Multi-microgrid Energy Management Systems: Architecture, Communication, and Scheduling Strategies

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***Abstract*—The increasing penetration of various distributed and renewable energy resources at the consumption premises, along with the advanced metering, control and communication technologies, promotes a transition on the structure of traditional distribution systems towards cyber-physical multi-microgrids (MMGs). The networked MMG system is an interconnected cluster of distributed generators, energy storage as well as controllable loads in a distribution system. And its operation complexity can be decomposed to decrease the burdens of communication and control with a decentralized framework. Consequently, the multi-microgrid energy management system (MMGEMS) plays a significant role in improving energy efficiency, power quality and reliability of distribution systems, especially in enhancing system resiliency during contingencies. A comprehensive overview on typical functionalities and architectures of MMGEMS is illustrated. Then, the emerging communication technologies for information monitoring and interaction among MMG clusters are surveyed. Furthermore, various energy scheduling and control strategies of MMGs for interactive energy trading, multi-energy management, and resilient operations are thoroughly analyzed and investigated. Lastly, some challenges with great importance in the future research are presented.**

***Index Terms*—Energy management system (EMS), microgrid, communication, renewable energy, multi-energy system.**

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I. Introduction

In recent years, the growing concerns on energy crisis and environmental pollutions caused by fossil fuels have led to a widespread use of renewable energy sources (RESs) such as solar, biomass, wind, and geothermal power. Nevertheless, due to the inherent volatility and intermittency of wind and solar energies, the direct integration of these RESs into power grids may raise the problems with respect to reliability, energy efficiency, and power quality [1]. To this end, the Consortium for Electricity Reliability Technology Solution (CERTS) reports the concept of microgrid in [2] for the hybridization of different RES technologies to enhance system schedulability and localized energy utilization. A microgrid is referred as a self-sufficient distribution system comprising various distributed generators (DGs), energy storage and controllable loads, and it can operate in the grid-connected or islanded mode [3]. Microgrids are often located near the consumption sites at the low- or medium-voltage level, and have a great potential for system enhancement on the economic operation, peak shaving, reliability, resilience and power quality, etc. [4]. Also, a large number of power electronic devices used in the microgrid can contribute to improve its operation flexibility for mitigating fluctuating RES outputs and strengthening the main power grid [5]. So far, a lot of demonstration projects of microgrids have been deployed over the world such as Kythnos, Bornholm, Huatacondo, Sendai, and Eigg Island [6], and these projects can promote the rural electrification and energy sustainability with significant benefits for both consumers and society [7].

With the increasing penetration of various RESs at the consumption premises, it has become infeasible to coordinate and accommodate a large amount of DGs in a single microgrid due to the high uncertainties of RESs [8]. The recent advancements on power electronics, smart metering, and communication technologies promote these microgrid clusters to be networked to form a cyber-physical multi-microgrids (MMGs) architecture for large-scale DG integrations [9]. The MMG system refers to an interconnected cluster of adjacent microgrids for coordinated energy management and interactive supports between each other [8]. References [10] - [13] present that the interconnection of microgrids can benefit from numerous aspects such as efficient utilization of RESs, reduction of operation cost, black-start support, improvements of reliability and resiliency. MMGs can also offer various auxiliary services including power flow control, energy trading, energy storage sharing, corrective maintenance, frequency and voltage regulations, etc. [9], [14].

For the stable and economic operations of MMGs, a multi-microgrids energy management system (MMGEMS) is required to manage and coordinate dispatchable DGs, controllable loads, and energy trading among microgrids for maintaining dynamic power supply-demand balances [15]. The operation objectives of MMGEMS can be summarized as follows: ① to minimize the overall operation cost of MMGs in the grid-connected mode [10]; ② to provide the reliable power supply and stable voltage quality for customers in each microgrid in the islanded mode [16]; ③ to maximize the renewable energy utilization with the aggregation of uncertainties from various RESs and loads [11]; ④ to manage information interactions among interconnected microgrids while protecting customer privacy [17]; ⑤ to minimize energy transmission losses from power exchanges with the main grid and among networked microgrids [14]; ⑥ to maintain a sustained power supply for critical loads with the apportion of available resources among microgrids for resilient operations during extreme events [13]; ⑦ to achieve the smooth mode switching of MMGs including the off/on grid switching and the combination of islanded operations [8].

So far, a few research works have been reported to investigate the existing important techniques for MMGs and MMGEMS. Various types of MMGs at different voltage levels are surveyed in [8] for rural, residential, office and industrial applications. References [10] and [15] review the basic and intuitive structures, functionalities, control objectives and techniques for MMGs and MMGEMS. In [18], the islanding, protection and control strategies for DC MMG clusters are analyzed. However, these reviews mainly focus on the physical structure and optimal operation of MMGs. Recent developments in the MMGEMS such as the multi-carrier energy management and resilient operation are not involved. Moreover, the emerging advanced communication technologies, especially wireless networks, are critical in MMGEMS for the realization of reliable and secure information interactions among distributed microgrid clusters. Consequently, we aim to fill this gap for a comprehensive understanding on these important issues and techniques of MMGEMS.

In this paper, the recent development on the MMGEMS are surveyed from the perspectives of architecture, communication and scheduling strategies. Compared with the existing studies on similar topics, the contributions of this paper include: ① the typical architectures and functionalities of MMGEMS as well as the emerging communication security issues are elaborated; ② various energy scheduling and control strategies for MMGEMS, including decentralized dispatch, energy trading, multi-energy management, and resilient operations, are thoroughly analyzed; ③ the main challenging problems arising from the development of MMGEMS such as large-scale complex optimization methodology, multi-energy couplings and 5G communication, are explored. This paper can help power industry practitioners to optimize the operation modes of the system and scheduling strategies of MMGEMS for efficient utilization and accommodation of RESs.

The remainder of this paper is organized as follows. Section II provides a comprehensive overview on the typical functionalities and architecture of MMGEMS. The emerging communication techniques and issues for decentralized microgrid clusters are surveyed in Section III. Section IV investigates the major aspects of energy scheduling strategies for MMGEMS. Section V discusses several challenging problems for the future development of MMGEMS. Finally, the conclusion is presented in Section VI.

II. Typical Architectures of MMGs and MMGEMS

A. Architectures of MMGs

MMGs generally fall into three categories, namely AC MMGs, DC MMGs, and AC/DC hybrid MMGs [19]-[21]. So far, AC MMGs are still the most widely-used MMGs as AC MMGs take advantage of the original topology of the power system. In DC MMGs, DGs, energy storage system (ESS) and loads are commonly connected to a DC bus through converters. The reactive power and eddy current losses in DC MMGs can be neglected. Thus, DC MMGs can provide lower operation cost than AC MMGs. The hybrid MMGs combine the advantages of the AC microgrid and the DC microgrid, exhibiting a high flexibility. Figure 1 presents the architecture of a typical MMG system consisting of one DC microgrid 1 and three AC microgrids 2-4. The electric vehicle (EV), wind turbine (WT), microturbine (MT), photovoltaic (PV) generator, and ESS in each microgrid are connected to a common bus through the power converter, the microsource controller (MC) and the load controller (LC). Microgrids 2 and 4 are three-phase microgrids, while microgrid 3 is a single-phase microgrid. Each microgrid can operate in the islanded or grid-connected mode. When these microgrids are interconnected to each other, each one can exchange the power with the main power grid or other microgrids. The optimal sizing and configuration of hybrid MMGs have been analyzed and summarized in [22]-[24].

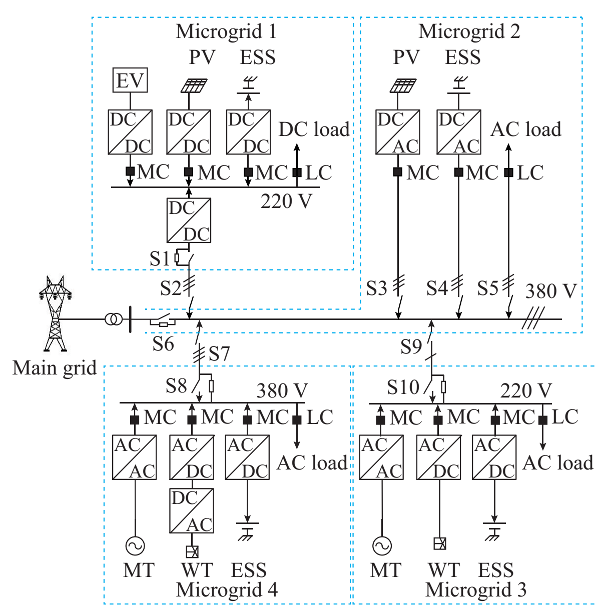

Fig. 1. Architecture of a typical MMG system.

B. Functionalities of MMGEMS

All microgrids in MMGs should be cooperatively managed in MMGEMS to ensure their economic and secure operations. In general, MMGEMS has four functionalities, i.e., information interaction, control and scheduling, resilient operation, and ancillary services, as shown in Fig. 2.

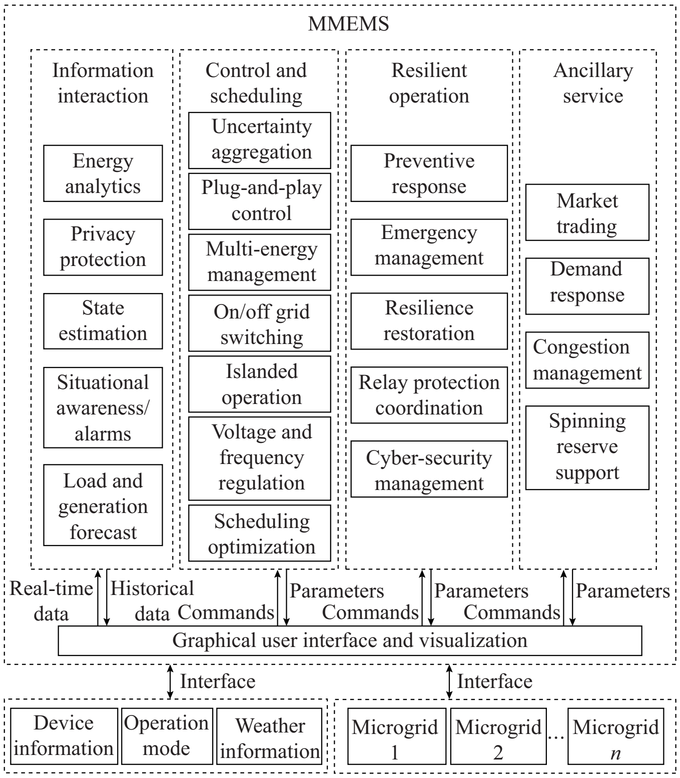

Fig. 2. Functionalities of a typical MMGEMS.

The information interaction module is responsible for privacy protection, energy analysis, prediction of RES generation and load demand, MMG state estimation and situation awareness [9], [25]. The privacy protection is to protect the energy consumption pattern of microgrids during information exchange processes [17]. The primary objectives of control and scheduling modules are designed to optimally maintain the power balance in MMG, and correlations between different RESs are modelled based on the aggregated uncertainties to formulate optimal bidding strategies, thereby promoting the involved energy trades within MMGs [9]. Three types of scheduling strategies, including centralized, decentralized and hybrid formats, are investigated in [14]-[16]. In the centralized scheduling, the central controller of MMGs collects detailed information from each microgrid as well as the market information, and then makes decisions by executing global optimization [15]. In the decentralized scheduling, each microgrid controls all functions locally and independently, and shares essential global information with other microgrid controllers through a consensus algorithm [10]. Furthermore, the hybrid scheduling can take the advantages of centralized and decentralized scheduling strategies to alleviate the computation burden and protect the privacy of customers [14]. These modules can also provide the functions for multi-energy conversion, on/off grid switching and voltage/frequency regulation.

The resilient operation modules aim to improve the survivability of MMG under various disturbances, cyber-attacks and severe weather conditions [10]. Generally, the modules are designed to prepare for unknown nature disasters and recover from major disruptions due to extreme events. The cyber security is essential to defend against cyber-attacks, as MMG operations are heavily dependent on communication technologies [13]. The ancillary service modules include market trading, demand response, congestion management, spinning reserve support, black start capacity and supporting interaction with the main grid [9]. Finally, the human-machine interface module tries to solve the interoperability problem of the above four modules and achieve real-time visualization.

C. Architectures of MMGEMS

So far, four types of MMGEMS architectures have been developed in literatures, namely centralized, decentralized, hybrid, and nested structures, as shown in Fig. 3.

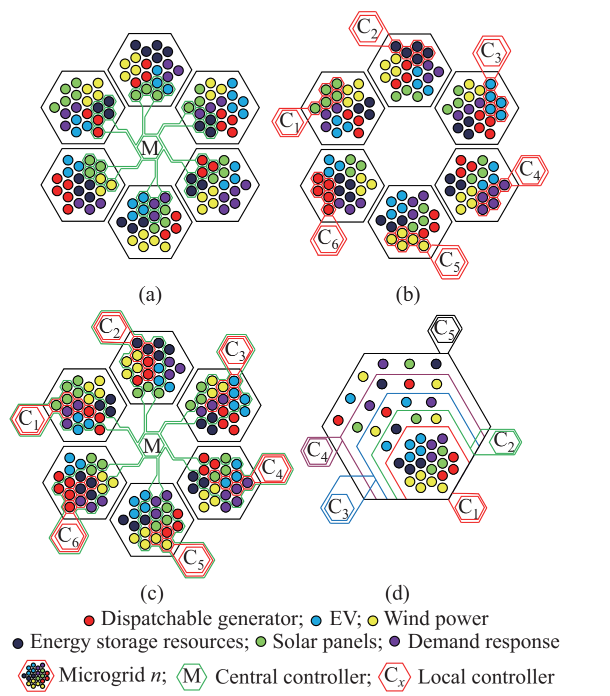

Fig. 3. Typical architecture of MMGEMS. (a) Centralized structure. (b) Decentralized structure. (c) Hybrid structure. (d) Nested structure.

A comprehensive comparison of the four MMGEMS architectures is given in Table I. In the centralized MMGEMS structure, all of the controllable generation and consumption devices are controlled by a central controller, failing to protect customer privacy. The central controller not only manages the power interaction among microgrids and the generation scheduling of DGs [26], but also participates in market bidding, stability control, and switching of microgrid operation modes. In general, the centralized MMGEMS structure can maximize the overall benefits of all MMGs [27], [28]. Nevertheless, the centralized MMGEMS structure requires a high computation capability as the penetration of renewable generation continues to grow. The MMG system operates at a high risk of paralysis if the central controller fails. Consequently, the development of the centralized MMGEMS structure is largely limited.

TABLE I
CHARACTERISTICS OF DIFFERENT MMGEMS ARCHITECTURES

MMGEMS type	Advantage	Disadvantage	Application case	Methodology	Reference
Centralized	The minimization of conflicts Reduced operation cost Utilization of efficient components of each microgrid Easy standardization and implementation Reduction in external trading High reliability in islanded operation	Dependence on central controller Heavy computation burden Sensitive to single-point failure Weak plug-and-play functionality Failure to preserve customer privacy Sensitive to small system modifications Lack of adaptability and flexibility	Wanshan islands MMG in China	Particle swarm algorithm Imperialistic competitive algorithm Mixed-integer linear programming (MILP) Sequential quadratic programming	[26]-[28]
Decentralized	Strong privacy protection Strong plug-and-play functionality High computation efficiency High tolerance for communication error Robust against single-point failures	Difficult to establish a consensus for all microgrids High operation cost and unawareness of system-level resources Low resiliency in islanded mode High energy trading between MMG and main grid Expensive point-to-point (P2P) communication	Changdao MMG in China Yundian Science Park MMG in China	Column and constraint generation algorithm Gossip algorithm Dynamic programming Fuzzy map Average consensus algorithm	[29]-[35]
Hybrid	Preserve customer privacy (single level) Less dependence on central controller Relatively high plug-and-play flexibility compared with centralized MMGEMS High construction cost and relatively low operation cost Reduction on communication and computation burden of central controller High system redundancy	Easy disclosing of partial customer privacy of microgrids by central controller Low resilient performance of disconnected microgrids If central controller is compromised, all microgrids will operate independently High dependence on communication networks	IIT-Bronzeville MMG in America Luxi Island MMG in China Yuxi community MMG in China	MILP Hierarchical genetic algorithm Non-dominated sorting genetic algorithm Metaheuristic algorithm	[36]-[44]
Nested	Less operation cost compared with hybrid MMGEMS High resiliency Strong privacy protection Steady operation of microgrids when the outermost controller faults	Suboptimal operation Computation time exponentially expands as the number of microgrids increases High complex structure	Under research	MILP Column and constraint generation algorithm Distributed optimization	[45]-[47]

In the decentralized MMGEMS structure, every microgrid is an autonomous entity and has a local controller to maximize its own profit [29]. The local controller monitors the operation status of microgrid, and then independently determines the operation condition of DGs and controllable loads. The MMG system can still operate in the case of a local controller failure [30]. However, the decentralized MMGEMS structure may bring in the competition between microgrids, thus degrading the system-wide performance. The global optimal control of microgrids can be realized through the information exchange among microgrids. Generally, the decentralized MMGEMS structure is suitable for the MMG system with microgrids belonging to different owners.

The hybrid MMGEMS, which contains a central controller at the MMG system level and local controllers at the microgrid level, is developed to overcome the disadvantages of centralized and decentralized MMGEMS structures [36]. The local controller of each microgrid performs local energy management and optimization, and only informs the central controller on the total amount of surplus/deficit energy. The central controller is used for negotiating the control inconsistencies and economic conflicts between microgrids, ensuring that the MMG system operates in a global optimal state [37], [38]. Due to the two-level control and management architecture of hybrid MMGEMS, the local controller at the microgrid level connects the central controller and customers in the MMG system, so that there is only one information connection point between customers and the central controller, thus resulting in the single-level privacy protection for customers in MMGs [36]. Besides, the hybrid MMGEMS structure has the advantages of flexibility and low operation cost, making it popular in the MMG system [39]-[44].

The nested MMGEMS is a hierarchical structure with multiple levels, and each microgrid constitutes a level of the whole MMG system [45]. The privacy of customers with the nested MMGEMS can be preserved due to the multiple layered privacy structure. The microgrid at the lower-level only transmits the information on its surplus/deficit energy amount to the next upper-level microgrid, and the privacy data of customers are mixed with the data of all microgrids at the lower levels. Consequently, the MMG operator at the upper level cannot unveil the energy consumption behaviors of consumers at the lower levels, and the privacy of the innermost microgrid is strongest while that of the outermost is the weakest [46]. Furthermore, the local controller of the microgrid at the top level can obtain the information on the total amount of surplus/deficit energy of microgrids at all lower levels through the layered information interaction. And the total amount of surplus/deficit energy is considered as the energy resources/loads in the topmost microgrid. Then, the local controller at the top level can optimize the energy management and scheduling of the whole MMG system, and also performs the energy trading and exchanges with the utility grid considering the power balance and various security constraints [47].

III. Communication Issues in MMGEMS

A. Communication and Networking Structures

With the development of information and communication technologies, the traditional MMGs are gradually transformed into a cyber-physical system (CPS) with real-time sensing, dynamic control and bidirectional information exchange. To support the MMG operations, four types of communication networks are developed, i. e., P2P, mesh, aggregated and nested structures, as presented in Fig. 4. Here, the aggregator represents the local controller of a microgrid, and the nodes denote the distributed energy resources or electrical equipment and components with the information and communication capabilities [48].

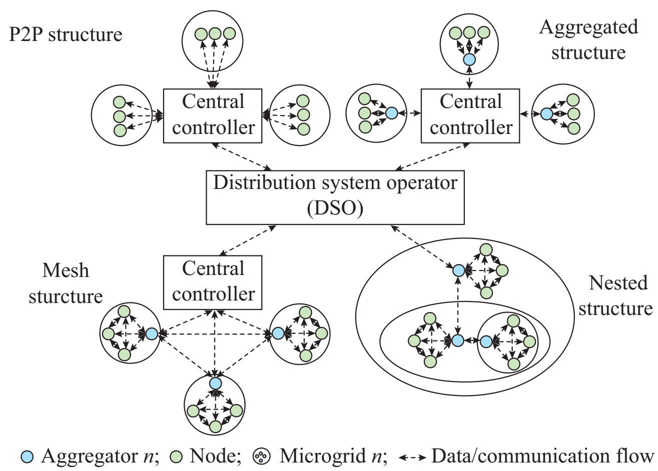

Fig. 4. Typical communication networking structure of MMGs.

In the P2P structure, each node is directly connected to the central controller and has no aggregators in the communication network [48]. The central controller takes charge of information collection and information exchange between MMGs and DSO. The main advantages of P2P contain fast control for critical loads, simple integration and low installation cost. Nevertheless, P2P structure has the single-point of failure (SPOF) problem as the broken central controller will make the whole communication network paralyzed [49]. In the aggregated structure, aggregators are embedded in the MMG system to connect nodes and the central controller, and shares the communication burden. This structure is suitable for large-scale MMG system with frequent information exchange [50], [51]. Nevertheless, aggregated structure also has SPOF problem and its trip time is relatively higher than P2P. In the mesh structure, communication connections generally exist between various nodes/aggregators. These redundant connections can effectively solve SPOF, thereby improving the flexibility and reliability of the communication network [52], [53]. However, the mesh structure has a high operation cost due to its redundancy. In the nested structure, the information interaction only exists between adjacent aggregators due to the layered communication structure, thus preserving the privacy of customers [45]. Besides, the main benefits of the nested structure contain the effectiveness to solve SPOF and low operation cost [47].

B. Communication Protocols and Techniques

Communication protocols refer to the principles and rules that both communication parties must follow to realize a secure and reliable information exchange [48]. The protocols in MMGs are similar to those of microgrids based on the enhanced performance architecture [54]. Recently, the Internet architecture is built based on transmission control protocol/internet protocol for fulfilling the end-to-end communication of autonomous microgrids in the MMG system [47], [53].

Wire and wireless communication technologies can be used to form the communication link between two MMG devices. Wireless communication technologies have been widely recognized for MMG communications due to its low investment cost, quick deployment, widespread access and high flexibility, while the wire communication will not suffer from interference problems [55]. So far, the commonly-used wireless communication technologies in MMGs are general packet radio service (GPRS), global system for mobile (GSM) communication, and Wi-MAX, etc. The wire network technologies include power line communication (PLC), digital subscriber line (DSL) and optical fibers. The comparison of these two types of technologies is given in Table II [48], [55]-[58]. According to their coverage ranges, the communication networks in MMGs can be divided into home-area network (HAN), field-area network (FAN), and wide-area network (WAN) [56]. HAN and FAN are inside a building and a microgrid [56], [57], respectively. WAN is generally used for the communication between central controller in MMGEMS or DSO and local controllers [58].

C. Communication Security

The MMG system is a typical CPS that facilitates its economic operation and real-time control. However, CPS may also bring in cyber-attacks to degrade the communication security of MMGs [59] - [61]. The reported attacks against MMGs include hijacking attack [62], false-data injection attack [63], denial of service attack [64] and power bot attack [62], resulting in various faults related to the controller, communication channel and sensor [65].

TABLE II
TECHNICAL COMPARISONS OF DIFFERENT COMMUNICATION TECHNOLOGIES APPLICABLE FOR MMGS

Type	Technology	Spectrum	Data rate	Range	Routing	Security	Initial cost	Application
Wireless communication [55]-[58]	GSM	900-1800 MHz	Up to 14.4 Kbps	1-10 km	Direct	64 bit A5/1	Costly	WAN, FAN
	GPRS	900-1800 MHz	Up to 170 Kbps	1-10 km	Direct	64 bit A5/1	Costly	WAN, FAN
	3G	1.92-1.98 GHz	384 Kpbs-2 Mbps	1-10 km	Direct	KASUMI cipher	Costly	WAN, FAN
	4G	2-8 GHz	10-100 Mbps	3-12 km	Direct	SNOW-3G, AES, ZUC	Costly	WAN, FAN
	Wi-MAX	2.5 GHz, 3.5 GHz, 5.8 GHz	Up to 75 Mbps	10-50 km	AODV, DSR, OLSR, ZRP	AES and TDEA	Moderate	FAN
	ZigBee	2.4 GHz, 868-915 MHz	Up to 250 Kbps	100-1500 m	AODV, HERA	AES	Low	HAN
	Wi-Fi	2.4 GHz	Up to 54 Mbps	100-300 m	More than 70 protocols	WPA	Moderate	HAN
	Bluetooth	2.4 GHz	Up to 24 Mbps	100 m	Master-slave structure	Encryption key	Low	HAN
Wire communication [56], [57]	PLC	1-30 MHz	2-3 Mpbs	1-3 km	RPL, DSR, and flooding	TDEA	Low	FAN
	Optical fibers	20 THz	100-2448 Mbps	10-20 km	SAN	Optical wave-guide structure	Costly	WAN
	DSL	0.24-1.5 MHz	1.3-200 Mbps	1-7 km	Direct	Unique ID	Low	FAN

Generally, the impacts of cyber-attacks on MMG include: ① instability of MMGs; ② communication link fault; ③ voltage, frequency and power imbalance; ④ privacy leakage [13].

The research works on detecting and defending against cyber-attacks in MMGs fall into three categories, i.e., communication, physical, and system security. Communication security applies encryption, authentication, and security protocols to prevent unauthorized access. The blockchain is a promising technology to provide a powerful and trust-worthy path for signal transmission in MMG [66], [67]. Physical security refers to the optimal deployment of protection equipment for improving the system observability [60]. The system security problem adopts statistical and non-statistical methods to identify abnormal states of MMGs. In [64], an adaptive protection scheme is proposed using supercapacitors against communication failures. An attack detection strategy based on sliding mode observer is presented in [68]. A cooperative control strategy [69] is proposed to suppress the spread of cyber-attacks to minimize the impact of the attacks on communication channels and controllers. A software-defined detection method [62] is developed to detect possible hijacking attacks on controllers in MMGs.

IV. ENERGY MANAGEMENT STRATEGIES FOR MMGEMS

A. Decentralized Scheduling Strategies

The energy scheduling of MMGs is a challenging optimization problem which cannot be readily solved by conventional methods because of high-dimensional variables, limited communication bandwidth, and uncertainties of RESs [70]. In the decentralized scheduling model, the complex MMG scheduling problem can be decomposed into local and reduced-complexity microgrid subproblems to reduce the dimension and communication burden, and improve the solution efficiency [15]. This model enables each microgrid to manage RESs and loads locally and autonomously, and coordinates with other microgrids by sharing essential global information [10]. There are two types of decentralized scheduling methods, decomposition methods and multi-agent game methods. The former includes dual decomposition [70], alternation direction method of multipliers (ADMM) [71]-[76], analytical target cascading (ATC) [77], and consensus algorithm [78]. The latter methods are various equilibrium game models including cooperative game [79], [80] and non-cooperative game [15], [81].

Most of the decomposition methods are developed based on augmented Lagrangian decomposition, and their mathematical iterative rules result in the differences in the optimization performance and theoretical convergence [29]. The dual decomposition method is commonly used with Lagrangian decomposition functions of the optimization problems with a separable framework [70]. The ADMM algorithm inherits and combines the decomposability of Lagrangian relaxation and convergence properties of Lagrangian multipliers [72], [73], [75]. ATC is proposed as a hierarchical, iterative decomposition approach for solving different distributed optimization problems [77]. The consensus algorithm is an effective mechanism to achieve the overall economic operation of the MMG system by means of the consensus among the local controllers of adjacent microgrids [78]. These methods can be applied in MMGEMS to decouple the multi-lateral energy trading with limited minimal information interactions [70]-[77]. Moreover, the main idea of multi-agent game models is used to divide the complex large-scale optimization problems into several intelligent agents with autonomy and communication capabilities [82]. The multi-agent game models, consisting of cooperative and non-cooperative models, are generally applied to solve the energy transaction problem in the networked MMGs [15]. The cooperative game model allows the microgrid to obtain an extra remarkable benefit than that without cooperation [79], [80], while the non-cooperative model focuses on maximizing the individual benefit of each microgrid in the MMG system [15]. These decentralized scheduling strategies have been widely used for RES output forecasting, privacy protection, and reliability enhancement [83]-[85]. In summary, the advantages and disadvantages of different decentralized scheduling strategies are tabulated in Table III.

TABLE III
COMPARISONS OF DIFFERENT DECENTRALIZED SCHEDULING STRATEGIES

Approach	Advantage	Disadvantage	Reference
Dual decomposition	Parallel processing of optimal energy management	Convergence cannot be ensured, even for convex problems Requiring a central coordinator	[70]
ADMM	Parallel processing of optimal energy management Guaranteeing convergence for convex problems ADMM can be designed as a full distributed manner	Difficult to achieve global consensus among microgrids Requiring an auxiliary procedures to exchange intermedia results with adjacent microgrids	[72], [73] [75]
ATC	Parallel processing of optimal energy management Easy to achieve global consensus among microgrids Convergence without the assumption on convexity	Requiring a central coordinator Requiring significant computation effort Difficult to handle MMG with mesh communication network	[77]
Cooperative game	Increasing the additional benefits of microgrids Achieving the global optimization of MMGs	Privacy of customers is easy to be disclosed due to the sharing of large amount of information	[79], [80]
Non-cooperative game	Maximizing the benefits of microgrids Protecting customer privacy	Global optimality cannot be guaranteed	[15]

B. Uncertainty Management Strategies

There are various types of uncertainties in MMGs caused from RESs, loads, and power prices. These uncertainties are usually strongly correlated [15], which uncertainties not only bring in challenges to maintain the supply-demand balance, but also cause negative impacts on energy transactions [86]. The existing methods for uncertainty management in MMGs are robust dispatch strategy [86]-[89] and stochastic dispatch strategy [90]-[101]. In the robust dispatch strategy, state estimation errors are formulated as uncertainty intervals or sets for optimizing the worst-case operation scenario [87]. However, robust dispatch strategy could give rise to the over-conservative solutions in MMG operations [86]-[89].

Recently, various distributed robust dispatch strategies are developed based on the distributionally robust optimization (DRO) to minimize the expected operation cost of MMGs with the worst-case probability distribution in the ambiguity set of an estimated distribution [32], [46]. The DRO method can offer two important advantages: ① the exact probability distribution of operation scenarios is not required; ② this method can provide robust solutions in the stochastic environment while avoiding over-conservative results [33].

The stochastic dispatch strategy requires a large number of scenarios using Monte Carlo simulation to estimate the accurate probability distribution of uncertainties [86], [90], thereby providing the probabilistic guarantee for constraint satisfaction [91]. For instance, it is assumed in [92] that prediction uncertainties from wind energy should meet the normal distribution or Weibull distribution. The scenario-based stochastic optimization and two-stage stochastic programming approaches have been utilized to address the source-load uncertainties [92]-[97]. The comparisons of robust dispatch strategies and stochastic dispatch strategies are given in Table IV.

TABLE IV
ROBUST DISPATCH VERSUS STOCHASTIC DISPATCH STRATEGIES

Performance	Robust dispatch strategy	Stochastic dispatch strategy
Reliability	High	Moderate
Major consideration	Worst-case scenario of uncertain variables	Probability distributions of uncertain variables
Sensitivity to uncertainties	Low	High
Computation burden	Low	High
Design complexity	Simple	Complex
Economic operation	Suboptimal	Optimal

C. Energy Trading Strategies

In general, energy trading strategies are designed to optimize energy transactions among multiple microgrids. The existing energy trading strategies fall into two categories, i.e., the cooperative strategies and the competitive strategies. In the cooperative strategies, all microgrids cooperate with each other to maximize the overall benefit of MMGs [102]. The microgrids with surplus power are called "the seller", otherwise they fall into "the buyer". It is generally assumed that the energy transaction with the least power loss should be traded in priority [103]. A price mechanism based on auction models provides a more reasonable trading price among microgrids through optimal biddings [104], [105]. A worst-case analysis based on transaction mechanism is proposed in [106] to improve the robustness of MMGs. Moreover, a coalitional game model based on Shapley value is widely-used techniques for the allocation of MMG profits [102], [105]-[108]. A distributed convex cost-minimization model is developed in [109] to safeguard the privacy of microgrids and optimize the MMG operation cost.

For the competitive energy trading strategy, each microgrid aims at maximizing its own profit without the concern of other microgrids [110]. Generally, the energy trading mechanisms in MMGs are designed to satisfy the demand locally. Each buyer (seller) microgrid hopes to purchase (sell) power from (to) seller (buyer) microgrids as much as possible. Thus, competitions usually exist among microgrids, and various non-cooperative game models are employed to formulate competitive strategies in [111]-[120]. The non-cooperative game models for competitive energy trading strategies have been presented in Table V . The priority-based trading mechanisms are investigated in [113] to solve the optimal trading decision based on the importance of microgrids in the competitive electricity market. Besides, the Stackelberg game can be used to solve the competition between DSO and microgrids [115], [116]. Two-level game models are also proposed for the trade-off of competitions between DSO and microgrids, and among microgrids simultaneously [118] - [120]. A comparison between these cooperative and competitive trading strategies is presented in Table V .

TABLE V
COMPARISONS OF ENERGY TRADING STRATEGY

Feature	Cooperative trading strategy	Competitive trading strategy
Optimization objective	Maximizing overall benefit of MMGs	Maximizing individual benefit of each microgrid or DSO
Optimization model	Coalitional game model [102], [105]-[108] Distributed convex cost-minimization model [103], [104], [109]	Nash bargaining game model [110] Differential game model [112] Stackelberg game model [115], [116] Two-level non-cooperative game model [118]-[120]
Solution algorithm	Column and constraint generation method [86], heuristic algorithms [102],[106]-[108] ADMM method [103], subgradient algorithm [104], [109]	ADMM method [110], consensus algorithm [112] Column-and-constraint generation method [116], heuristic algorithms [118], [120]
Allocation of benefits	Shapley value	Self-interest
Privacy protection	Easy to leak privacy	Well protected

D. Multi-energy Management Strategies

The multi-energy microgrid can be modelled as an energy hub, in which the production, conversion, storage and consumption of diff erent types of energy carriers are formed to satisfy multi-energy demands [121], [122]. The multi-energy management strategies aim at solving the scheduling problems of the multi-energy coordination and exchanges among interconnected microgrids with the multi-energy couplings and inherent nonconvexities [123]. Multi-energy interconnected microgrids increase the overall degree of freedom for energy management and supply with the complementary nature of different types of energy forms [123]. Also, through exchanging the energy with each other, microgrids can make full use of the flexibility and synergies of multi-energy supplies to enhance mutual benefits. Generally, the optimal scheduling of multi-energy microgrid for maximizing operation efficiency can be formulated as an MILP problem with a high degree of variables and complexity [122], [124] - [126]. An MMG multi-energy coupling matrix is formulated in [70] to exploit the inherent biogas-solar-wind energy couplings among microgrids, and the couplings among electricity, gas, and heat flows are subsequently decomposed into the internal multi-energy coordination within individual microgrids and external multi-energy exchange among interconnected microgrids for the improvement on the scheduling optimality and scalability. Various distributed optimizers have been used in [123], [127], [128] to solve the problem of multi-energy exchange among microgrids in MMGs. Furthermore, a price-based trading mechanism for multi-energy MMGs with demand response is proposed in [126], and the concept of quality-of-service is introduced in [129] to improve the service quality of multi-energy supplies with a Lyapunov optimization technique.

E. Voltage and Frequency Control Strategies

Supply-demand imbalance usually leads to voltage and frequency biases, and voltage and frequency control strategies are important to ensure the power quality of MMGs. The existing voltage/frequency control strategies focus on eliminating these biases within one single microgrid [130] - [132]. The droop control is the most widely-used method to regulate the voltage and frequency based on drop characteristics of DGs, including active power-frequency properties [132] - [136], reactive power-voltage properties [137], [138], DC power-voltage characteristics [139], [140], and the interlinking converter droop characteristics between two microgrids [141].

In recent years, various voltage and frequency coupling control methods such as coordinated droop control [142], model predictive control [143], adaptive control [144], [145], and hierarchical control [146], have been developed to guarantee the stability of MMGs. In [147], a probabilistic index is proposed to quantify the controllability of bus voltages in MMGs. The decentralized control in [148] - [150] can enable the autonomous operation of microgrids and solve voltage issues locally by the regional autonomy or collaboration, thus providing the voltage support with a quick response. For the load frequency control, a robust sliding mode control based on adaptive event-triggered mechanism is developed in [151], [152] against the frequency deviation caused by power unbalance or time delays. The feasibility and profitability of MMGs for providing the primary frequency reserves in ancillary-service market are investigated in [153] for additional economic profits. An auction mechanism to enable the competition among microgrid agents for the provision of the local area frequency support is also proposed in [154]. In [155], a coordinated control method considers multi-energy conversion of MMGs with the combined effect of diversified energy storages to improve the frequency stability of the MMG system.

F. Emergency Management Strategies

Generally, the MMG reliability can be measured by the frequency and duration of power outages experienced by power consumers [13]. Emergency management strategies are usually designed to enhance the reliability of MMGs against potential low-impact/highly-probable contingencies such as $N-1$ event, $N-2$ event, overloading, excessive generation, and short-circuit fault [10]. A formal analysis is proposed in [156] and [157] to estimate the stability margin of MMGs with large disturbance, offering the provably secure operation for networked microgrids. An emergency market mechanism is designed in [158] to motivate microgrids with surplus energy and provide microgrids with energy shortage so that their critical loads can be satisfied.

So far, emergency management strategies can be divided into preventive measure, fault protection and outage management. The preventive measure deploys infrastructural and operation measures before the contingency happens. A supervisory control method is proposed to provide a timely warning for MMGs contingencies [159]. Besides, an internal fault protection method is proposed in [160] by analyzing current and voltage characteristics of different feeders considering the faults at different locations. Time-domain simulations are used in [161] to identify critical reasons that degrade the stability of microgrids. The outage management during contingencies is used to reduce the duration of power outage and maintain the power supply of critical loads [162]. Various emergency management strategies, including hierarchical outage management, self-healing control and coordinated emergency dispatch, have been investigated in [162] - [164] to form emergency power sharing mechanisms so as to avoid the curtailment of critical loads.

G. Resilient Operation Strategies

The resiliency of MMGs is defined as the capability to prepare for unknown conditions and recover from major disruptions due to extreme events [13]. The resilient MMG system should be survived with severe natural disasters, destructive man-made incidents, and a combination of these events [165]. The resilient operation of MMGs includes situation awareness, robustness and preparedness before an extreme event, responsiveness and survivability during an event, and the recoverability after an event [13].

In order to improve the resiliency of MMGs, it is important to proactively cope with emergencies caused by extreme events [25]. A smart situation awareness framework is developed in [9] to perceive the real-time system situations, and even predict potential disruptions through internal factors and external conditions. The robustness and preparation before extreme events indicate that infrastructures and operation measures shall be well-deployed before an extreme event happens to limit the impact of potential disruptions [21]. Recently, the networking of microgrids and sparse communication architecture have been recognized as effective solutions to further enhance the resiliency of MMGs [165] - [168]. In addition, MMGs can also be used as backup devices to maintain the power supply of critical loads, thereby improving the resiliency of the main grid [169]-[171].

MMG operators should respond to disruptions in a timely and effective way for strong responsiveness and survivability during extreme events while preserving a minimum level of system functionalities [172]. The three-stage resilience-constrained scheduling model is presented in [173] and [174] to mitigate the damaging impact of power interruptions by exploiting MMG capabilities. The recoverability of MMGs reveals that the system performance should be recovered quickly back to its normal operation level after an extreme event [54]. The optimal load recovery problem can be formulated as an MILP model to maximize the amount of served loads after an event [175], [176]. The change of MMG topologies posed by disasters prevents energy exchanges among microgrids, and the transportable ESS (TESS) can timely transfer the energy among microgrids with power deficit to significantly improve the resiliency of MMGs [13], [177]. A joint post-disaster restoration scheme for optimal scheduling of TESS and DGs in the MMG system is proposed in [178] to minimize the total system cost.

H. Scenario Analysis for MMGEMS Scheduling Strategies

Research works in [70], [123] show that the multi-energy interconnection of MMGs can improve the operation efficiency of the system. Three types of scenarios of multi-energy scheduling have been proposed and analyzed in [123], and the comparative performances are shown in Table VI. In scenario 1, a joint operation scheduling strategy of electricity, heat and natural gas networks is performed. In scenario 2, the electricity-gas network and heat network are independently scheduled. Scenario 3 is the conventional electricity-natural-gas operation plan without a heat network. Compared with scenario 2, the system operation cost, wind curtailment, energy loss and environmental cost of scenario 1 are reduced by 5.54%, 1.90%, 8.81% and 18.92%, respectively. Compared with scenario 3, the system operation cost, wind curtailment, energy loss and environmental cost of scenario 1 are reduced by 1.43%, 0.90%, 2.23% and 5.70%, respectively. Scenario 1 has the largest natural gas consumption and lowest pollutant emission among the three scenarios. Therefore, the interconnected multi-energy system generally has better scheduling performance in terms of operation cost, wind curtailment, efficiency and environmental protection compared with any individual scheduling method.

TABLE VI
COMPARISONS OF DIFFERENT MULTI-ENERGY SCHEDULING SCENARIOS

Scenario	System operation cost ($)	Natural gas consumption (m^3)	Fired generation (MWh)	Energy loss (MWh)	CO_2 emission (10^4 lb)	Wind energy curtailment (%)
1	13127.33	6447.60	98.18	238.12	19.03	0
2	13897.78	4125.74	123.55	261.15	23.47	1.9
3	13318.14	5799.06	104.81	243.55	20.18	0.9

V. CHALLENGES

The operation of MMGEMS still has some challenges related to the large-scale interconnection of MMGs, 5G communication, and multi-energy coupling and trading issues.

1) Solving large-scale MMG optimization problems: with

increasing number of networked and interconnected microgrids, the optimal scheduling of MMGs is still a challenging optimization problem due to the curse of dimensionality. Although distributed methods such as Lagrangian relaxation and ADMM can be used to decompose the problem complexity, the convergence of boundary-exchanged variables will suffer sharp variations and oscillation issues in the distributed optimization process, leading to local optimal solutions or even the failures of convergence after a limited number of iterations.

2) Multi-energy couplings: the future MMG system should be networked with multi-carrier energy forms. Hence, multi-energy couplings among electricity, gas and heat networks in MMGs further strengthen the complexity of the modeling, control and coordinated operations of MMGEMS due to diversified energy characteristics, severe networking constraints and strong multi-energy couplings.

3) 5G communication for MMGs: in the near future, the 5G wireless communication technique would be extensively used in MMGs and several issues relating to the 5G deployment such as the privacy protection of consumers, high energy consumption of anntenna arrays, and intercell interference caused by network densification. The 5G communication network would be vulnerable to cyber-attacks which would hamper the operation of the entire MMG system.

4) Multi-energy trading mechanism: the existing studies focus on the modeling of electricity trading among MMGs, while the potential of MMGs participating into the multi-energy trading has not been explored. Each microgrid in an MMG system is an independent entity, which aims to optimize their own performance and expect to gain benefits from multi-energy trading. However, multi-energy pricing and bidding mechanisms are still open issues to coordinate the interests of individual microgrid and the public interest of the entire MMG system within an optimal multi-energy trading framework.

VI. Conclusion

MMG and its energy management system play a significant role in improving energy efficiency, power quality, and reliability of distribution systems, especially for enhancing the resiliency of the system during contingencies. In this paper, a comprehensive overview on the architecture, functionalities and communication techniques of MMGEMS is surveyed as well as the detailed investigations on energy trading and scheduling strategies, multi-energy management, voltage and frequency control, emergency and resilient operation strategies. The research works indicate that the resiliency of MMGs can be improved significantly with a transportable energy storage for flexible and efficient energy transfer among microgrids in appropriate time and locations to facilitate critical load restoration after disasters. Moreover, the scenario analysis demonstrates that multi-energy interconnections among MMGs can mutually support the stable and reliable multi-carrier energy supplies with lower operation cost and renewable energy curtailment. Therefore, developing a smart MMGEMS has become a common global priority to support the trend towards a more sustainable and reliable green energy supply for smart grid.

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