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Ma, Guolong; Li, Jianing; Zhang, Xiao-ping

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TOPICAL REVIEW

A Review on Optimal Energy Management of Multimicrogrid System Considering Uncertainties

GUOLONG MA[1], JIANING LI[2], (Member, IEEE), AND XIAO-PING ZHANG[1], (Fellow, IEEE)
[1]Department of Electronic, Electrical and Systems Engineering, University of Birmingham, Birmingham B15 2TT, U.K.
[2]WSP U.K., The Mailbox, Birmingham B1 1RQ, U.K.

Corresponding author: Jianing Li (jianing.li@ieee.org)

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ABSTRACT Microgrid (MG) is one of the most effective solution to integrate distributed renewable energy into power system. However, modern MG has several technical challenges such as migration to multi vector energy system, increasing renewable energy penetration, and the uncertainties that arise from the large-scale incorporation of renewable energy. Recent development of multi-microgrid (MMG) could potentially mitigate these challenges. MMG has obvious advantages in improving the system stability, reliability, economy, and energy efficiency of power grid operation through autonomous management and coordinated control among networked MGs. In the meantime, uncertainties from many elements and operators in the MMG system also pose huge challenges in modeling. This paper will present and review typical architecture of MMG, including physical layer, information layer and application layer. Moreover, this paper will critically review and analyze challenges in uncertainty modelling and solution in MMGs. Finally, the paper will also discuss future research areas and development trends of MMG.

INDEX TERMS Microgrid, multi-microgrid system, energy management, optimization, architecture, uncertainties.

I. INTRODUCTION

Due to the rising public awareness in environmental concerns, several countries and organizations have established legal commitments in delivering a more suitable energy system [1], [2]. Meanwhile, the volatility in electricity price caused by reduction of fossil fuel reserves, renewable energy generation has become the most popular solution to meet energy demand in future energy scenarios [3]. Particularly, in the electricity sector, wind and photovoltaic power are experiencing the highest growth in different countries. Owing to their intermittent and distributed nature, the integration of large-scale renewable energy in conventional way is a challenging process. MG is one of the most effective solution to integrate distributed renewable energy into power system, which usually consist of confined cluster of loads, energy storages and small generators [4]. Based on the reports from IMARC, the global MG market size will reach $25.9 billion in 2021and the market will reach $49.2 billion by 2027, with a CAGR of 11.2% from 2022-2027. As shown in Figure 1.

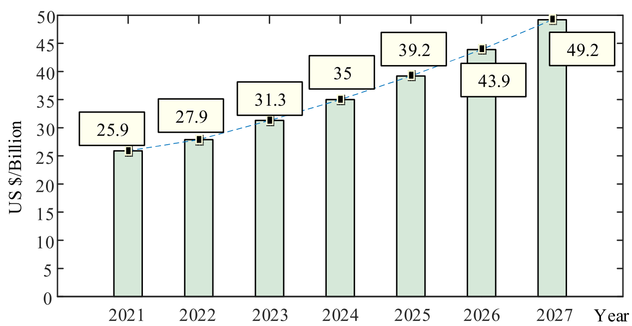

FIGURE 1. Global microgrid market size (2021-2027).

However, MG has several technical challenges, including migration to multi vector energy system, increasing renewable energy penetration, and the uncertainties that arise from

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the large-scale incorporation of renewable energy. Connecting multiple MGs to construct multi-microgrid system could mitigate these challenges. MMG refers to a grid formed by interconnecting two or more single MGs through a common coupling point, and this interconnection enables power interaction between multiple MGs or with the upper-level grid [5]. According to the IEEE Standard 1547.4 [6], the operation and reliability of a distribution system can be improved by splitting it into multiple MGs. MMG's technical advantages are mainly reflected in the following aspects: 1) in MMG, the energy sharing among the MGs allows the MGs to satisfy their power demand with their own cheaper renewable energy resource which can reduce the cost of fossil fueled generation [7]; 2) the interconnected MGs will effectively improve the utilization of renewable energy, reduce the burden on the main grid, and can also improve the reliability not only for themselves but also for the main grid [8]; 3) in MMG, each microgrid has high self-healing feature and it can also operate in a stable way by sharing extra energy and spare resources with other connected MGs [9]–[12]; 4) in MMG, the interconnected MGs can support each other with local generation capacities to achieve the overall reliability and minimize the total load curtailment in the system [13], [14]. Based on these technical advantages, MMG has been used in practical applications, reference [15] introduced the Illinois Institute of Technology DC MMG, which mainly is used for economic dispatching analysis. In [16], U.S. Department of Energy want to design a master controller for achieving a seamless integration of Bronzeville community microgrid and the Illinois Institute of Technology campus microgrid. What's more, a company called CESI built MMG simulation platform consisting of super capacitor storage and flywheel energy storage, is beneficial to energy quality analysis, communication, and the upper control in MG [14].

Meanwhile, for the stable and economic operation of MMG, a multi-microgrid energy management system is required to manage and coordinate dispatchable distributed generators, controllable loads, and energy trading among networked MGs. The operation objectives of MMG can be summarized as follows: 1) to minimize the overall operation cost of MMG in the grid-connected mode [17] and islanded mode [18]; 2) to maximize the distributed renewable energy penetration with the influence of uncertainties from various DREs, loads and electricity price [19]–[21]; 3) to minimize energy transmission loss from energy exchanges with the main-grid and among networked MGs [22]; 4) to maximize the economic goals of different subjects by designing multi-microgrids cluster architecture and its energy transaction mechanism [23]; 5) to minimize the communication delay between MMGs and improve the security and reliability of communication system [24].

Although MMG has obvious advantages, due to its relatively complex structure and large number of elements, it still faces great challenges suffering from uncertainties [25]–[27]. These uncertainties include load forecasting, varying photovoltaic and wind power generation, charging/discharging behavior of electric vehicles, stochastic topology of MMG systems and forecasted electricity price, etc. [28]–[30]. Based on these uncertainties, the security, reliability, and economy of MMG system will be deeply affected. To have a realistic modeling and making better decisions in MMG systems, the uncertainties must be considered. Considering the influence of the above uncertain factors, the optimal energy management of MMG system becomes the optimization decision problem with multiple uncertainties. The common approaches for dealing with these uncertainty problems can be classified into three main categories. In the approaches of the first category, referred to as stochastic programming, which need to assume uncertainty variables follow a predefined probability distribution and then we can transform it into a deterministic mathematical programming problem and solve it [31]. In the approaches of the second category, referred to as robust optimization, which can express the fluctuation range of the uncertain parameters by setting up an uncertain set and the robust optimization can generally obtain feasible solutions [32], [33]. The third category called distributionally robust optimization which remedies the stochastic optimization's concreteness of probability information and robust optimization's ignorance of probability information is proposed to solve the uncertainties in MMG system [34], [35].

To provide a look-up reference for fledgling researchers on the status of MMG research, this paper summarizes the review papers on MMG related research in recent years, which mainly focusing on the following issues: 1) MMG architectures [14], [24], [36]–[38]; 2) MMG communication [24]; 3) energy management of MMG [37], [38]; 4) operation, protection, and resilience of MMG [12], [24], [36], etc. Reference [12], [24], [38] examine the possible multi-microgrid architectures to form a grid of microgrids, and there are some comparisons between the different architectures is performed in terms of operation, protection, reliability, stability, communications, and energy management in [24], [36]–[38]. But the above review papers deal with the uncertainty problems in the MMG relatively roughly and lack a comprehensive analysis of uncertainty impact on the operation control and energy management of the MMG. Based on these challenges, the thesis of this paper is to examine the literature on the uncertainties of energy management in MMG system in recognition of the detrimental impacts of different uncertainties including operation, energy market and power grid faults on energy management. On the one hand, this paper aims to provide a look-up reference for fledgling researchers on the status of MMG research and can also help researchers to establish a theoretical framework quickly and accurately for energy management of MMG by citing related articles on the operation and management of MMG; On the other hand, this paper aims to analyze the characteristics and influences of different uncertainties and then to provide a complete solution about the operation, modeling, and control for the energy management of MMG.

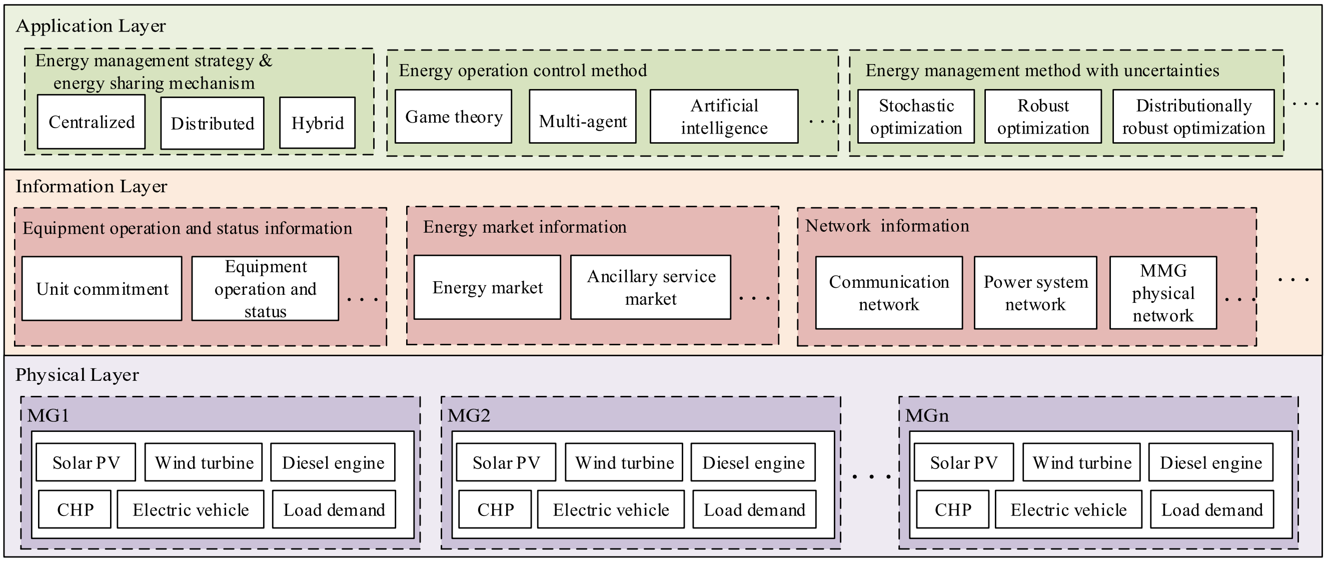

FIGURE 2. Energy management architecture of MMG.

In summary, the contributions of this paper are as follows.

- The typical architecture and functionalities of MMG, including physical layer, information layer and application layer, which includes energy management strategy, energy operation control method, and energy management method with uncertainties, are thoroughly analyzed.
- The main challenging problem of MMG is suffering from all kinds of uncertainty elements. This paper analyzes the uncertainties and methods to deal with these uncertainties in power system analysis, operation, and control.
- Various model and solving method in this paper are clearly introduced to deal with MMG with various uncertainties, including statistic optimization, robust optimization and distributionally robust optimization are thoroughly analyzed.

The remainder of this research paper is organized as follows: Section II provides a comprehensive overview on the typical architecture of MMG. The uncertain challenges in MMG are surveyed in Section III. Section IV investigates the model and solving method of energy scheduling for MMG with uncertainties. Section V discusses several challenging problems for the future development of MMG. Finally, the conclusion is presented in Section VI.

II. ENERGY MANAGEMENT ARCHITECTURE OF MULTI-MICROGRID SYSTEM

The energy management of MMG system is the core of ensuring the economic and stable operation of the system. The main function of the architecture is to collect, process and analyze various kinds of information, such as the state of the system equipment, market information, etc. and on this basis, make decisions and control on the real-time operating state of MMG [39], [40].

Based on the above idea, this paper proposes that the energy management framework of MMG can be divided into three levels including physical layer, information layer and application layer, and the framework is shown in Figure 2. The first one is the physical layer, which mainly includes the power generation units, electrical equipment, energy storage equipment and other physical equipment of the MG [41], [42]. The second layer is the information layer of MMG, which mainly includes state of the system equipment, energy market information and network information, etc. This layer mainly realizes the collection, storage, and process of information and data. The third layer is the application layer, which contains the energy management strategy, energy operation control method and energy management method with uncertainties. Energy management strategy is mainly to select different control strategies of MMG [43]. And energy management control method has main function of power coordination and economic dispatching [44], [45].

A. ENERGY MANAGEMENT STRATEGY

The main difference between MMG and single MG is that MMG needs to further consider the coordination strategy in different MGs, because under different control strategies, MMG has different communication network requirement [46], [47]. Reasonable strategy design plays a key role in simplifying the control complexity of MMG system and improving the economy of system operation. At present, there are mainly three control strategies for the research of MMG [48].

1) CENTRALIZED

Centralized strategy is the centralized management of each single MG through a central energy management system [8], [49]. In this strategy, each MG connects to the main

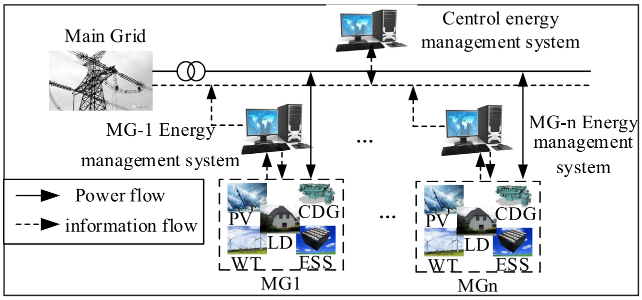

FIGURE 3. Centralized control strategy of MMG.

grid directly. As shown in Figure 3, there is no energy trading directly among the MGs. It shows the local energy system consisting of *n* MGs, as well as the information exchange among the MGs and a central energy management system (CEMS). Each MG is allowed to respond to the decision of the CEMS and its own energy management system. The energy sharing and trading mainly rely on dedicated power exchange lines. For instance, if one of the MGs is unable to satisfy its own load demand, it can purchase electrical power from the main grid through the bus line. On the other hand, an MG with surplus energy can benefit by selling the extra power to the main grid through the bus line. The main advantage of centralized strategy is its simple structure, which can use the central energy manager to deal with the interaction information of each single MG in a centralized manner, without setting complex communication rules and energy interaction protocols [50]. However, as the number of MG increases, there will be a sharp increase in information exchange, data volume and energy interaction frequency, and the computing speed of the CEMS may not meet the real-time requirements of power system scheduling [51]. In addition, if a single MG has a connection failure, it cannot be supported by the other MGs. Moreover, centralized strategy still has scalability limits, performance degradation and lack of robustness [52].

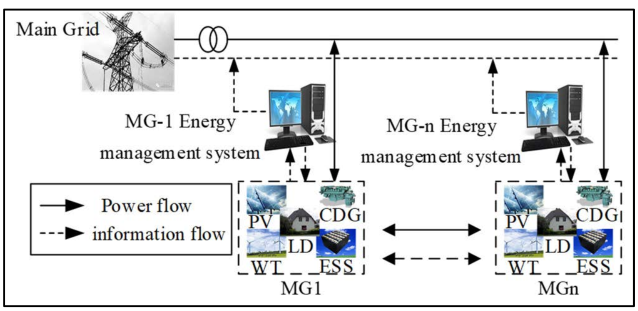

FIGURE 4. Distributed control strategy of MMG.

2) DISTRIBUTED

In the distributed strategy, each MG is locally interconnected through a certain connection mode and realizes energy and information interaction with the main grid respectively [53], [54]. In particular, 1) when one of the MGs failures or energy supply and demand is unbalanced, this MG can communicate with the neighboring MGs and main grid through the internal energy management system, and then the networked MGs/main grid can supply energy support, so that it can operate stably again [24]; 2) when the main grid fails and all the MG are disconnected from main grid, that is, when multiple MGs are in an islanded mode, the MGs can also realize energy interaction through the interconnection between them [55]. A significant difference regarding the other strategy is that individual agents are allowed to discover or exchange other agent information through communication and coordination with their neighbors.

As shown in Figure 4, each MG is fully connected with neighboring MGs, its stability will be the highest, but this strategy has higher control complexity and poor economy. Although stability of distributed control strategy is superior to the centralized one, but distributed also exists some shortcomings, due to the lack of global information, this control strategy is difficult to achieve the global optimization goal [56]. Specifically, when the system wants to get the global optimization result, it must iterate many times until convergence. Even though, the global optimal solution may not be obtained.

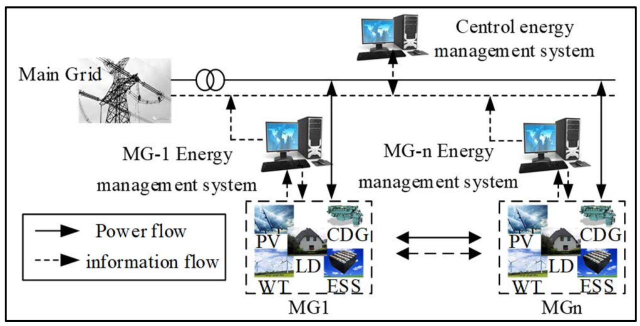

FIGURE 5. Hybrid control strategy of MMG.

3) HYBRID

The MMG adopt hybrid strategy can realize energy and information interaction and sharing by interconnected with adjacent MGs [57]. Hybrid strategy combines the advantages of centralized strategy and distributed strategy. Mainly reflected in the following aspects: 1) Can easily achieve the global optimization. In hybrid strategy, the CEMS controller can get the global information, which can help reduce the operation cost [58]. 2) Reduction on communication and computation burden of CEMS controller. In hybrid strategy, it can effectively alleviate the performance bottlenecks caused by the central energy router in the centralized strategy, such as information congestion caused by excessive information, user's privacy disclosure, poor real-time performance, etc. [24].

The hybrid strategy structure, as shown in figure 5, can effectively reduce the communication and calculation time of the central energy manager, which is helpful for real-time

TABLE 1. ROS and cons for the three management strategies of MMG.

Strategy	Economy	Stability	Scalability	Data privacy	Communication complexity	Control complexity	ref
Centralized	good	poor	limited	easy to leak	low	low	[8], [49]-[52], [61], [62]
Distributed	poor	good	strong	not easy to leak	high	high	[53]-[55], [63]-[65]
Hybrid	moderate	moderate	moderate	moderate	moderate	moderate	[9], [40], [57]-[60], [66]-[70]

energy scheduling [59], [60]. When one of the MG failure or energy imbalance occur, the requirement information could be sent to the neighboring MG, and then obtain energy support from the adjacent MGs; If the adjacent MG cannot meet the demand, the sub-energy management system can transfer information to the CEMS and then the CEMS can coordinate to complete energy exchange through the sub-microgrid system in other areas.

Table 1 is mainly to compared advantages and disadvantages of different energy management strategies. Specially, the MMG will be connected to many distributed renewable energy and power loads in the future, the selection of MMG control strategy will mainly consider its economy, stability, scalability, communication complexity, control complexity and other indicators [38]. Economy is largely determined by infrastructure and operating cost. Infrastructure cost will depend on the number of components, their power rating and the technology used, while operating cost will be affected by factors such as generation cost, ancillary service cost or power transmission loss; Stability refers to the ability of the MMG to recover to a stable state after being disturbed, that is, whether a MG can quickly get the energy support from other MGs to restore stable operation when energy shortage or system failure occur. Scalability refers to the ability of the system to accept new elements, such as the ability to accept the internal distributed system of the existing MG, the ability of load growth and the ability to accept the access of the new MG. Communication complexity refers to the size of communication volume and communication delay time, etc. Data privacy represents the data or information leakage in energy interaction or transaction in MMG. Control complexity refers to the difficulty of setting control policies for different topologies to achieve stable operation.

B. POWER ENERGY SHARING MECHANISMS AND CONSTRAINTS

The interaction mechanism between information and energy depends on the network topology, which including MMG physical topology and communication network [71]. In this section, information, and energy interaction mechanisms in MMG are shown in Figure 6.

The dotted lines represent the power generated in MGs is equal to the load demands. The light blue color depicts the amount of electricity generated (surplus) by MG after its local optimization. The light orange color depicts the

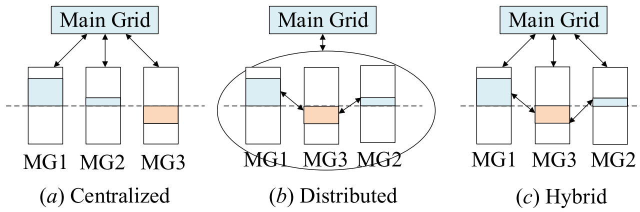

FIGURE 6. Power energy sharing mechanism.

amount of electricity generated (shortage) by MG after its local optimization. Specially, we assume that the electricity price in different MG is different.

From the figure 6, in the centralized mechanism each MG can only exchange the energy with the main grid [72]–[74]. In the distributed mechanism, MG1, MG2 and MG3 can form a cluster, which can realize the whole cluster optimization. In this cluster, MG1 and MG2 can send the surplus amount to fulfill shortage amount of MG3. The remaining surplus of this cluster can be sent to the main grid and the MGs in this cluster can obtain profit by selling the surplus energy. In the hybrid mechanism, each MG can make energy transaction with the other MGs and the main grid [56]. From Figure 6(c), we can know that MG2 can send the surplus to the main grid, and it can also to fulfill shortage of MG3, which one can get the surplus energy depending on the money who can give more; at the same time, MG1 can also fulfill shortage of MG3 (generation cost of MG1 is lowest). Especially, when the remaining surplus amount of MG2 is sent to MG1, and then MG1 can reduce its generation (generation cost of MG1 $>$ selling price). Similarly, when shortage of MG3 in Figure 6(c) cannot be fulfilled only by MG2. MG3 must buy the remaining shortage from MG1 (MG1's generation cost $<$ buying price from the main grid). MG1 can increase its generation and send to MG3. In short, under this transaction mechanism, we can maximize the benefits of the whole society, and we can also make the best use of the power generation resources from each MG.

C. ENERGY MANAGEMENT STRATEGY AND OPERATION CONTROL METHOD FOR MULTI-MICROGRID SYSTEM

The energy management strategy of MMG is mainly to coordinate different MGs and superior distribution network, to maximize the use of renewable energy, improve the stability and economy of the whole system. The cooperative approaches in the existing studies are mainly clarified into

TABLE 2. Energy management scheduling strategy and operation control method for MMG.

Ref	The cooperative approaches			Research work			Solving methods	Objectives
	Centralized	Decentralized	Hierarchy distributed	Energy transaction strategy	Information interaction strategy	Artificial intelligence technology		
[75]	√	-	-	√	-	-	cooperative game theory	economy
[76]	-	-	√	√	-	-	cooperative game theory	economy
[77]	√	-	-	√	-	-	non-corporative game theory	economy
[78]	-	√	-	√	-	-	real-time digital simulator (OP4510) from OPAL-RT.	improve fault-ride-through capability
[79]	-	√	-	√	-	-	mixed-integer linear problem (MILP)	resilience and economy
[83]	-	√	-	-	√	-	multi-agent	global optimization; regional autonomy
[84]	-	√	-	-	√	-	multi-agent; leader-follower consensus algorithm	global optimization
[85]	-	-	√	-	√	-	multi-agent	minimize operation cost; improve traffic condition
[86]	-	√	-	-	√	-	improved multi-agent consensus algorithm	maximum consumption of renewable energy
[80]	√	-	-	-	-	√	deep neural network; Reinforcement learning	economy
[81]	-	√	-	-	-	√	deep reinforcement learning; Neural network	economy
[82]	-	-	√	-	-	√	radial basis functional neural network	power quality
[83]	-	√	-	-	-	√	adaptive deep dynamic programming	frequency control

three categories, namely centralized schemes, distributed approaches, and hybrid control strategies [57]. The centralized schemes work well for conventional power system by introducing a MG central controller. The methods implemented in a centralized manner require an information center to collect global information and a central controller to process the amounts of received data. Thus, the required computational capacity of the control center is rapidly growing with the increase of the power devices, and it may be more vulnerable to the single-point failures [52]. The distributed approaches may be robust and less costs in terms of no communication network are needed. However, in [8], it shows that the available resources in the network would be not utilized in a cost-effective way because of the deficiency of broader available information. In contrast, the cooperative solution in the distributed way that only utilizes local information through a local private communication network. In the future development, it will consist of more hierarchy distributed controllable power-electronics devices with the ability to exchange information through a communication network. Therefore, the emerging management solution should be efficient and low-cost for an economically viable smart grid. The main research directions of current MMG energy management and operation control in different cooperative approaches can be summarized as the following three aspects:1) energy transaction strategy [75]–[79]; 2) information interaction strategy [80]–[83]; 3) artificial intelligence technology in MMG [87]–[93]. Table 2 summarized and compared the different solution methods and optimization objectives of energy management and operation control of MMG under different cooperative approaches.

1) ENERGY TRANSACTION STRATEGY

Energy transaction strategy for MMG often involves multi-partner, which can be solved by game theory, as an advanced optimization tool, is mainly used to study how multiple stakeholders make optimization decisions and has been widely used in the field of power system. Energy interaction and cooperative control methods between MMG can generally be transformed into cooperative game model or non-cooperative game model [75]–[77]. Reference [75] discussed the possibility of MMG cooperating through coordinated economic scheduling, and proposed Nash-Harsanyi cost allocation scheme under the framework of cooperative game theory to ensure fair and stable cost sharing among MGs. Reference [76] proposed a scheme for the collaborative energy and reserve scheduling model to participate in the optimal operation of MMG. However, in most cases, it is difficult for MMG cooperative operation to simultaneously meet the profits of each MG, so it is necessary to set power transaction strategies based on non-cooperative game according to the preferences of decision makers. Reference [77] developed a non-corporative games theory model based on distributed energy management algorithm for multiple smart distribution systems of MG including real-time electricity price, which can effectively coordinate the operation of MGs and achieve energy balance among different MGs. Reference [78] proposed a decentralized control model to improve the fault ride-through of a multi-microgrid system. Reference [79] introduce an energy interaction framework for a decentralized operation in a stand-alone multi microgrid system to improve the economic and resilience.

2) INFORMATION INTERACTION STRATEGY

Aiming at the information interaction strategy of MMG, researchers put forward an information interaction strategy based on multi-agent technology [37], [80]–[84]. It regards each MG as an agent, and each agent can spontaneously communicate and exchange information with the neighboring agents according to the pre-set communication protocol, to realize power flow and intelligent control between MMG [81]. At the spatial scale, MMG information interaction based on multi-agent system adopts a three-level linkage hierarchical control strategy of system layer, node layer and device layer. Its multi-level target information is delivered from top to bottom, and at the same time, the scheduling information is uploaded from bottom to top, to achieve coordinated and optimized control of energy in the whole system [82]. Reference [83], based on the MMG 3-level energy coordination control framework of multi-agent system, discussed the influence of MMG operation and energy storage system operation, and proposes the solution process of global optimization and regional autonomy. In particular, the privacy disclosure problem caused by a large amount of information interaction in MMG is a big challenge. Reference [84] proposed a distributed scheduling consistency algorithm based on multi-agents to solve the energy management problem of MMG. This method only needs information exchange between adjacent agents to achieve the global optimization, which greatly reduces communication volume and effectively improves the problem of user privacy disclosure. Reference [85] proposed a multi-agent based optimal scheduling and trading scheme to co-optimize the coupled system in which multi-microgrids integrated with an urban transportation network. Reference [86] proposed an improved multi-agent consensus algorithm to improve the utilization rate of renewable energy resources and solve energy dispatch optimization of islanded multi-microgrids.

3) ARTIFICIAL INTELLIGENCE TECHNOLOGY

With the rapid development of artificial intelligence technology, deep learning, enhanced learning, and other theoretical methods showed great advantages in data analysis, prediction, classification, and other aspects, especially in the processing of massive data [87], [88]. At present, many related technologies have been applied in MMG operation, energy management and other aspects [89]–[91]. Reference [89] proposed the combination of deep neural network and reinforcement learning. In this model, there is no need of user's information, and it use the historical data to train the deep neural network, which can automatically generate MMG power exchange strategy under given new input conditions. Then the model-free reinforcement learning technique is used to optimize the retail price of local MG to maximize the profit by selling energy. Reference [90] proposes an Internet of Things (IoT) platform for energy management in multi-microgrid system to enhance the power quality. Reference [91] design a framework of integrated frequency control to reduce the frequency deviation of a multi-area multi-microgrid system. In addition, traditional artificial intelligence algorithms, such as particle swarm optimization and genetic algorithm, have obvious advantages in solving the energy management of single MG [92]. But for MMG system, due to the energy management process involves many nonlinear constraints, optimization variables and interaction with the system information, it is easy to lead dimension disaster problem, which make the optimization algorithm unable to fast convergence, and then cannot use in the real-time operation. To solve this problem, reference [93] used the deep reinforcement learning algorithm to calculate the energy optimization strategy online, and effectively improves the energy efficiency of building through real-time feedback and control.

III. THE UNCERTAIN CHALLENGES IN MULTI-MICROGRID SYSTEM

From the MMG that have been studied so far, uncertainty factors exist widely in power system [94]. In addition, MMG has higher renewable energy penetration, the impact of uncertainty on MMG is generally higher than that of in single MG. Therefore, this section focuses on discussing the MMG energy management model with uncertainties, which includes three aspects. The first one is the uncertainties in operation, including the output of renewable energy and the uncertainty of various load demands [95]. Although MMG can make the system run stably through energy complementarity; it is still a system with limited capacity in essence compared with large power grid. The power fluctuation of renewable energy and load demand are more random, which will affect the real-time power balance of the system. The second is the uncertainty of the real-time electricity price caused by the reform of the electricity price system. This type of uncertainty essentially belongs to the category of the electricity market. If the demand uncertainty from users and the market cannot be reasonably addressed, it will be difficult for the MG operator to make the optimal power scheduling plan. Thirdly, the uncertainty caused by power system faults and accidents. In the initial design and planning of MMG, the scenarios involved in power system faults and accidents should be fully considered, to provide reasonable countermeasures when accidents occur, reduce the probability of system collapse, and make it more robust [96].

A. CHARACTERISTICS AND MODELING OF UNCERTAIN

The modeling of uncertain factors is the basis of analyzing the uncertainty of MMG. The cognitive degree of uncertainty can be divided into randomness, fuzziness, and unknowability [94]. This paper mainly studies randomness, which is the most widely discussed in power system analysis. The uncertainty characterization methods at randomness level mainly include statistical uncertainty characterization method (which can give probability distribution function) and scenario-type uncertainty characterization method (which can give fluctuation interval) [97].

In the past decade, the modeling of uncertainty factors in power system has made great progress. Various statistical methods have been applied to the modeling and analysis of renewable energy generation [98], diversified load demand [99], energy market transaction price [29] and equipment operation state evaluation [100], all of which accurately reveal the random statistical behavior of uncertainty factors.

1) POWER SUPPLY AND LOAD DEMAND

Probability prediction technology is divided into interval prediction and density prediction. The former gives the confidence interval of distributed renewable energy output or load demand at a certain confidence level, and the latter is the probability density function or cumulative distribution function of the output at the future time [101]. Compared with interval prediction, density prediction can provide more reference information. The commonly used density prediction methods include quantile regression, kernel density estimation and so on [102]. Probability prediction technology has the obvious difference from other uncertain factor modeling methods is that the traditional modeling method is based on the analysis of historical data, while the probabilistic prediction tries to obtain the variation characteristics of uncertain factors in the short-term future, so the probabilistic prediction is more suitable for the short-term operation of power system.

Although many literatures have carried out relevant studies on probability prediction of wind power [103], photovoltaic power generation [104] and load demand [105], there are still several problems to be solved in probability prediction: 1) Quantile crossover exists in quantile regression method, that is, quantile predicted value does not increase as the corresponding probability value increases [106]. 2) Density leakage in kernel density estimation leads to the problem that the predicted value exceeds the value range of the random variable [107]. 3) The technical bottleneck of high dimensional probability prediction considering the temporal and spatial correlation of power output and load demand has not been broken [108]. With the improvement of the penetration of distributed renewable energy and diversified load demand in the power system, it is more significance to overcome the above technical problems and improve the accuracy and reliability of probability prediction.

2) ELECTRICITY PRICE

Electricity price forecasting is essential to the operation of electricity market which has critical influence on economic operation of modern power system. Electricity market needs a constant balance between power supply and load demand, and it could not be stored at a large level due to some economic reasons [109]. There are various factors on which electricity price forecasting depends such as weather conditions, bidding process, renewable power generation, and load demand [110]. All these uncertainties factors make electricity price volatile and uncertainty.

Different authors have provided various methods for electricity price forecasting. 1) Statistical models; 2) Fundamental models; 3) Artificial intelligence models. Statistical models are a mathematical model which include previous electricity prices and exogenous variables such as weather, production variables, etc. These models can use different methods to solve, such as time series models, regression models, and exponential smoothing methods [111]. For example, Time series methods with seasonality and exogenous factors for short term electricity price forecasting in the Russian power market, Nord pool and PJM market [112]. Regression models, e.g., multiple regression models are used to learn the relationship between dependent (interest) variable and other independent variables. Reference [113] used double seasonal exponential smoothing model to forecast hourly spot prices from the Spanish market. Fundamental models can establish the mathematical model of the factors affecting the price of electricity, it can also use the multi-agent simulation, equilibrium, game theory, simulating the operation of different agents generating units and demand load which are being interacting with each other and give the price process by comparing the demand and supply in the desired market. Artificial intelligence models can handle complex and non-linear problems. For example, the artificial neural network and artificial cooperative search algorithm was applied in [114] to forecast electricity price. Different deep neural network has also been applied to forecast the Austrian electricity wholesale market price [115]. Reference [116] presents the hybridization of global sensitivity analysis with data-driven techniques to evaluate the Mexican electricity market interaction and assess the impact of individual parameters concerning marginal prices.

3) POWER SYSTEM RANDOM FAULTS

Compared with power fluctuation of distributed renewable energy and load demand, random faults of power system components such as lines, generators and transformers have a more significant impact on system operation, and their uncertainties are more difficult to characterize [117]. In the present study, discrete probability distribution function is generally used to represent random faults of components. Reference [118] pointed out that the statistical index of component failure is difficult to accurately express the possibility of line failure in actual operation, so fuzzy mathematics is adopted to express the uncertainty of operation of overhead line.

For the modeling of power system fault components, a feasible idea is to establish the fuzzy set of its probability distribution based on the historical data of component faults, other than to directly establish its probability distribution model, and then solve the stochastic optimization problem considering component faults, to deal

TABLE 3. Uncertainty modeling technologies in MMGEMS.

Ref	Classifications	Sources of uncertainties	Modeling methods
[102]	operation	wind power generation	extreme learning machine
[103]	operation	photovoltaic power	improved quantile convolutional neural networks
[104]	operation	load demand	multivariate quantile regression
[112]	energy market	short-term electricity price	seasonal component autoregressive with exogenous factors model
[113]	energy market	Spanish day-ahead electricity spot price	double seasonal exponential smoothing model
[114]	energy market	load demand; electricity price	artificial neural network
[116]	energy market	generation; fossil fuel costs; load zone	machine learning
[118]	power system faults	line failure	stochastic optimization; distributionally robust optimization
[119]	power system faults	potential damages of infrastructure	stochastic program

with the influence of component faults on power system operation [119].

Uncertainty problems and modeling methods encountered by mmg are summarized in TABLE 3

B. ANALYSIS OF THE INFLUENCE OF UNCERTAINTIES

1) UNCERTAINTY AFFECTING ASSESSMENT

Aiming at the uncertainty problems encountered in the process of energy management of MMG, quantitative evaluation of the influence of the above uncertainty factors becomes the key to the uncertainty analysis of power system. The influence of uncertain factors includes the following aspects.

a: SECURITY

The uncertain characteristics of distributed renewable energy and various load demand will directly affect the safety of power system operation [120]. Random failure of components and random fluctuation of distributed renewable energy output will both increase the probability of line power flow overload and node voltage exceeding the limit in operation, and further affect the safety power supply in system.

b: RELIABILITY

With the improvement of renewable energy penetration, and considering the uncertainty of renewable energy output, to guarantee system has plenty of power supply capacity, the number of renewable energy generators will significantly increase [1], [2], in this situation, when it meets the extreme weather conditions, the energy power cuts will influence power reliability [119], [121]. In addition, the uncertainty of users' energy consumption behavior and transaction behavior will bring great challenges to the system operation, affect the real-time supply-demand balance of the system, and further affect the reliability of the system operation.

c: STABILITY

As we all know, some uncertainty factors will increase the probability of the system frequency and node voltage fluctuation, and it will lead renewable energy generators are easy to go off the main grid under the condition of significant frequency or voltage fluctuation, thus affecting the stable operation of the system [122], [123]. Uncertainty factors will make the system operation stability index (such as static voltage stability and transient voltage stability) have probability characteristics. And system operation stability needs to further consider the boundary of the probability distribution range, which can lead to the system operation in an extreme danger scenario [124].

d: ECONOMY

In the dispatching of high proportion distributed renewable energy power system, it is necessary to consider the influence of system operation uncertainties. The fluctuation of diversified load demand, distributed renewable energy output and other factors will directly affect the output allocation and reserve capacity retention of unit on-off plan, thus affecting the economy of system operation. In addition, the electricity price will be affected by the uncertainty of supply and demand balance of real-time electricity market transactions, which will further affect the economy of users' energy consumption [125].

2) MITIGATION MEASURES FOR UNCERTAINTY

The uncertainty faced by the MMG will bring many problems to the operation of the power system. To solve these operation problems including security, reliability, stability, and economy, the researchers generally consider the following technical methods to tackle these mentioned uncertainties:

a: ENERGY STORAGE DEVELOPMENT AND APPLICATION

Compared with other power supply and load demand, energy storage can transfer power and energy in different time and different space, which make its operation more flexible [126]. At present, energy storage has been applied in energy arbitrage and electric energy regulation. In addition, energy storage has the capacity of active and reactive power coordinated scheduling, which plays an important role in frequency and voltage regulation of power system, alleviating grid congestion and improving power quality. Aiming at the challenge brought by large-scale distributed renewable energy to power system operation, energy storage can be configured to suppress the volatility generated by renewable energy, to avoid abandon of renewable energy, and to promote renewable energy consumption [127].

In recent years, energy storage technology develops towards high energy density, high conversion efficiency and low cost, which promotes the widely application of energy storage in the power system [128]. Electrochemical energy storage has the characteristics of flexible configuration and easy operation and maintenance. In recent years, remarkable achievements have been made in theoretical research and engineering practice. Electrochemical energy storage is widely used in energy storage power stations and electric vehicles, including lithium-ion batteries, ultracapacitors and full vanadium liquid flow battery, etc. [129]. At the same time, liquid air energy storage and megawatt flywheel energy storage have been applied in micro-energy network. With the development of low-carbon transformation of energy structure and energy storage technology, energy storage with low cost and high reliability will become an important regulation means of energy system to solve the uncertainties.

b: LOAD DEMAND RESPONSE AND REGULATION

Take advantage of users' side load control technology to deal with the fluctuation of renewable energy has become a research focus on the whole world [130]. Usually, the loads in MMG can be divided into flexible and inflexible loads. And the flexible loads can response to price signals and participate in the demand response programs. Based on the demand response characteristics, MMG operator can reduce its total daily costs [131]. Reference [132] presented a smart home energy management system that includes flexible appliances, electric vehicles, and energy storage units, this system can transform the consumer into an active prosumer by demand management. In addition, some researchers studied the regulation model and parameter identification technology of temperature load on different time scales (hour, minute and second) [133], to solve the power fluctuation problem of renewable energy. Similarly, in industrial users, user-side resources such as electrolytic aluminum and irrigation pump stations can also provide auxiliary services to solve the problem of power fluctuation of renewable energy generation. Reference [134] introduced the demand response and economic energy storage dispatch to enhance self-coordination and self-balancing ability among different resources and established an effective modeling and optimization method to maximization of renewable energy utilization and minimization of overall system costs in MMG.

With the gradual opening of the electricity market, the rapid development of distributed renewable energy and the experimental application of blockchain technology to support decentralized trading, the tradable energy system and mechanism for distributed market are gradually emerging [135]. The transaction mechanism based on the tradable energy market will coordinate the flexible resources on the user-side to participate in the operation of the power system through the price signal, which can promote the consumption of renewable energy, and realize the privacy protection of the user.

c: MULTI-ENERGY COMPLEMENT

Through multiple energy networks interconnection and flexible energy conversion, the regional integrated energy system can satisfy various energy demand and achieve clean and efficient energy utilization [136]. To reduce the influence of the uncertainty of renewable energy generation, the electric energy generated by intermittent energy is converted into other forms of energy through different coupling mechanisms during the operation of the power system.

Electrical energy and heat/cold can be coupled in a variety of ways. Electric boilers, water heaters and other devices based on Joule's law convert electrical energy directly into heat and store it, thereby promoting renewable energy consumption [137]. The heat pump drives the compressor by electric energy and absorbs or discharges heat energy with the refrigerant as the carrier to meet the needs of users for heating or cooling [138].

In particular, the continuous development of power to Gas technology in recent years will become the key to promote the absorption of renewable energy and the integration of heterogeneous energy [139]. P2G converts electrical energy into stable high energy density gas, such as hydrogen and methane, thus storing intermittent and fluctuating renewable energy in the form of stable chemical energy. Gas power plants, micro-gas turbines and other electrical coupling equipment have good dynamic response speed, which can quickly adjust the output according to the renewable energy and load fluctuation to ensure the smooth operation of the system [140].

Compared with the traditional optimal scheduling of power system, the coordinated operation of multi-energy complementary integrated energy system can give full attention to the different time scales advantages of dispatching response of different energy systems and realize the complementary of cold-heat-power-gas.

C. MULTI-MICROGRID SYSTEM DISPATCHING WITH UNCERTAINTIES

MMG's energy management and control strategy is the basis of influencing the coordination and stable operation of MGs, but MMG still faces the influence of uncertain factors on its safe and economic in the process of operation [25]. Therefore, it is a major difficulty of MMG energy management system modeling to effectively deal with various uncertainties in MMG. The following three types of models proposed by researchers for uncertain factors are mainly introduced.

1) STOCHASTIC OPTIMIZATION

Stochastic optimization includes uncertain parameters, and we assume these uncertainties variables follow a predefined probability distribution and then we can transform it into a deterministic mathematical programming problem and solve it [141]. To a certain extent, this method can reduce the complexity of scenarios faced by MMG system in energy management. Reference [142] adopted the method based on random scenarios to deal with the uncertainty of renewable energy generation and used a backward scenario reduction method to reduce the generated scenarios and the amount of calculation. Reference [143] proposed an energy management strategy based on unexpected events for MMG system. Power operators consider the probability of unexpected events in energy management and adopt random optimization strategies based on different scenarios. The results show that this model has obvious advantages in preventing economic losses.

There are also related literatures that use chance constrained programming, which is also a SO. It stipulates that the probability of the establishment of some constraints should be greater than a certain confidence level, which may better meet the needs of decision makers in practical application [27]. SO mainly use related mathematical methods to generate random scenarios to describe the possible uncertainty problems in power system, but the difficulty is how to generate a small number of random scenes to represent more uncertain scenes. Reference [144] used Monte Carlo algorithm to generate discrete random scenarios to describe the uncertainty of relevant parameters, but Monte Carlo method has a slow convergence rate and a large amount of calculation. Reference [145] proposed a two-point estimation method instead of Monte Carlo method to be embedded into the gradient-based particle swarm optimization algorithm, to avoid the problem of too slow convergence speed and reduce the computational burden. In addition, the main technical difficulty of stochastic optimization is how to accurately describe the probability distribution of uncertain parameters. Compared with single microgrid system, the energy interaction and power transaction between each microgrid and the main grid will increase. Power transmission loss and real-time electricity price will make the optimization operation of MMG system more complicated [146]. All of these make it difficult to accurately obtain the probability distribution of uncertain parameters. What's more, the stochastic optimization always faces the balance of calculation complicity and solution accuracy, which is the key problem that restricts the further development of the stochastic programming model.

2) ROBUST OPTIMIZATION

Different from the stochastic optimization, the robust optimization (RO) does not need to know the probability distribution of the uncertain parameters in advance but expresses the fluctuation range of the uncertain parameters by setting up an uncertain set. If the uncertain parameters fluctuate within the given uncertain set, the RO can generally obtain feasible solutions [147]. Under the same conditions, the computation of the model is less than that of the method based on SO. At present, there are relatively few studies on the application of RO in MMG, and most of them are two-stage robust optimization models, because compared with static robust optimization or single-stage robust optimization methods, two-stage robust optimization models have greatly improved the conservatism of robust optimization [148]. Reference [149] proposed a two-layer, two-stage robust optimization model for the uncertainty of renewable energy output, load demand and line faults in AC-DC hybrid MMG. The column-and-constraint generation algorithm was used to transform the Min-Max-Min problem into a two-stage mixed-integer linear programming problem, which can be solved quickly and effectively. Reference [150] formulated a cost minimization robust model for MMG energy management, which considers the renewable energy output and load demand uncertainty, it has been transformed to a min-max robust counterpart. The developed model provides immunity against the worst-case realization within the provided uncertainty bounds. At present, the main problem of robust optimization is to improve the conservatism of uncertain sets, because the robust optimization ignores the probability distribution of some available uncertain parameters, resulting in the uncertain sets' description of uncertain parameters is too conservative. In addition, robust optimization models usually use the worst scenario to deal with uncertainty, which often leads to high conservatism and poor economy [151].

3) DISTRIBUTIONALLY ROBUST OPTIMIZATION

It is well known that the deterministic probabilistic distribution needed in stochastic optimization can only be observed indirectly through finite datasets and robust optimization has an over-conservativeness feature because it ignores probability distribution information. Recently, a distributionally robust optimization (DRO) method that remedies the SO's concreteness of probability information and RO's ignorance of probability information was proposed in [152], [153].

Distributionally robust optimization is a modeling program, adopting the worst-case approach, where the worst case is chosen from a proscribed ambiguity distribution set. In many situations, the probability distribution function of renewable energy, load demand and electricity price cannot be exactly obtained; instead, its partial information such as mean vector and covariance matrix can be collected from the historical data. Unlike the SO approach that requires full PDF specification, the assumption for DRO-based models is that only partial information about the distributions of the uncertain parameters is available.

More recently, DRO approaches have been applied to model uncertainty in power system problems such as economic dispatch [154], optimal power flow [155], investment decisions [156], and unit commitment [157], etc. Reference [155] adopted a statistical inference technique to construct ambiguity sets for the discrete distributions, which is data-driven, and more data leads to the less conservative solution. Reference [157] proposed a Wasserstein metric-based distributionally robust approximate framework, for unit commitment problem to manage the risk from uncertain wind power forecasted errors. From the studies that have been

TABLE 4. Method of solving MMG dispatching with uncertainties.

Ref	Method	Sources of Uncertainties	Methods for characterizing uncertainty	Solution techniques	Objectives
[142]	SO	renewable generations	stochastic scenario-based approach	second-order cone relaxation technology	optimal power flow
[143]	SO	renewable generations; load demand; electricity price	stochastic scenario	multi-objective particle swarm optimization	smooth the load curve; economy
[27]	SO	renewable resources; loads	Chance constrained	chance-constrained programming	decreasing emissions
[144]	SO	renewable energy sources; variability of loads	Chance constrained	Monte Carlo algorithm	economy
[149]	RO	electricity prices; WT&PV outputs; AC/DC load power	the upper/lower deviations	The column-and-constraint generation algorithm	economy
[151]	RO	renewable energy sources; electric loads	Uncertain set	linear programming	economy
[154]	DRO	renewable energy	uncertainty set; scenarios	solving semidefinite programming; convex quadratic programming. linear programming	reserve dispatch; economy
[155]	DRO	distributed generation and loads	Ambiguity set; scenarios	The column-and-constraint generation algorithm	dynamic optimal power flow
[157]	DRO	Wind power	Ambiguity set; scenarios	Monte Carlo simulations	economy

done so far, instead of using a certain probability distribution or constructing a deterministic uncertainty set, DRO lies all possible probability distributions in an ambiguity set, which is data-driven and assumed to contain the true distribution. The best decision is made under worst- case probability distribution so that all possible probability distributions in ambiguity set are immunized.

The methods of solving MMG dispatching model with uncertainties are shown in Table 4.

D. SOLVING METHODS OF MULTI-MICROGRID SYSTEMS

The energy management of MMG contains not only discrete variables such as transaction strategy formulation and transaction intention analysis of different subjects [23], but also continuous variables such as power energy outputs of different MGs [25]. Both single objective optimization [34] and multi-objective optimization [143] can be considered. There are both linear and nonlinear constraints in the constraints [155], [158]. It is faced with an uncertain environment, including the random fluctuation of renewable energy and the real-time change of diversified load demand, as well as the volatility of electricity price and fuel price. Therefore, the energy management problem of MMG is essentially a problem of multi-scenes, multi-objectives, nonlinear and mixed uncertainty. To solve this problem, enumeration method [27], [141]–[145], mixed integer programming method [79], [159], heuristic algorithm [88]–[91] have been studied respectively. Enumeration, as the name implies, enumerates all possible combinations of optimized variables. When the number of combinations is small, the method is simple and efficient, and can ensure the global optimal solution. However, if the number of variables is large and the solution space is large, the combination will show exponential growth, which is extremely time-consuming [160]. The mathematical programming method has strict requirements on the objective function and constraint conditions, and the complexity of energy management of MMG limits its application. However, through appropriate model simplification, the energy management problem of MMG can transform as mixed integer linear programming of multi-stage and multi-game players, and relevant mature algorithms can be used to solve it. However, the simplification of the model means the loss of some useful information, thus by using the simplification means losing the opportunity to find the global optimal solution. However, the heuristic algorithm is usually independent of specific application problems, and the modeling method is relatively loose, which can easily deal with the uncertainty of information. Therefore, it is widely used in the energy management of MMG. But meanwhile, this method cannot guarantee to find the optimal solution, and the solving efficiency is low.

IV. CHALLENGES AND FUTURE DIRECTIONS

With more and more power electronic devices (including distributed energy resources and loads) connected to multi-microgrid systems, the development of communication technology, the design and implementation of complex power control modules, the maturity of energy transaction market and the emergence of emerging technologies, The smart power grid industry will face new challenges. These challenges will not only affect the realization of multi-microgrid energy management, but will also have different characteristics in MMG research fields, such as, 1) massive distributed energy resources will provide a new possibilities for MMG planning and distributed operation control [20], [59]; 2) different energy characteristics and differences in time and space scales in the integrated energy system will significantly improve the MMG energy efficiency [136], [161], [162]; 3) the development of information technology such as blockchain technology will make energy transactions more inclusive and convenient [163], [164], etc. In summary, these technologies will bring some new development opportunities to different research fields such as the planning, operation, control, and energy transaction of MMG.

A. PLANNING, OPERATION AND CONTROL

1) PLANNING

As for the planning of MMG system, the existing research is relatively simple which mainly considering the location of distributed renewable energy, the long-term fluctuation of renewable energy output, the growth of load demand, the economic and social benefits in the whole life cycle of equipment, etc., and it is urgent to establish a comprehensive systematic and scientific planning and design method. In the future, the main challenges of MMG system planning are as follows.

- Aiming at the planning and design of multi-micro energy network including cold, heat and power combined supply system. The multi-microgrid system with combined cooling, heat and power system can not only meet users' demand for electric energy, but also meet users' demand for heat energy. In this case, the multi-microgrid system is a multi-micro energy network. For this kind of multi-microgrid with the characteristics of integrated energy network, the coupling characteristics between the optimal ratio of cooling, heating and electricity corresponding to different structures and different energy flows are the main challenging.
- Coordinated planning of distribution network and multi-microgrid. As wind and photovoltaic and other renewable energy are continuously connected to the power grid in the form of microgrid, the planning and expansion planning of distribution network also need to consider the impact of multi-microgrid access.
- Economic analysis and planning of energy storage system. Technically speaking, the space-time translation characteristics of energy storage devices are of great significance to the planning and operation of multi-microgrid systems. At the same time, in the market environment, the economic analysis of the energy storage system and the impact of its life on the planning of the multi-microgrid system need to be reasonably demonstrated.

2) OPERATION

MMG is a complex system which contains multi-microgrids and various distributed power generation device. With the increasing penetration rate of renewable energy and the extensive use of diversified loads, the increasing uncertainty will lead to power imbalance between generation and load, and the stability of frequency and voltage will be more serious than that of traditional power system, all of which will bring challenges to the future application of MMG. On the other hand, MMG topological structure is changeable, especially in emergency situations such as failure or faults. How to design MMG topological structure with dynamic self-reconstruction capability will be a key direction of future MMG planning and operation. In addition, the system oscillation and circulation suppression in parallel with multiple converters are the basis of stable operation of the system. Therefore, under different line impedance environments, the oscillation condition failure mechanism and group-controlled oscillation suppression method of multiple converters in parallel, as well as the method of circulation suppression and power equalization of multiple converters in parallel with different capacities and types, are also key points for the stable operation of MMG.

3) CONTROL

In the process of operation, MMG must face the switching of on-off grid and the recombination of regional isolated microgrid. The central controller or distributed controller of MMG system should meet the requirements of control strategy at different time scales. However, the current central controller or distributed controller is mainly designed for a specific time scale. Therefore, how to reasonably design multiple time scales for each controller is the key to ensure the safety and reliability of MMG, which is also an urgent problem to be solved for the current MMG controller. In addition, as the number of microgrid increases, its structure gradually changes from vertical to flat and from centralized control to distributed control. If each microgrid individual needs to communicate, massive data communication will affect the MMG system's work efficiency and user privacy. How to design effective control strategy to achieve optimal control effect with minimum information traffic and reduce user privacy leakage will be an urgent problem to be considered in the future development of MMG system.

B. ENERGY MANAGEMRNT

For energy management of MMG system, further research can be carried out in the following three aspects.

- First, most MMG energy management only considers the energy form of electricity, while future MMG systems are more likely to exist in the form of integrated energy system of combined cold, heat and electricity. How to solve the coupling optimization among various distributed systems containing cold, heat and electricity is an urgent problem to be solved in future MMG energy management.
- Second, considering the stochastic programming model and robust optimization model has its own advantages and disadvantages, especially in the real world we can also use the method of mathematical statistics such as approximate interval probability distribution. Therefore, how to further benefit by using this type of probability distribution well to effectively improve the conservatism of the robust optimization model is the next main work. In addition, due to the

high renewable energy penetration of MMG, robust optimization theory has limited ability to describe the uncertain sets. If uncertain parameters fall outside the uncertain sets, how to deal with such risks will also be an urgent problem to be solved in the application of robust optimization theory in MMG field.

- Thirdly, reinforcement learning has been widely used in energy management modeling, but it can still be further studied from the following aspects: training corresponding reinforcement learning model methods for typical problems by analyzing and condensed typical energy management optimization models in different scenarios, including comprehensive use of the model-based reinforcement learning and model-free reinforcement learning methods can improve the generalization ability of deep reinforcement learning network and make it more robust in energy management modeling. Furthermore, advanced intelligent optimization methods are adopted to optimize the network structure of deep reinforcement learning and improve the accuracy of energy management control optimization strategy.

C. MARKET TRANSACTIONS

In the new generation of information and communication technology, blockchain technology, as a brand-new distributed infrastructure and accounting technology, can provide trust foundation for multi-microgrid collaboration in energy management with its ingenious technical design and data governance [163].

The energy transactions of MMG face several problems: the high platform management cost, the low security, and the untimely consumption of scattered electricity [164]. The core application value of blockchain technology in the field of power transaction is establishing trust and solving the trust problem in the information world. At the same time, it has the advantages of traceability, openness, transparency, and preventing single point of failure [165]. Using the above advantages of blockchain technology can significantly reduce the complexity of energy transactions and protect the information security [164], [166], etc. In the future electricity market, blockchain is a good solution to exert group collaboration and coordinate the rights and obligations of participants. Combined with the technical characteristics of blockchain and the characteristics of the future development of power energy market, blockchain technology has important application scenarios in power wholesale market, power retail market, distributed power generation market transaction, power derivatives transaction, credit evaluation of market players and other aspects [167].

V. CONCLUSION

MMG and its energy management system play a significant role in improving energy efficiency, power quality, reliability of distribution systems. In this paper, the typical architectures, and functionalities of MMG has been introduced, including physical network topologies, energy trading mechanisms and various energy scheduling and control strategies. The research works indicate that different kinds of uncertainty elements which suffering from operation, electricity price and power system faults will bring great challenges to MMG. Meanwhile, these uncertainties can be mitigated by energy storage technology, electricity market technology and complementary collaboration among different kinds of energy (cold, heat and power). Finally, various model and solving method are introduced to deal with MMG energy management with various uncertainties, including statistic optimization, robust optimization and distributionally robust optimization. This paper summarizes the MMG architecture, influence of uncertain elements, model characteristics and solution methods, etc. It provides an integrated solution for MMG with uncertainties. The challenges and future directions of MMG are also highlighted.

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GUOLONG MA received the bachelor's and master's degrees in electrical engineering from the South China University of Technology, Guangzhou, China, in 2017 and 2020, respectively. He is currently pursuing the Ph.D. degree with the University of Birmingham, Birmingham, U.K. His current research interests include renewable energy integration and distribution system optimization and scheduling.

JIANING LI (Member, IEEE) received the B.Eng. degree in electrical and electronic engineering from the Huazhong University of Science and Technology, Wuhan, China, and from the University of Birmingham, Birmingham, U.K., respectively, in 2011, and the Ph.D. degree from the School of Electronic, Electrical and Systems Engineering, University of Birmingham, in 2016. He was an Assistant Professor in smart energy systems with the University of Birmingham. He then joined WSP as a Principal Power Systems Engineer, in 2022. His research interests include distributed energy resource, energy storage systems, electric vehicle, energy management systems, and smart grid technology. He is currently the Chair of IEEE U.K., and Ireland Power and Energy Society.

XIAO-PING ZHANG (Fellow, IEEE) received the B.Eng., M.Sc., and Ph.D. degrees in electrical engineering from Southeast University, China, in 1988, 1990, and 1993, respectively.

He was an Associate Professor with the University of Warwick, U.K. From 1993 to 1998, he was with the China State Grid EPRI (NARI Group) on EMS/DMS advanced application software research and development. From 1998 to 1999, he was visiting UMIST. From 1999 to 2000, he was an Alexander-von-Humboldt Research Fellow with the University of Dortmund, Germany. He is currently a Professor of electrical power systems with the University of Birmingham, U.K. He is also the Director of the Smart Grid, Birmingham Energy Institute. He has coauthored the first and second edition of the monograph *Flexible AC Transmission Systems: Modelling and Control* (Springer, in 2006 and 2012). He has coauthored the book *Restructured Electric Power Systems: Analysis of Electricity Markets with Equilibrium Models* (IEEE Press/Wiley, in 2010). His research interests include modeling and control of HVDC, FACTS and renewable energy, distributed generation control, energy market operations, and power system planning.

Dr. Zhang has been made a fellow of IEEE for contributions to modeling and control of high-voltage dc and ac transmission systems. He is an IEEE PES Distinguished Lecturer on HVDC, FACTS, and wave energy generation. He is the Chair of the IEEE WG on Test Systems for Economic Analysis. He is an Advisor to the IEEE PES U.K. and Ireland Chapter. He has been appointed to the Expert Advisory Group, U.K. Government's Offshore Transmission Network Review, since 2020.