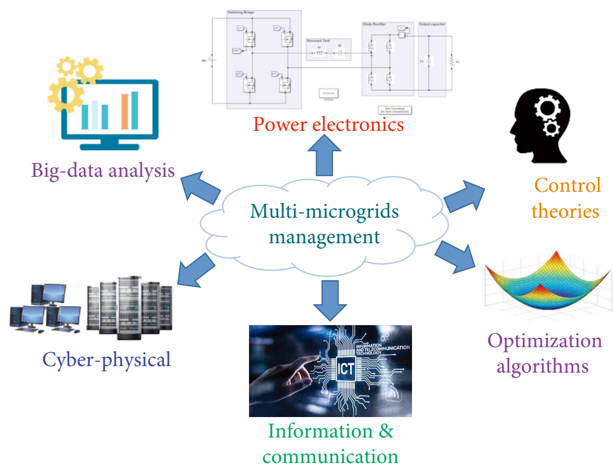

Fig. 2 The needed knowledge for multi-microgrids.

- Coordinated protections associated with multi-microgrids are necessary to detect, locate, and identify faults, as well as to reconfigure the power distribution network at a cluster level.

2 Operation architecture of multiple microgrids

The operation architecture of multiple microgrids can be classified into three types: (1) Decentralized architecture without communication or with only binary signal transmission as shown in Figure 3(a). It is normally used in small scale microgrid clusters for residential households. The objective is to stabilize bus voltage and frequency, meanwhile achieve power sharing or preliminary coordinated control among the clustered microgrids with only local measurements or limited information exchanges. A SoC-based adaptive I–V droop method is proposed to ensure the coordinated power sharing among the contributing nanogrids[15]. Power line communication is used to transmit the power dispatch binary signal to mitigate the uncertainty in the availability of power generation[16]. (2) with a centralized controller and communication links as shown in Figure 3(b). A centralized controller based on hierarchical control structure is used to achieve the high-level coordination and optimal operation for the clustered microgrids. A two-layer hierarchical optimization method is presented for the energy management of a microgrid community[17]. The lower layer deals with each microgrid while the upper layer is responsible for community level's management. (3) Distributed hierarchical architecture with peer to peer (P2P) communication networks as shown in Figure 3(c). The distributed architecture and P2P information exchanges decrease the communication network complexity and costs especially in a large scale microgrid cluster and effectively avoid single point of failure issues, thereby enhancing the communication and control system reliability. A pinning-based hierarchical and distributed cooperative control strategy, which is divided into distributed generation layer, micro-grid -layer, and microgrid cluster-layer, is presented in ref. [18].

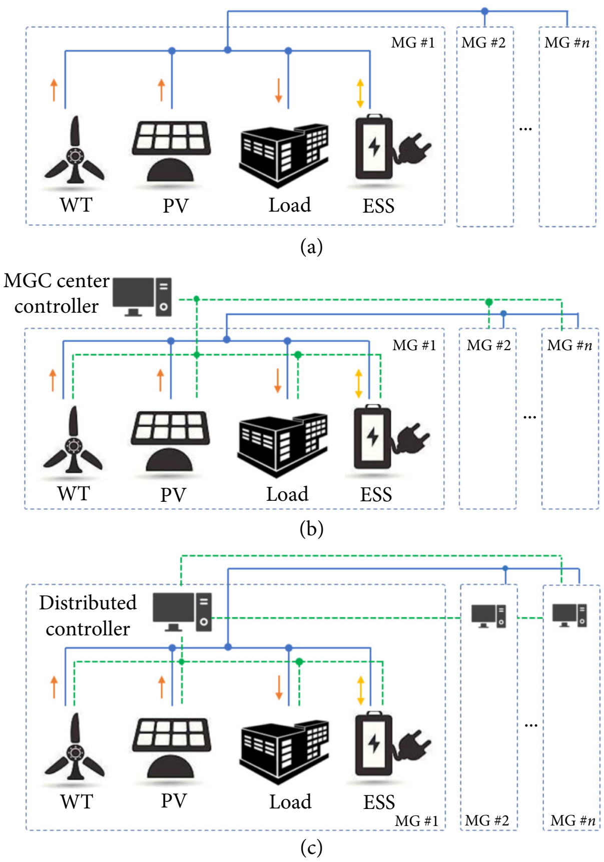

Fig. 3 Operation architecture of multiple microgrids: (a) decentralized architecture, (b) centralized controller, and (c) distributed architecture.

3 Energy management system for multi-microgrids

EMS manages available DGs optimally while ensuring the power quality and reliability of the power supply in microgrids.

3.1 Hierarchical control

In general, a hierarchical control structure for microgrid consists of three levels, as shown in Figure 4[19]:

1. The low-level named primary control is the local controller, e. g. droop method. In this level, the main objective is to stabilize the voltage and frequency, and achieve power sharing among the DGs.
2. The medium-level is secondary control which aims to restore the frequency and voltage deviations caused by the primary controllers. In addition, it is in charge of power quality improvement, synchronization, and coordinated control among different DG units.
3. The high-level is tertiary control which objects to manage the power flow between the microgrid and the external electrical distribution systems. Moreover, energy management system and optimal operation considering economical factors are also at the tertiary layer.

However, the conventional hierarchical control method is only for a single microgrid. It is necessary to add a higher-level above the tertiary control for multi-microgrids, the quaternary control level. "Quaternary Control" level should control multi-microgrids to handle economics, efficiency, and reliability, as shown in Figure 5.

Shafiee et al. designed a distributed hierarchical control strategy for DC multi-microgrids to ensure reliable operation by connecting neighbor microgrids[20]. In the low-level, a common bus voltage regulator is proposed to control each microgrid. In the medium-level, a distributed voltage control strategy based on consensus techniques is designed to remove the voltage deviation in the microgrids. Wang et al. proposed a novel secondary control method to enhance dynamic performance in regards to fast-changing load current condition in DC multi-microgrids[21]. The proposed method eliminates the voltage deviation and improves the accuracy of the current sharing performance in the multi-microgrids. A model predictive control (MPC) based outage management strategy is developed for multi-microgrids by using mixed integer linear programming in ref. [22]. Such an outage management method not only optimally minimizes the unfavorable effects of natural disasters but also enhances the resilience of multi-microgrids. A bi-level model to handle an optimal operation problem of both distribution network and microgrids with hierarchical structure and multiple participants, where the higher-level controller calculates the optimal capacity of microgrids to guarantee minimum power losses and improves voltage quality in a distribution grid with consideration of output power range of microgrids, power flow constraints, and available dispatch capacity limitation is proposed in ref. [23]. Based on higher-level decisions as constraints, the lower-level optimally manages DGs in each microgrid.

A cooperative power dispatching control scheme for multi-

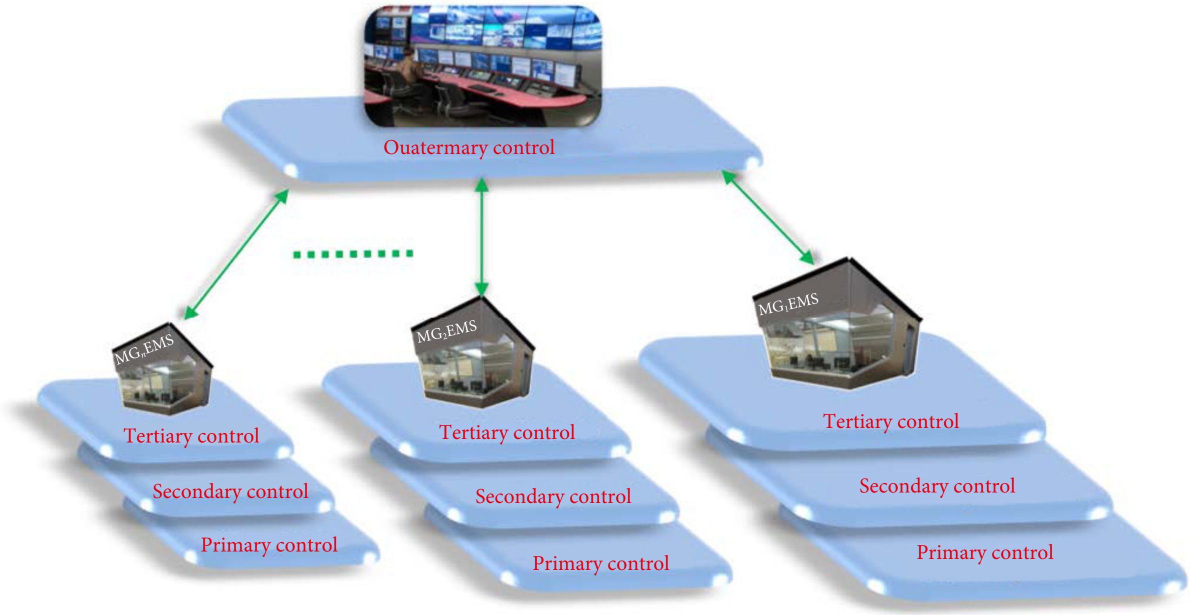

Fig. 4 Hierarchical control architecture of multi-microgrids.

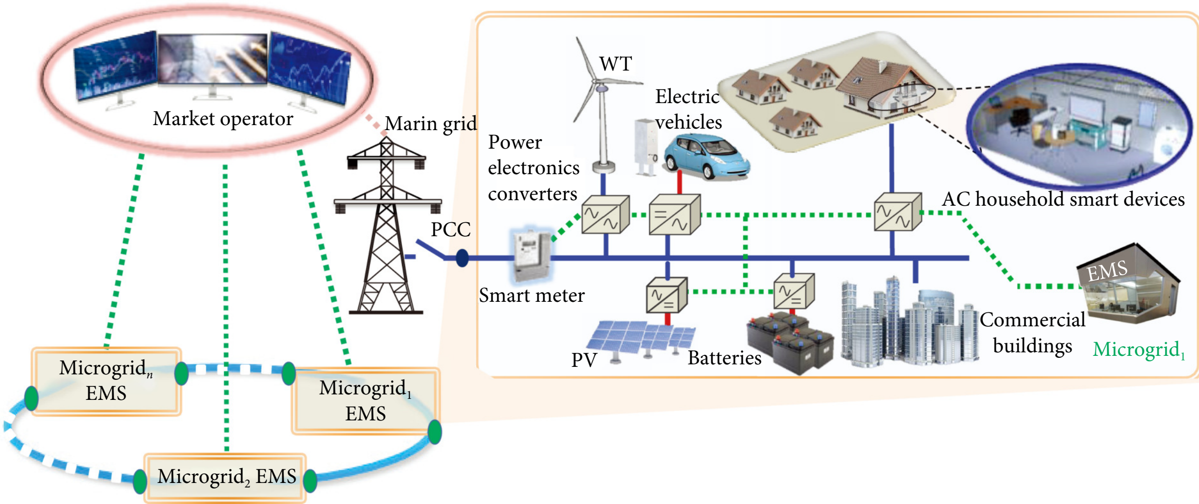

Fig. 5 Cooperative power dispatching for multi-microgrid.

microgrids is designed to minimize operational cost in ref. [24]. It uses a communication infrastructure and defines parameters such as dynamic purchase prices for each microgrid. It is shown that a lower price can be guaranteed in the grid-connected mode rather than in the stand-alone operation when using the cooperative power sharing scheme. Tushar *et al.* proposed a decentralized energy management strategy based on a non-cooperative Stackelberg game[25]. It is a benefit to reduce the total cost of energy purchased in the system. Zhang and Xie proposed an online dynamic security assessment method for multi-microgrids[26]. It shows the coordinated and distributed stability conditions for the multi-microgrids using linear matrix inequalities and dissipative system theory. A cooperative energy dispatch solution for autonomous islanded multi-microgrids is presented in ref. [27]. With consideration of power loss and reliability, the proposed method solves an optimization problem based on the minimum spanning tree algorithm. Wang et al. developed a coordinated decentralized power dispatch for multi-microgrids with consideration of renewable energy sources[28], and also proposed a transformative architecture for the optimal operation and self-healing of microgrids connected by a two-layer communication network[29]. Arefifar et al. designed a day-ahead energy management to perform optimized and coordinated manner in multi-microgrid systems[30]. It shows that the energy losses of the total system and the operational costs are reduced. Kow et al. proposed a distributed economic MPC strategy to minimize the operation cost of the whole multi-microgrids[31]. It handles non-Gaussian uncertainties in wind generation and Gaussian uncertainties in microgrid loads.

3.2 Demand side management

Energy management system may also be unable to maintain the demand and supply balance if the total maximum available power of distribution generators is less than the total consumption power due to volatile distribution generators like wind and solar. Under such cases, it is helpful to use backup systems (diesel generators or energy storage systems)[32]. Compared with the installation of some new backup systems, demand-side management techniques are less costly to intelligently influence loads[33]. One of the key demand-side management techniques is demand response, which is defined by U.S. Department of Energy such as: *changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*[34]. Demand response allows end-use customers to directly participate in peak demand reduction and energy efficiency improvement while getting certain incentive based on electricity price. Figure 6 shows a demand response configuration of microgrids based on smart meters, which are key devices to implement its program.

Various kinds of literature has been researching demand response mechanisms for multi-microgrids. An intelligent demand response algorithm is proposed to manage and trade power in multi-microgrids with a reduction of the peak demand. The method maintains two virtual global and local energy markets that enable customers to make a role in the management system[32,35]. The main idea is that the method exploits diversity in load consumption patterns between the end-use customers and distribution system availability (e.g., renewable energy resources, energy storage systems, demand responses, etc.) in order to reduce the peak demand and minimize their costs of operation. Then, a modified demand response method is proposed to cater the incentives to the end-use customers based on the frequency of participation in energy management and their contributions to the whole system while deciding the priorities for end-users[36]. Moreover, another demand response energy management method is proposed for industrial facilities in terms of the predefined electricity prices[37]. It transforms a demand response problem into a mixed integer linear programming one, in which the objective function is to minimize the energy cost of industrial facilities based on a set of constraints, which guarantee DGs' process operations as well as their advantages.

In addition, it is shown that demand response energy management can reduce the capacities of energy storage systems in the multi-microgrid. However, it is concluded that the best result for each defined scenario is the demand response energy management with each technical index (e.g., supply-adequacy, voltage profile, efficiency, and reliability), whereas it leads to a higher usage of energy storage systems.

3.3 Multi-agent based management

A multi-agent system (MAS) may consist of large numbers of multiple intelligent agents operating in rapidly evolving dynamic environments[38]. Various optimization problems of microgrid applications are solved by using MAS architectures. In ref. [39], it introduces a hierarchical energy management system to optimally manage multi-microgrids based on MAS, where the advantages of hierarchical energy management and MAS are used based on the concept of cooperative multi-microgrids operation. A two-level architecture (market level and field level) is proposed for distributed-energy-resource management of multi-microgrids using MAS[40]. For the market level, it is designed to provide the dealing service among the microgrids or with the grid while maintaining market fair and clear. For the field level, it is designed to balance the local supply and demand in individual microgrids. Ren et al. proposed three-level MAS system to achieve local and global control objectives (coordinating, controlling and optimizing)[41]. The level 1 agents consist of load and DG agents, the level 2 agents are microgrid agents, and the level 3 agent is multi-microgrid agent. In ref. [39], a cooperative multi-microgrid problem is formulated considering operation cost, power generation and transmission losses, user utility, distributed storage, and grid load smoothing. The control structure is shown in Figure 7. Both the power loss and the operation cost can be reduced with cooperative microgrids. In order to coordinately solve the real-time power imbalance problems of multi-microgrids, an MAS-based cooperative control framework is proposed to allow multi-microgrids autonomously form coalitions and negotiate the power trading among each other[42]. In addition, an effort index is developed based on the recorded data of each microgrid to effectively manage the load shedding in the multi-microgrid[43]. For lower the energy imbalances and less reliant on the utility grid in multi-microgrids, an MAS-based management with agents delegating the physical entities was proposed[44]. Energy imbalances problems in multi-microgrids are solved by optimally managing the demand response and energy storage systems in primary phase while the energy mismatches and forecast deviations problems in multi-microgrids are solved by using a transactive energy in the secondary phase.

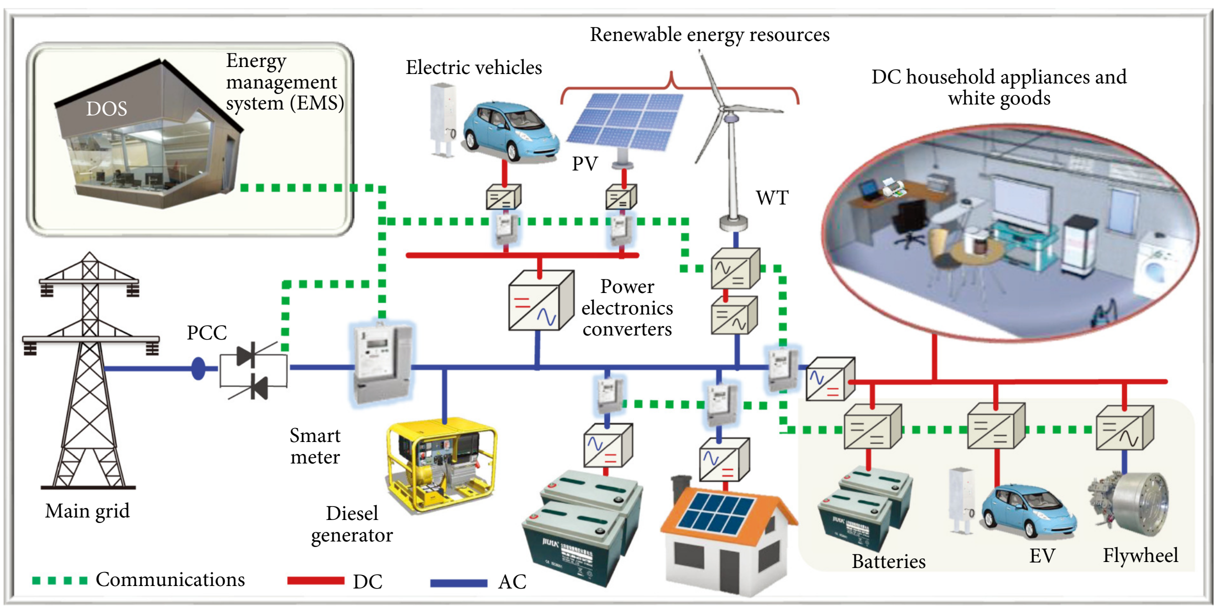

Fig. 6 Demand response in microgrids using smart meters.

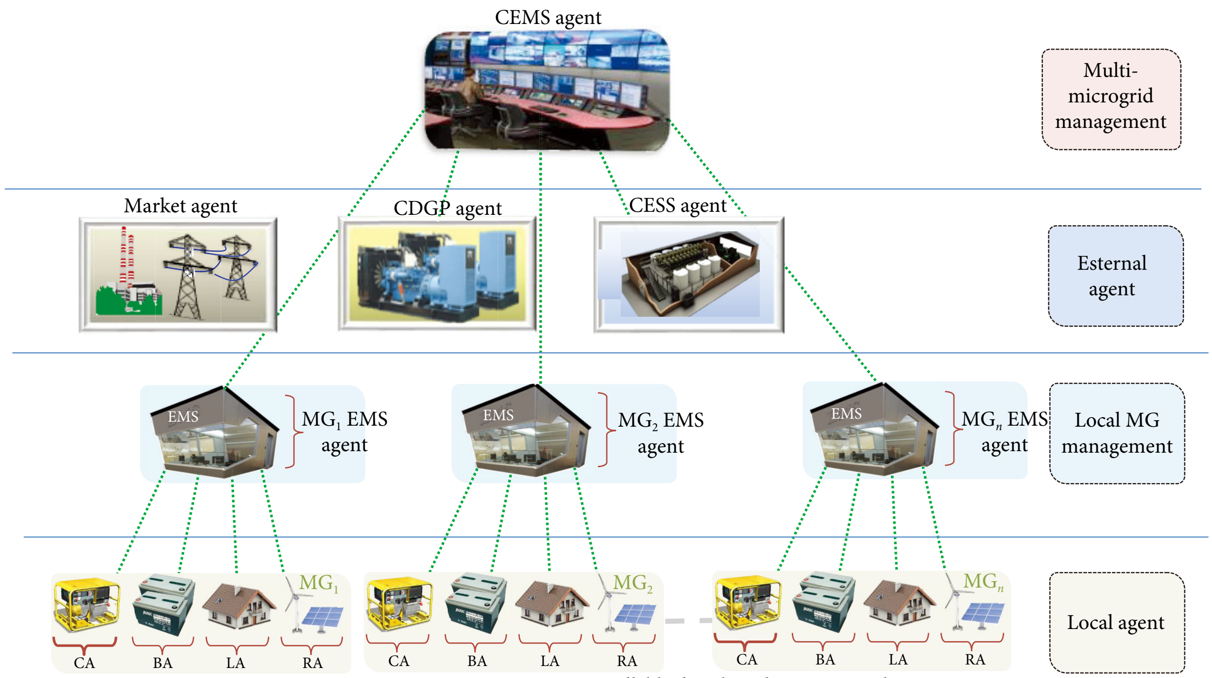

Fig. 7 Configuration of the MAS management for multi-microgrids[39].

3.4 Artificial intelligence management

With the development of artificial intelligence technology, various intelligent energy management strategies have been investigated for multi-microgrids. In ref. [45], both deep neural network and model-free reinforcement learning algorithms are used to optimize the pricing strategy between maximizing profit of selling energy and minimizing peak-to-average ratio of the demand side. One of its advantages is that there is no need to require the local generation or consumption information from local microgrid operators, which increases customer privacy security. However, it obtains a near-optimal solution and the difference between the real optimal and near-optimal is not discussed. Two-level hierarchical structure power management using reinforcement learning for multi-microgrids is proposed to optimize operation in a cooperative and economic manner[46]. At level 1, a cooperative agent determines optimal prices in order to maximize the revenue of the entire system with limited information. At level 2, each microgrid calculates the optimal power management with the consideration of price from the cooperative agent.

3.5 Assets and resources management for building-based microgrid clusters

The building-based microgrid clusters target the management of a community-scale microgrid implemented within the municipal setting. The microgrids serve with a cluster of Municipal buildings with its power and heat requirements. The energy flows through the microgrid-enabled energy network, from both the generation and demand sides, must be managed and maintained at minimum cost and maximum technical efficiency levels. Effective management can only be obtained from knowledgeable and informed decisions. This will be achieved by gathering data from sensors and energy system information models that will reduce the amount of time needed to elaborate on a decision.

3.6 Others

Two models are proposed to simulate the interaction of energy services provider, the entity managing a number of microgrids and the electricity market[47]. One is a decentralized control structure to examine the case where a bilateral agreement is set and the other is a centralized one to manage the central production unit and the microgrids. In order to solve the energy trading problem among multi-microgrids operating in islanded mode, an algorithm is proposed in a distributed manner[48]. It optimally manages the energy exchanges between the interconnected microgrids with minimum energy production and transportation costs of the total system. In ref. [49], a distributed energy trading algorithm is proposed based on game-theoretic for multi-microgrids. In ref. [50], a graph theory-based routing algorithm is designed to determine the minimum loss paths based on minimization of power loss and optimal management of congestion. A real-time power transaction strategy is designed by using a minimum loss routing algorithm in order to reduce the power loss from the conversion and transmission[51]. In ref. [52], it shows that a proper regulation of active power outputs of ESS as well as reactive power outputs of STATCOM in each microgrid can effectively damp the oscillations, which are caused by the interaction of standard microgrid controllers. A robust distributed control is developed to achieve the optimal power regulation by coordinating DG units and ESS/STATCOMs of each microgrid. In ref. [53], a probabilistic index is defined to assess the controllability of voltages and currents in multi-microgrids. With allocation of the DGs in the multi-microgrids, an enhanced operation of the total system is obtained with optimum controllability of voltage and current, reliability, and supply-security.

4 Future perspective and challenges

Cooperative control of multi-microgrid could consider the following aspects to support ancillary services to the grid. Those properties have to be shifted from one microgrid to multi-microgrid clusters.

1. **Economics** of power supply is one of the most important features for control and management of the multi-microgrid clusters. Optimal power flow among the microgrids can obtain several advantages such as reduction of the operation cost of the entire system and the system expansion planning cost, as well as increment of less costly renewable energy sources penetration in the power grid.
2. **Resiliency** is another key property that denotes an ability of the multi-microgrid clusters to minimize the negative impacts on low-probability high-impact incidents[54]. At the cluster-level, it is possible to be supported coordinately by each microgrid when incident occurs in one node.
3. **Reliability** is one of the core trends that ranges from device-level to system-level due to safety requirements. Cooperative power flow management at a cluster-level leads to improved reliable energy support to the end-users in each microgrid.
4. **Security** from potential cyber attacks is one of the important problems in the multi-microgrid cluster due to its complex communication network. At the cluster-level, it is possible to be supported by other microgrids when one of microgrids has been attacked or lost in the system.
5. **Flexibility** can be supported by flexible loads and DGs in each microgrid. The cooperative power flow management can support flexible power flow among the microgrids.
6. **Efficiency** of each system can be improved by its local advanced control strategy. Moreover, cooperative power flow management at a cluster-level leads to maximum energy efficiency by using their potential capability of ancillary services from each microgrid as well as each DG.

The following challenges could be expected.

1. **Stability:** The stability analysis for single microgrid including DGs and loads has been investigated in various literatures. However, due to large-scale interconnected and complex structure of the multi-microgrid cluster, the cluster-level stability needs to be guaranteed with a novel control theory.
2. **Power Quality:** The proper control strategies have been designed for power converters in microgrids to improve power quality such as voltage fluctuation and harmonics. How to improve the power quality coordinately from device-level or microgrid-level to cluster level needs in-depth investigation.
3. **Protection:** Since in a microgrid the power flow is multidirectional, protections cannot be performed as in the conventional power system in which power flow is unidirectional. Additionally, in a multi-microgrid system, protections at different layers needed to be investigated, for instance, converter-based protection and circuit-breaker-based protections.
4. **Cyber Security:** Due to its complex communication networks, different cyber attacks such as false data injection, denial service, and replay attacks should be considered. The resilience capability and system behavior with different cyber attacks should be evaluated.
5. **Data Processing:** A huge data will be received from sensors, actuators, smart appliances, and smart meters located in the DGs and the multi-microgrids. As a consequence, data collection, analysis, and processing are important for multi-microgrids control, management and optimization.
6. **Privacy & Benefits:** The solution should respect end-use customers privacy and security requirements. In addition. the optimal solution could be designed to balance the benefits of all participants (e.g., market operators, stakeholders, end-use customers, etc.). All the participants can get the benefits from this new technology.

5 Conclusions

This paper introduced an overview of the operation architectures and energy management system for multi-microgrid cluster, including the outstanding features, architectures, typical applications, existing control mechanisms as well as the challenges. Due to the emerging novel energy infrastructures, a transition from simple and isolated microgrids to multi-microgrid clusters, which has several features including economics, resiliency, reliability, security, flexibility, and efficiency, becomes an urgent need. To achieve such features, various control strategies, as well as energy and power management algorithms have been researched, including hierarchical energy management, demand side management, multi-agent-based management, artificial intelligence management. For the future works in multi-microgrid cluster, a more intelligent and comprehensive control methodology is needed to guarantee its stability, improved power quality, protection, robust to cyber-attacks, big-data processing, and privacy & benefits of all participants.

Acknowledgements

This work was supported by VILLUM FONDEN under the VILLUM Investigator Grant (No. 25920): Center for Research on Microgrids (CROM); www.crom.et.aau.dk

Article history

Received: 29 June 2022; Revised: 1 August 2022; Accepted: 13 August 2022

Additional information

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

References

[1] Office of Electricity Delivery and Energy Reliability Smart Grid R&D Program (2012). Summary report: 2012 DOE microgrid workshop. Chicago, Illinois.

[2] Vasquez, J. C., Guerrero, J. M., Miret, J., Castilla, M., de Vicuna, L. G. (2010). Hierarchical control of intelligent microgrids. *IEEE Industrial Electronics Magazine*, 4: 23–29.

[3] Guerrero, J. M., Blaabjerg, F., Zhelev, T., Hemmes, K., Monmasson, E., Jemei, S., Comech, M. P., Granadino, R., Frau, J. I. (2010). Distributed generation: Toward a new energy paradigm. *IEEE Industrial Electronics Magazine*, 4: 52–64.

[4] Vandoorn, T. L., Vasquez, J. C., de Kooning, J., Guerrero, J. M., Vandevelde, L. (2013). Microgrids: Hierarchical control and an overview of the control and reserve management strategies. *IEEE Industrial Electronics Magazine*, 7: 42–55.

[5] Parhizi, S., Lotfi, H., Khodaei, A., Bahramirad, S. (2015). State of the art in research on microgrids: A review. *IEEE Access*, 3: 890–925.

[6] Rocabert, J., Luna, A., Blaabjerg, F., Rodriguez, P. (2012). Control of power converters in AC microgrids. *IEEE Transactions on Power Electronics*, 27: 4734–4749.

[7] Olivares, D. E., Mehrizi-Sani, A., Etemadi, A. H., Cañizares, C. A., Iravani, R., Kazerani, M., Hajimiragha, A. H., Gomis-Bellmunt, O., Saeedifard, M., Palma-Behnke, R., et al. (2014). Trends in microgrid control. *IEEE Transactions on Smart Grid*, 5: 1905–1919.

[8] Sahoo, S. K., Sinha, A. K., Kishore, N. K. (2017). Control techniques in AC, DC, and hybrid AC–DC microgrid: A review. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 6: 738–759.

[9] Meagher, K. (2016). Secure automated microgrid energy system (SAMES). Power Analytics Raleigh United States.

[10] Moayedi, S., Davoudi, A. (2015). Distributed tertiary control of DC microgrid clusters. *IEEE Transactions on Power Electronics*, 31: 1717–1733.

[11] Meng, L. X., Shafiee, Q., Trecate, G. F., Karimi, H., Fulwani, D., Lu, X. N., Guerrero, J. M. (2017). Review on control of DC microgrids and multiple microgrid clusters. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 5: 928–948.

[12] Alam, M. N., Chakrabarti, S., Ghosh, A. (2019). Networked microgrids: State-of-the-art and future perspectives. *IEEE Transactions on Industrial Informatics*, 15: 1238–1250.

[13] Guan, Y., Feng, W., Palacios-Garcia, E. J., Vásquez, J. C., Guerrero, J. M. (2019). Vicinity platform-based load scheduling method by considering smart parking and smart appliance. In: Proceedings of the 2019 15th International Conference on Distributed Computing in Sensor Systems (DCOSS), Santorini, Greece.

[14] Harmon, E., Ozgur, U., Cintuglu, M. H., de Azevedo, R., Akkaya, K., Mohammed, O. A. (2017). The internet of microgrids: A cloud-based framework for wide area networked microgrids. *IEEE Transactions on Industrial Informatics*, 14: 1262–1274.

[15] Nasir, M., Jin, Z., Khan, H. A., Zaffar, N. A., Vasquez, J. C., Guerrero, J. M. (2018). A decentralized control architecture applied to dc nanogrid clusters for rural electrification in developing regions. *IEEE Transactions on Power Electronics*, 34: 1773–1785.

[16] Haidar, A. M., Fakhar, A., Muttaqi, K. M. (2020). An effective power dispatch strategy for clustered microgrids while implementing optimal energy management and power sharing control using power line communication. *IEEE Transactions on Industry Applications*, 56: 4258–4271.

[17] Tian, P. G., Xiao, X., Wang, K., Ding, R. X. (2016). A hierarchical energy management system based on hierarchical optimization for microgrid community economic operation. *IEEE Transactions on Smart Grid*, 7: 2230–2241.

[18] Wu, X. Y., Xu, Y., He, J. H., Wang, X. J., Vasquez, J. C., Guerrero, J. M. (2020). Pinning-based hierarchical and distributed cooperative control for AC microgrid clusters. *IEEE Transactions on Power Electronics*, 35: 9865–9885.

[19] Guerrero, J. M., Vasquez, J. C., Matas, J., De Vicuña, L. G., Castilla, M. (2010). Hierarchical control of droop-controlled AC and DC microgrids —A general approach toward standardization. *IEEE Transactions on industrial electronics*, 58: 158–172.

[20] Shafiee, Q., Dragičević, T., Vasquez, J. C., Guerrero, J. M. (2014). Hierarchical control for multiple DC-microgrids clusters. *IEEE Transactions on Energy Conversion*, 29: 922–933.

[21] Wang, P., Lu, X., Yang, X., Wang, W., Xu, D. (2015). An improved distributed secondary control method for DC microgrids with enhanced dynamic current sharing performance. *IEEE Transactions on Power Electronics*, 31: 6658–6673.

[22] Farzin, H., Fotuhi-Firuzabad, M., Moeini-Aghtaie, M. (2016). Enhancing power system resilience through hierarchical outage management in multi-microgrids. *IEEE Transactions on Smart Grid*, 7: 2869–2879.

[23] Lv, T. G., Ai, Q., Zhao, Y. Y. (2016). A bi-level multi-objective optimal operation of grid-connected microgrids. *Electric Power Systems Research*, 131: 60–70.

[24] Fathi, M., Bevrani, H. (2013). Statistical cooperative power dispatching in interconnected microgrids. *IEEE Transactions on Sustainable Energy*, 4: 586–593.

[25] Tushar, W., Chai, B., Yuen, C., Smith, D. B., Wood, K. L., Yang, Z., Poor, H. V. (2014). Three-party energy management with distributed energy resources in smart grid. *IEEE Transactions on Industrial Electronics*, 62: 2487–2498.

[26] Zhang, Y., Xie, L. (2015). Online dynamic security assessment of microgrid interconnections in smart distribution systems. *IEEE Transactions on Power Systems*, 30: 3246–3254.

[27] Fang, X. L., Yang, Q., Wang, J. H., Yan, W. J. (2016). Coordinated dispatch in multiple cooperative autonomous islanded microgrids. *Applied Energy*, 162: 40–48.

[28] Wang, Z., Chen, B., Wang, J., Begovic, M. M., Chen, C. (2014). Coordinated energy management of networked microgrids in distribution systems. *IEEE Transactions on Smart Grid*, 6: 45–53.

[29] Wang, Z. Y., Chen, B. K., Wang, J. H., Chen, C. (2016). Networked microgrids for self-healing power systems. *IEEE Transactions on Smart Grid*, 7: 310–319.

[30] Arefifar, S. A., Ordonez, M., Mohamed, Y. A. R. I. (2017). Energy management in multi-microgrid systems—Development and assessment. *IEEE Transactions on Power Systems*, 32: 910–922.

[31] Kou, P., Liang, D. L., Gao, L. (2017). Distributed EMPC of multiple microgrids for coordinated stochastic energy management. *Applied Energy*, 185: 939–952.

[32] Nunna, H. S. V. S. K., Doolla, S. (2012). Demand response in smart distribution system with multiple microgrids. *IEEE Transactions on Smart Grid*, 3: 1641–1649.

[33] Palensky, P., Dietrich, D. (2011). Demand side management: Demand response, intelligent energy systems, and smart loads. *IEEE Transactions on Industrial Informatics*, 7: 381–388.

[34] DOE (2006). Benefits of demand response in electricity markets and recommendations for achieving them. A report to the United States Congress Pursuant to Section 1252 of the Energy Policy Act of 2005 (February 2006). U.S. Department of Energy (DOE), Washington, DC, USA.

[35] Kumar Nunna, H. S. V. S., Doolla, S. (2013). Energy management in microgrids using demand response and distributed storage —A multiagent approach. *IEEE Transactions on Power Delivery*, 28: 939–947.

[36] Nunna, K. H., Doolla, S. (2014). Responsive end-user-based demand side management in multimicrogrid environment. *IEEE Transactions on Industrial Informatics*, 10: 1262–1272.

[37] Ding, Y. M., Hong, S. H., Li, X. H. (2014). A demand response energy management scheme for industrial facilities in smart grid. *IEEE Transactions on Industrial Informatics*, 10: 2257–2269.

[38] Kantamneni, A., Brown, L. E., Parker, G., Weaver, W. W. (2015). Survey of multi-agent systems for microgrid control. *Engineering Applications of Artificial Intelligence*, 45: 192–203.

[39] Bui, V. H., Hussain, A., Kim, H. M. (2018). A multiagent-based hierarchical energy management strategy for multi-microgrids considering adjustable power and demand response. *IEEE Transactions on Smart Grid*, 9: 1323–1333.

[40] Kumar Nunna, H. S. V. S., Doolla, S. (2013). Multiagent-based distributed-energy-resource management for intelligent microgrids. *IEEE Transactions on Industrial Electronics*, 60: 1678–1687.

[41] Ren, J. S., Tan, K. T., Sivaneasan, B., So, P. L., Gunawan, E. (2014). Energy management of a multi-agent based multi-microgrid system. In: Proceedings of the 2014 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Hong Kong, China.

[42] Luo, F. J., Chen, Y. Y., Xu, Z., Liang, G. Q., Zheng, Y., Qiu, J. (2017). Multiagent-based cooperative control framework for microgrids' energy imbalance. *IEEE Transactions on Industrial Informatics*, 13: 1046–1056.

[43] Hussain, A., Bui, V. H., Kim, H. M. (2020). An effort-based reward approach for allocating load shedding amount in networked microgrids using multiagent system. *IEEE Transactions on Industrial Informatics*, 16: 2268–2279.

[44] Nunna, H. K., Srinivasan, D. (2017). Multiagent-based transactive energy framework for distribution systems with smart microgrids.

IEEE Transactions on Industrial Informatics, 13: 2241–2250.
[45] Du, Y., Li, F. X. (2020). Intelligent multi-microgrid energy management based on deep neural network and model-free reinforcement learning. *IEEE Transactions on Smart Grid*, 11: 1066–1076.
[46] Zhang, Q., Dehghanpour, K., Wang, Z., Huang, Q. (2019). A learning-based power management method for networked microgrids under incomplete information. *IEEE Transactions on Smart Grid*, 11: 1193–1204.
[47] Asimakopoulou, G. E., Dimeas, A. L., Hatziargyriou, N. D. (2013). Leader-follower strategies for energy management of multi-microgrids. *IEEE Transactions on Smart Grid*, 4: 1909–1916.
[48] Gregoratti, D., Matamoros, J. (2015). Distributed energy trading: The multiple-microgrid case. *IEEE Transactions on Industrial Electronics*, 62: 2551–2559.
[49] Lee, J., Guo, J., Choi, J. K., Zukerman, M. (2015). Distributed energy trading in microgrids: A game-theoretic model and its equilibrium analysis. *IEEE Transactions on Industrial Electronics*, 62: 3524–3533.
[50] Razi, R., Pham, M. C., Hably, A., Bacha, S., Tran, Q. T., Iman-Eini, H. (2021). A novel graph-based routing algorithm in residential multimicrogrid systems. *IEEE Transactions on Industrial Informatics*, 17: 1774–1784.
[51] Guo, H., Wang, F., Li, L., Zhang, L. J., Luo, J. (2019). A minimum loss routing algorithm based on real-time transaction in energy internet. *IEEE Transactions on Industrial Informatics*, 15: 6446–6456.
[52] Hossain, M. J., Mahmud, M. A., Milano, F., Bacha, S., Hably, A. (2015). Design of robust distributed control for interconnected microgrids. *IEEE Transactions on Smart Grid*, 7: 2724–2735.
[53] Arefifar, S. A., Ordonez, M., Mohamed, Y. A. R. I. (2018). Voltage and current controllability in multi-microgrid smart distribution systems. *IEEE Transactions on Smart Grid*, 9: 817–826.
[54] Chanda, S., Srivastava, A. K. (2016). Defining and enabling resiliency of electric distribution systems with multiple microgrids. *IEEE Transactions on Smart Grid*, 7: 2859–2868.