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A Survey of Energy Management in Interconnected Multi-Microgrids

HUALEI ZOU[1], (Student Member, IEEE), SHIWEN MAO[2], (Fellow, IEEE), YU WANG[1], (Member, IEEE), FANGHUA ZHANG[1], XIN CHEN[1], (Member, IEEE), AND LONG CHENG[1], (Student Member, IEEE)
[1]Department of Electrical Engineering, Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing 210016, China
[2]Department of Electrical and Computer Engineering, Auburn University, Auburn, AL 36849-5201, USA
Corresponding author: Yu Wang (yuwang15@nuaa.edu.cn)

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ABSTRACT An interconnected multi-microgrids (IMMGs) system takes advantage of various complementary power sources and effectively coordinates the energy sharing/trading among the MGs and the main grid to improve the stability, reliability, and energy efficiency of the system. The core of this structure is to achieve the optimal distribution of energy sharing through proper strategies. However, the volatility and intermittent characteristics of renewable resources, time-varying loads in the MGs, their correlated power generations, and the coupled energy among the MGs during energy trading, all bring about new challenges to achieving a stable operation and optimal scheduling in the power system. Many solutions have been proposed to solve these problems. In this paper, we provide an overview of the current energy management systems (EMS) in IMMGs, focusing on the IMMG structure, EMS objectives, timescales, and scheduling optimization structure. We then provide a review of the distributed optimization algorithms in IMMGs. We conclude this survey with a discussion of future directions.

INDEX TERMS Smart grid, microgrid (MG), interconnected multi-microgrids (IMMG), energy sharing, energy management.

I. INTRODUCTION

The smart grid (SG) is an electricity network that can intelligently integrate the interactions of all users connected to generators and consumers, in order to provide sustainable, economic, and secure power supplies to users. The SG is characterized by the two-way flow of power and information, distributed renewable energy resources (DRERs), and the microgrid (MG), which is a controllable entity of interconnected loads and distributed energy sources that can operate in both the islanded mode and the grid-connected mode.

Considerable works have been focused on the design and management of MGs [8], [66]. Recently, the Interconnected Multi-microgrids (IMMGs) system has become an integrated, flexible network that incorporates multiple individual microgrids (MGs), which are often geographically close and connected to a distribution bus. Effective energy transfer and coordination of the MGs could help to improve the stability and reliability of the entire system [1]–[4]. The IMMG has become an increasingly important problem in the current SG research, where the key is high efficient utilization and sharing of renewable energy (RE), especially distributed renewable energy (DRE) [5]–[8], and promoting the efficient use of distributed energy and consumption [4], [9]–[12].

IMMGs have many obvious advantages. First, IMMGs have good economic characteristics [7], [9], [13]–[15], no matter in the grid-connected mode [3], [16], [17] or in the islanded mode [1], [4], [18], [19]. This is because in IMMGs, the energy sharing among the MGs allows the MGs to satisfy their power demands with their own cheaper, renewable energy sources. Thus the cost of fossil fueled generation could be reduced. Moreover, the energy trading among MGs is primarily achieved among MGs that are close to each other, thus reducing the potential energy loss incurred in long-distance transmissions [7], [20]–[22].

Second, compared with the traditional single MG, the IMMG is more apt to the future development trends of

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the smart grid. With the ongoing large-scale deployment of renewable energy resources, the interconnected MGs in the distribution network will effectively improve the utilization of renewable energy. IMMGs also reduce the burden on the main grid (because the MGs facilitate energy trading among themselves), mitigate the congestion in distribution lines, and improve the reliability of themselves and the main power grid [16], [23]–[26].

Third, a smart distribution multi-microgrids system usually exhibits a high self-healing feature when there is a fault or natural disaster caused geographical area outage [5], [27]–[32], an MG can be isolated from damaged portions of the grid. An MG can operate in a stable way by sharing extra energy and spare resources with other connected MGs [30], [31]. The distribution system can also be autonomously divided into multiple MGs to improve the operation and reliability of the distribution network. Then the interconnected MGs can support each other with local generation capacities to achieve the overall reliability and minimize the total load curtailments in the system [29], [30], [32].

In spite of the above advantages, there are still many challenges in achieving stable and reliable option of the IMMGs. First, compared to an islanded MG, there is a high penetration of renewable energy (RE) in IMMGs. As a result, the volatility and intermittent characteristics of REs and time-variability of the loads in the IMMGs will be stronger both temporally and spatially [23]–[25], [31], [33]–[36]. In IMMGs, it is important to reduce the impact of such volatility on energy management. Second, due to the interconnected structure, there could be strongly coupled energy during energy sharing, and when one MG tries to optimize its energy schedule, the result will affect that of the other MGs [37]–[39]. And with the increase in the number of MGs in IMMGs, the dimension of energy scheduling problem increases and the problem becomes increasingly complicated. Third, the main grid and the MGs may be owned/operated by different entities with different objectives. Generally, such owners are interested in autonomous management of the MGs and preserve the privacy when sharing surplus energy [7], [15], [18], [40]. Therefore, optimizing the scheduling algorithms will change the way how users utilize electricity, as well as the way they buy/sell electricity. The above challenges motivate researches to design diverse energy management strategies and algorithms to apply to different situations. This paper presents a survey of the existing published research on IMMGs. The focus is on energy management in IMMGs, from its topology design to detailed optimal scheduling algorithms.

The remainder of this paper is organized as follows. In Section II, we first review related existing surveys on the energy management systems (EMS) in MGs and the SG, with regard to different aspects. We then examine the IMMG configuration and categorize their interconnections into three different topologies in Section III. We review the existing studies of EMS in IMMGs in Section IV, and then focus on decentralized optimization approaches in Section V. Several open problems and future directions are summarized in Section VI, and Section VII concludes this paper. The acronyms used in this paper are summarized in Table 1.

TABLE 1. Summary of acronyms.

Acronym	*Description*
AC	alternating current
ADMM	alternating direction method of multipliers
BESS	
CHP	combined heat and power
DAROSA	distributed adjustable robust optimal scheduling algorithm
DC	direct current
DG	distributed generation
DNO	distributed network operator
DSO	distribution system operators
DRE	distributed renewable energy
EMS	energy management system
ESS	energy storage system
EV	electric vehicle
IGM	interactive game matrix
IMMG	interconnected multi-microgrids
LC	load controller
MAS	multiagent system
MC	microsource controller
MG	microgrid
MGC	microgrid cluster
MGen	micro-generation
NE	Nash Equilibrium
OPF	optimal power flow
PV	photovoltaic
RE	renewable energy
VPP	virtual power plant
WT	wind turbine

II. RELATED WORK

In order to maintain the operation of MGs and the SG in a stable, economic, and resilient manner, EMS is generally adopted to achieve optimal scheduling of the distributed resources, according to power generation, load demand, and market information, and so on. Recently, there are several literature surveys that are focused on various aspects of the optimal operation of MGs and the SG, which are discussed in this section.

In [41], the role of EMS in MGs is described with respect to economic evaluation, dispatch, demand side management, and planning. This paper also summarizes the means/methods for achieving economic operation of the MG. Reference [42] investigates the feasibility, control, and energy management strategies of the low-voltage AC and DC MG systems. In [43], the authors present an overview of power management strategies for a hybrid AC/DC MG system, which includes different system structures, different operation modes, and a thorough study of various power management and control schemes in both steady state and transient conditions. With the development of MGs, standard IEC/ISO 62264 has been developed, and authors in [44] introduce the application of this international standard in MGs and Virtual Power Plants (VPP), considering the hierarchical control structures, energy storage, and marketing participation.

The study presented in [45] is focused on the smart home energy management system, along with related definitions, applications, and information about the manufacturing of its components. Reference [46] reviews the current MG control methods and energy management systems. The structure of the hierarchical control in MGs is briefly introduced, and the function of each layer in the hierarchical structure is recommended. Although the authors summarize commonly used optimization approaches in MG EMS, this paper is mainly focused on centralized EMS related definitions, functions, and methodologies.

In [47], the existing optimization objectives, constraints, solution approaches, and tools used in MG energy management are examined. The study in [48] is focused on the Network Reconfiguration technique in power systems with distributed generation. By changing the on/off state of the segment and the tie switches within the network, the distribution system can reduce the transmission power loss and improve the voltage profile. For the intermittent and weather-dependent renewable power generation, reference [11] investigates the stochastic modeling and optimization tools in MG energy management. The contribution of [49] is to provide a literature review on the distributed energy resources scheduling problems in MG and VPP from the aspects of modeling techniques, solution methods, reliability, emission, uncertainty, stability, demand response, and multi-objectives.

To ensure the static stability of the MG/SG system, the optimal power flow (OPF) must be achieved. Reference [50] reviews the current OPF under different objectives and constraints in MG and the SG. Furthermore, the current methods for solving the OPF are summarized and their computational performances are compared in this survey. In [51], a review of distributed algorithms for offline solutions to the OPF problem, as well as online algorithms for real-time solutions to the OPF problem, optimal frequency control, optimal voltage control, and optimal wide-area control problems are presented. The main goal of [52] is to provide multiagent system (MAS)-based distributed coordinated control strategies for MGs and MG clusters (MGCs), while considering balancing the power and energy, stabilizing voltage and frequency, and achieving economic and coordinated operation. Future research directions of MAS-based distributed coordinated control and optimization in MGs and MGCs are also discussed.

Since interconnected MGs has been recognized as a future trend of the SG, there are several recent surveys on MGCs. In [41], some current research on MGCs are reviewed, such as economic benefits and approaches to achieve this goal. In [53], a simple introduction of the DC MGCs is presented, along with some advantages of MGCs and the existing research in DC MGCs, such as modeling and stability, voltage regulation, and power management. Reference [52] gives a brief review on the MAS-based hierarchical control structure applied to controlling MGC, and it mainly introduces the power balance in the MGC system for energy trading under the objective of minimizing the energy cost. The surveys in [54]–[56] focus on the power control techniques in MGs, which is defined as the secondary control in the hierarchical control system, aiming to compensate voltage and frequency error. In [57], the authors provide a review of applying game theory to MG systems, demand-side management, and communications.

The above mentioned surveys focus on various aspects of EMS in MG and the SG, such as objective functions, reactive power, stability, power quality, and reliability in power systems. However, unlike the EMS in MG/SG, how to fairly share energy in IMMGs is an important problem, while how to protect users' private is also a critical issue. Moreover, how to effectively achieve energy trading with other MGs or the main grid in IMMGs is an interesting problem that arises in IMMGs. The EMS in IMMGs needs to have higher autonomy in this complex environment. In order to help readers to better understand the EMS of the new IMMG paradigm, this paper provides a comprehensive survey of the EMS in IMMGs for achieving the optimal energy distributions in IMMGs.

III. TOPOLOGIES OF INTERCONNECTED MULTI-MICROGRIDS

Interconnected multi-microgrids (IMMG) can operate in either the grid-connected mode or the islanded mode. All the MGs in IMMGs are interconnected and can exchange, share energy among themselves and with the macrogrid through power exchange lines. Thus they form an interconnected network system with multiple AC and DC microgrids with different topologies [10], [16], [22]. In addition, the distributed network operator (DNO) supervises the power-flow control and market operation, such as buying and selling active and reactive power to the grid, and mitigating the possible network congestion for transferring energy in the trade. Each MG consists of renewable energy generators, energy storage system (ESS), load (e.g., school, hospital, and residents), MG-EMS that manages energy autonomously, the microsource controllers (MCs) that control the microsources and the ESSs, and the load controllers (LCs) that manage the controllable loads, which can be achieved mainly based on an efficient, reliable, and low-delay communication infrastructure [9]. The three types of common topologies of the IMMGs are illustrated in Figs. 1, 2, and 3, and will be discussed in the remainder of this section.

A. MODEL 1: RADIAL TOPOLOGY

In this structure, every MG connects to the main grid directly, thus forming a typical star, or radial, topology, where each MG attaches to a bus firstly and achieves energy exchange with the main grid through the bus [9], [17], [58]–[63]. As shown in Fig. 1, 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 distributed network operator (DNO). Each MG is allowed to respond to the decision of the DNO and its

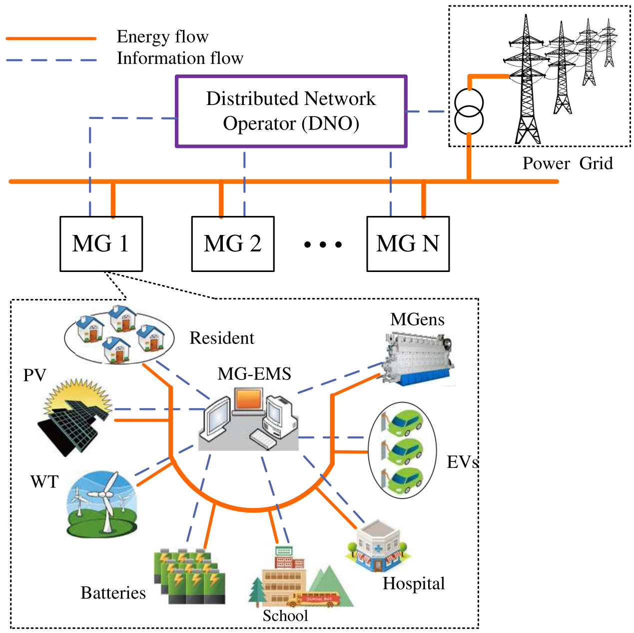

FIGURE 1. System architecture of IMMGs with a star, or radial, topology.

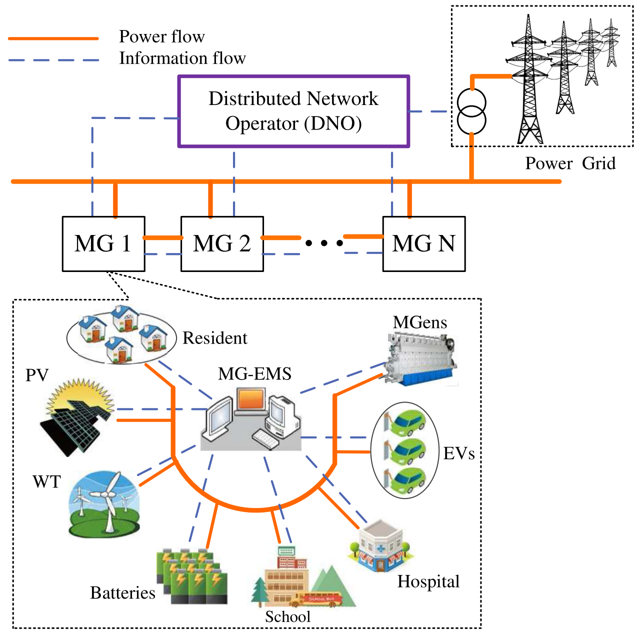

FIGURE 2. System architecture of IMMGs with a daisy-chain topology.

own MG-EMS. 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 exchange bus. On the other hand, an MG with surplus energy can benefit by selling the extra power to the main grid through the bus [3], [59]. Therefore, the important issues of energy management for the IMMGs with such a structure, are to consider the power sharing capability of the bus, to keep the energy exchange with the utility grid within a safe arrange, to relieve the power distribution line congestions, and to improve the reliability of the main grid [3], [9], [32].

B. MODEL 2: DAISY-CHAIN TOPOLOGY

In this structure, the IMMGs are connected to form a daisy-chain topology, where energy and information can flow bidirectionally between two adjacent MGs and between an MG and the main grid, as shown in Fig. 2. It can be seen that every microgrid not only connects to the main grid, but also to its two neighbors on both sides [4], [16], [24], [31], [36], [64]. With this topology, the IMMGs can form a line or a ring, and each MG can exchange energy and information directly with its adjacent MGs and the main grid [2], [13], [18], [65].

The EMS in this topology needs to coordinate the power exchange with its neighbouring MGs as well as the with the main grid. So its design is different from that in Model 1. This topology allows energy and information exchanges between adjacent MGs and the DNO, thus enables energy collaboration among adjacent MGs. There is stronger interactions among the MGs, leading to additional network constraints and coupled energy schedules in the optimal scheduling [10], [36]. In addition, each MG-EMS needs to act as an independent entity to determine its own operation schedule based on peer-to-peer communications of non-critical information with its neighboring MGs, because the users' privacy should be protected [22], [69].

C. MODEL 3: MESH TOPOLOGY

As shown in Fig. 3, the interconnected MGs can also form a mesh topology, as they are interconnected with each other through a power transmission infrastructure and a communication network [7], [23], [70], [71]. In this structure, the MGs usually contain diversified renewable resources. The IMMGs can exchange electricity and information with each other, and the operational performance can be enhanced and operating cost can be reduced effectively by cooperation of the MGs [7], [23]. On the other hand, it can be seen that this structure is more complex compared to the above two topologies, and thus the energy collaboration and coordination are more complicated. Each interconnected MG's scheduling is not only affected by its local power supply and demand, but also influenced by any other connected MGs in this IMMG network [18], [23], [71].

From the radial topology, to the daisy-chain topology, and to the mesh topology, an increased level of interaction and cooperation is allowed for the IMMGs, which leads to a larger search space for (and hence higher potential to find) the optimal energy management solution. However, the design of the energy management algorithm will certainly become more complicated and challenging.

IV. EMS IN IMMGS

The EMS in IMMGs is essential for the operation of the MGs in both grid-connected and islanded modes. The main responsibilities of an EMS are to assign generation

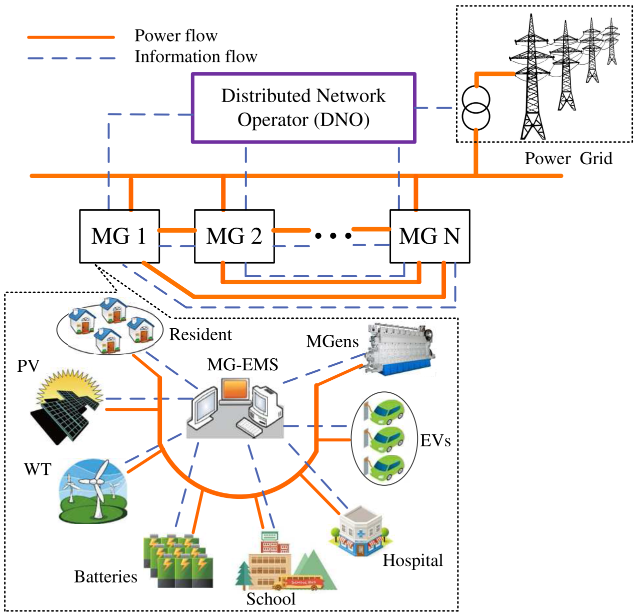

FIGURE 3. System architecture of IMMGs interconnected with a mesh topology.

references to every MG and dispatchable DGs and manage the controllable loads so as to control the power production and energy consumption in the system for sharing surplus energy [13], [25].Energy cooperation among microgrids has been proposed as a promising new solution to achieve resilient and cost-effective operation of MGs, rather than relying solely on the ESSs and fueled generators due to their limited capacity and high operation cost [7], [26], [72], [73]. In addition, the MGs in IMMGs may belong to the same entity or different entities with common/different interests, which make it necessary for energy management to consider various factors in a holistic and comprehensive manner [7], [40].

Energy management and coordination among MGs and distribution system operators (DSO) become more challenging since a variety of types of uncertainty arise from renewable resources, loads, and the electricity market, and these uncertainties are usually strongly correlated [40]. For the entire system, the EMS should encourage proactive energy trading in a stable and economic way, for an individual MG, the MG-EMS needs to interact with other MGs externally and coordinate the local power supply and demand internally [23], [63].

A. IMMG OPTIMIZATION OBJECTIVES

The commonly used optimization objectives in IMMGs include: operating costs, user satisfaction, renewable resources utilization, energy transmission loss, environmental benefits, etc. We discuss these objectives in this section.

1) OPERATING COST

IMMGs not only enable the energy interaction with the main grid and among the interconnected MGs, but also can minimize their own operating costs in the process of interaction. Common approaches for achieving the cost minimization goal include (i) to maximize the utilization of renewable energy sources [4], [9], [23], [25], [31], [36], [63], [65], [71], [72], [74], [75], (ii) to sell extra electricity to the main grid at a high price and buy electricity from the main grid at a low price [23], [71], [72], and (iii) to reduce the cost introduced by fueled generators [4], [75].

2) CUSTOMER SATISFACTION

This is a subjective objective measure since the customers are usually different; their satisfaction level maybe different even for the same energy demand and supply. To have a quantitative, parametric measure that can be incorporated into an optimization or control framework, various models have been developed on the relationship between the actual power allocated to users and their expected demand [9], [23], [65]. A user's satisfaction level will be high if its demands are satisfied, and be low if the demands are violated [66]–[68].

A common approach is to classify loads into different types, e.g., dispatchable loads and non-dispatchable loads, or elastic loads and non-elastic loads. The former is hard demands that must be satisfied at the given time (e.g., lighting), while the latter are soft demands that can either be partially satisfied or delayed to a certain extend. The user satisfaction level for the latter type of loads is a decreasing function of gap between demand and allocated power, or a decreasing function of delay. A scheduling algorithm can then be used to delay or sacrifice the elastic loads for given demand and supply of power, to achieve maximization of social welfare [23], [67]. Another commonly used method is to introduce a combined heat and power (CHP) system into the IMMG to regulate the electric energy and thermal energy [3], [9]. This way, the electric energy satisfies the load demand as much as possible, and the heat energy satisfies the user's satisfaction with the indoor temperature Indicator Requirements [65].

3) USAGE OF RENEWABLE RESOURCES

Maximizing the usage of renewable resources is an important goal of IMMGs, which is generally achieved in two ways. The first approach is by sharing the system's surplus energy with the MGs that have a high demand [4], [5], [9], [11], [23]–[25], [31], [36], [63], [65], [71], [72], [74], [75]. The second approach to achieving the maximum utilization of renewable energy, is by tracking the output power of DGs through shaping the load profile [3]–[5], [11], [23], [25], [31], [36], [63], [65], [71], [72], [74], [75].

4) TRANSMISSION LOSS

For energy trading among the MGs and the main grid, there are two types of energy transmission losses. The first type is the transmission loss among the MGs, while the focus of several recent works is on reducing such losses [24], [72]. The other type is the transmission loss between an MG and the main grid. Since the connected MGs are generally a low voltage system and the main grid is actually a high voltage system, the power exchange between the MGs and the main grid will cause greater losses [72]. In [24], transmission energy loss is calculated in proportional to the amount of the transmission real power.

5) SYSTEM FLEXIBILITY, STABILITY, AND ENVIRONMENTAL BENEFITS

System flexibility, stability, and environmental benefits are also important performance measures. Usually flexibility is measured in the form of energy complementarity, while stability is usually indicated by the number of power failures [4] or sudden blackouts [31], which should be avoided. Environmental benefits are usually measured by greenhouse gas emission [76].

From the above discussions, it can be seen that in the current optimization framework of the MMG, a commonly used principle is multi-objective optimization; optimizing an objective function in the form of a combination of some or all the objectives from Section IV-A1 to IV-A5 according to the actual demand, is the current trend of research.

B. TIMESCALE

For optimization and control problems, how frequent a new decision/adaptation is made and executed, is a critical system parameter that needs to be carefully chosen. There are two commonly used timescales for the optimization of IMMGs.

1) OFF-LINE OPTIMIZATION

This approach is usually adopted for day-ahead energy scheduling or IMMGs planning based on the assumption that all the forecast information (e.g., renewable resources power generation, load controllable rates, market price, etc.) are known. Then the EMS obtains an optimal scheduling for all the sub-systems [36], [63], [65], [77], [78]. This optimization method lacks consideration of future uncertainties in IMMGs. On this basis, a widely used optimization method to cop with uncertainties is based on the probability characteristics of uncertainties and achieve the maximum possibility through Monte Carlo simulation and scene reduction techniques. Then a deterministic or a random optimization method is utilized to obtain the optimal allocation of power [77], [79].

2) REAL-TIME OPTIMIZATION

Although day-ahead optimization can obtain the global optimum power scheduling, it is often not possible to achieve the expected result of the optimal results calculated by the day-ahead approach, because the actual values of the day could be different from the predicted values (i.e., unavoidable prediction errors). In practice, the varied and strong related uncertainties of DERs complicate the design of the energy management in microgrids. More and more researches tend to optimize the real-time scheduling to reduce the complicated impact of such uncertainties [7], [9], [10], [15], [24], [25], [59], [69], [72], [74]–[76], [80]. The real-time optimization in IMMGs should simultaneously schedule their external traded power among the main grid and the MGs, and achieve optimal option of the internal devices at the same time [2].

Although there are several disadvantages for off-line optimization, it still has an auxiliary effect on online optimization in the distributed network of IMMGs. First, the results of offline optimization can be used to test the convergence of online optimization algorithms [7]. Second, when the energy interaction between interconnected microgrids is coupled and the objectives can be decomposed, the offline optimization model can be decomposed into independent microgrid energy optimization subproblems, and distributed optimization algorithms can be developed to solve energy optimization problems of microgrids in parallel with reduced computational complexity [7], [15], [18], [40].

C. SCHEDULING OPTIMIZATION STRUCTURE

1) CENTRALIZED ENERGY MANAGEMENT

The centralized controller in IMMGs gathers detailed global information from every individual MG as well as the market information, and then makes decisions by executing an optimization algorithms [13], [32], [64], [71]. In this method, coordination can be satisfied, but it implies higher communication and computation requirements. Besides, for the sake of privacy, users may be unwilling to expose their key information to others, which, however, is required in this model [69]. Furthermore, the entire IMMG relies on the proper operation of the central controller, which becomes a single point of failure, and there is a lack of autonomous optimization [25], [36], [78]. Due to these reasons, centralized energy management policies are not very popular in IMMGs.

2) DISTRIBUTED ENERGY MANAGEMENT

Different from centralized energy management in IMMGs, a distributed method can achieve optimal energy distribution in IMMGs by individual decisions at each MG, which may incur less exchanged information and have a lower computational complexity [9], [20], [24], [31], [31], [40], [58], [63], [71], [81]. Multi-agent systems (MAS) is a common distributed approach used for optimizing energy scheduling [31], [63], MAS is particularly suitable for large-scale systems involving various types of interacting system participants [82]. For more about the application of this method in the IMMG, interested authors are referred to a recent work [52], [82]. Some other widely adopted strategies include hierarchical decision, game theory, alternating direction method of multipliers, consensus algorithm, heuristic algorithms, and so on [9], [20], [24], [31], [58], [63], [71], [81]. In fact, distributed energy management policies are more popular than centralized ones in IMMGs. Therefore, we provide a more detailed review of distributed approaches in Section V.

V. DISTRIBUTED OPTIMIZATION EMS IN IMMGS

As the distributed networks shown in Section III (i.e., Fig. 1 to Fig. 3), the MGs and the main grid are physically connected, the scheduling and operation of one entity will affect that of the others. The interactions among them include energy trading, sharing, and competition. To pursue autonomous energy management, a distributed energy management system for coordinated operation of the networked microgirds (MGs) is of critical importance [7], [18], [20], [23], [24], [26], [35], [40], [51], [61], [62], [65], [70], [73], [78], [83]–[92]. We discuss the main techniques used in the literature for distributed optimization EMS in this section.

A. DUAL DECOMPOSITION

Dual Decomposition is a widely used optimization method, which is suitable to the situation that the DSO and MG are owned by different entities and/or need to schedule renewable and non-renewable DGs based on their own objectives and constraints and policies [40]. Furthermore, in order to safeguard the users' private information and keep the system operation secure, only limited information sharing should be allowed between the DSO and MGs, while the optimal scheduling using the dual decomposition technique can meet such requirements [7], [15], [18], [40]. Moreover, for such multi-entity, distributed systems, dual decomposition enables distributed and parallel processing for the optimal energy management problem.

During operation, the cost of an individual MG consists of both the operation costs of MG-owned DGs and the cost of buying electricity from adjacent microgrids and from the main grid. Similarly, the revenue of an MG results from selling electricity to neighboring MGs and the main grid. Therefore, energy trading of the MGs is coupled in variables and/or constraints. When the objectives are separable, constraints are coupled, and the problem is convex. The dual decomposition algorithm can be adopted to decouple the energy exchange in the trading under limited, minimal information. Generally, the coupled mathematical model of energy trading can be formulated as

$$\min: \quad \sum_{n=1}^{N}\sum_{t=1}^{T} f_n(p_{n,g}^t) + g_n(x_n^t) + h_n(p_{n,m}^t) \tag{1}$$

s.t.:

$$p_{n,g}^t + p_{n,m}^t = p_{n,d}^t, \ \forall n \in \mathcal{N},\ m \in \mathcal{M},\ t \in \mathcal{T} \tag{2}$$

$$p_{n,g}^{min} \le p_{n,g}^t \le p_{n,g}^{max}, \ \forall n \in \mathcal{N},\ t \in \mathcal{T} \tag{3}$$

$$p_{n,m}^{min} \le p_{n,m}^t \le p_{n,m}^{max}, \ \forall n \in \mathcal{N},\ m \in \mathcal{M}, t \in \mathcal{T} \tag{4}$$

$$P_{cap}^{min} \le \sum_{n=1}^{N} p_{n,m}^t \le P_{cap}^{max}, \ \forall n \in \mathcal{N},\ m \in \mathcal{M},\ t \in \mathcal{T} \tag{5}$$

$$x_n^{min} \le x_n^t \le x_n^{max}, \ \forall n \in \mathcal{N},\ t \in \mathcal{T}, \tag{6}$$

where $\mathcal{N}$ and N are the set and the total number of MGs in the system, respectively; $\mathcal{M}$ denotes the set of the MGs that exchange energy with MG m, $m \in \mathcal{N}$ [18], [24]; f_n is the cost produced by MG n's own power generation [24], [61], [62], mostly, it is a polynomial function; g_n represents the cost caused by other variables in MG n, such as the transmission cost, the construction cost, and the cost caused by consumer's discomfort, and so on [24], [83], [84]; h_n is the fee caused by trading energy with the main grid and other MGs [24], [40]; $p_{n,g}$ stands for the energy power generation yielded by MG n; $p_{n,m}$ symbolizes the energy exchanged between MG n and MG m; x_n implies the other variables, such as voltage, temperature, decision variable, and so on [40], [80], [83]–[85]; P_{cap}^{max} and P_{cap}^{mix} are the upper and lower bounds of the electricity exchange capacity, respectively [84].

The coupled variables in problem (1) for the IMMGs can be the exchanged energy power [24], [84], heating/cooling and gas usage [9], the time in the expected objective [61] or constraints [62]. The coupled relationship in the objectives and/or constrains makes the optimal scheduling problem highly complicated. Mostly, on the assumption that problem (1) is convex, and according to the duality theory, problem (1) can be rewritten in the form of a Lagrangian function or an augmented Lagrangian function to relax the coupling in constraints [24], [40], [62], [84]. If the energy distribution problem includes both coupling variable and coupling constraints, hierarchical primal/dual decomposition is employed. The centralized scheme is then transformed to N subproblems. And the dual variables are regarded as shadow price updated by the master problem. Based on the given dual variables, each subproblem, which denotes the optimal scheduling problem for every individual MG, can be solved autonomously with its own objective and constrains [15], [18], [24], [40], [62], [80], [84]. Then these separable subproblems can be optimized in parallel with a much reduced computational burden.

With the above analysis, the information of all the MGs that must be shared, is only the shadow price of each MG. Thus this algorithm is sufficient for the stringent requirement on users' privacy and the strong demand on autonomous interconnected MGs scenario.

B. GAME THEORY

In the IMMGs system, the operation cost of the entire network can be reduced by cooperation, while each MG aims to maximize its own profit. There exist interests and conflicts among multiple MGs when sharing the surplus renewable energy [63]. According to their own capabilities and the information they have, it is a challenge how to make decisions that are beneficial to themselves or groups in such a competition. To this end, game theory provides a powerful tool to achieve the cooperative power control strategies in the network of interconnected MGs. Researchers often use cooperative and non-cooperative game theory to solve the above problem under different settings [20], [21], [23], [26], [65], [70], [72], [73], [78], [86]–[88].

In the IMMG, cooperative game theory is usually used to allow each MG to gain a more noticeable benefit than it operates alone without cooperation, under proper control methods in a cooperative structure. In addition, for evident additional benefits that can be gained by this cooperation structure, various coalitional game theory-based algorithms have been proposed to achieve additional benefits for the MGs with diverse requirements [23], [70], [87].

In [23], [70], a Nash bargaining based incentive mechanism is proposed for fair and effective energy trading among multiple interconnected MGs. For distribution of cooperative benefits in the MGs, a Nash bargaining problem for energy trading can be formulated as a product of performance improvements of all the MGs, under constraints on the energy exchange with the main grid and other MGs. With this strategy, the objective function is given by

$$\max : \prod_{m \in \mathcal{M}} \left[u_m^* - \left(f_{m,g} + \sum_{k \in \mathcal{K}_m} f_{m,u}^k + f_{m,s} + f_{m,e} \right) \right], \quad (7)$$

where $\mathcal{M} \subseteq \mathcal{N}$ is the set of MGs that are willing to trade energy with each other. Equation (7) denotes the additional benefits due to cooperation. The objective function has two main parts. The first part u_m^* denotes the minimum cost that MG m can achieve without trading energy with other MGs. The second part is used to present the overall cost when MG m participates in energy trading, where $f_{m,g}$, $f_{m,u}^k$, $f_{m,s}$, and $f_{m,e}$ are the cost of purchasing power from the main grid, users' discomfort cost, the energy storage operation cost, and the payment to other MGs, respectively. The detailed explanation of these parameters can be found in [23], [70]. In addition, $\mathcal{K}_m$ is the set of users in MG m. The difference in the square brackets corresponds to the cost reduction of MG m. From (7), it can be seen that the Nash product can guarantee that the benefits of cooperation are shared by each MG in a fair manner.

Similarly, the coalitional game theory is applied to optimize the sharing and trading of renewable energy in smart interconnected households in [87], and to reducing the total cost of MGs in [91]. In this method, the worth (or revenue) of the coalition, defined as the amount of cost savings achieved by the coalitional group, should be distributed among all the members of the coalitional group using a fairness rule. For example, authors can choose Shapley value as the fairness indicator during profit distribution, and the worth of the coalition is distributed among the players according to the average marginal contribution that each player is bringing to the coalitional game and to the cost savings. This way, the greater the contribution of any MG i in alliance cooperation, the more benefit it will have. The payoff assigned to each player is given in Eqn. (21) in [87].

For the non-cooperative game theory, there is no binding agreement between the participants. And the distinguishing feature of this strategy is that there are multiple decision-making bodies, each of which attempts to maximize its own benefits [20], [21], [26], [65], [73], [78]. In [26], [65], [73], [78], Nash Equilibrium (NE) is adopted to handle the competition among buyer MGs, for every MG with a different energy demand in the IMMG. Nash equilibrium is applicable to the situation where all the MGs in the IMMG participate in energy interaction and sharing equally and simultaneously, and there is no difference between them.

In order to achieve fair energy sharing among MGs, each buyer MG follows the Nash equilibrium strategy based on its priority factor. This way, every buyer MG competes as much energy as possible from the local energy market via the energy market operator. Generally, the logarithmic function is adopted to measure the MG's satisfaction level, given by

$$U_n = \gamma_n^\alpha \cdot \log\left(1 + \frac{E_n}{S_n}\right), \quad n \in \mathcal{N}, \quad (8)$$

where the $\mathcal{N}$ is the set of participants, γ_n^α denotes the energy allocation parameter in IMMG, α represents the weight factor, E_n is the energy allocated to MG n in the system, and S_n is the strategy of MG n in this competition for energy sharing [26], [65], [73].

Then in order to get the optimal strategy for each buyer, the utility functions of all the participants in the IMMG is given by

$$U(S) = \arg\max_{\mathbf{E}} \left[\sum_{n \in \mathcal{N}} \gamma_n^\alpha \cdot \log\left(1 + \frac{E_n}{S_n}\right) \right] \quad (9)$$

$$\text{s.t.: } 0 \le E_n \le S_n, \ \forall n \in \mathcal{N} \quad (10)$$

$$\sum_{n \in \mathcal{N}} E_n \le E, \quad (11)$$

where $\mathbf{E}$ stands for the allocated energy vector with elements E_n, and E represents the total amount of energy that can be adjusted in the system. With this problem, the energy competition among the IMMG participants is formulated as a non-cooperative continuous strategic form of game

$$G = (S_n, U_n)_{n=1}^N, \quad (12)$$

where N is the total number of participants. Authors in [26], [73] prove the existence of the NE assuming that the utility function is continuous and quasi-concavity, and the strategic domain is convex. They also prove that only a unique NE exists in the proposed non-cooperative game among buyer MGs.

For the sake of fair energy allocation in IMMGs, the authors in [73] define a parameter γ_n^α as the consumer MG's contribution. In [26], [65], the parameter γ_n^α is used as a priority factor to allocate energy to individual buyer MGs. This priority factor consists of the contributions made by the MG in the past by selling its excess energy to neighboring MGs and the load demand in each buyer MG. In this mechanism, MGs are encouraged to trade energy among themselves in proportional to their past contributions and their local load demands. Furthermore, under this strategy, the amount of energy traded with the main grid can be reduced, thus effectively reducing the burden on the main grid.

In [17], [20], [21], [88], another well-known non-cooperative game theory, Stackelberg game is applied to the electrical market to adjust the energy trading among interconnected MGs. It is a typical two-level hierarchical distributed energy management solution. In [20], the seller MGs are defined as the leader player at the top level of the competition, and the buyer MGs as the followers in the game.

Energy is allocated to the buyers in proportion to their bids. In [17], the regional coordination control center is the leader and the village MGs are the followers. To promote the trading system, in [88], a consumer-side reward concept is introduced to procure energy in the Stackelberg game. In addition to the payoffs in all the MGs, power flow constraints and voltage angle regulations are also considered in [21], and a Stackelberg game-theoretic solution is proposed to realize distributed optimization that merely requires the information of voltage angles.

C. OTHER DECENTRALIZED STRATEGIES

Alternating direction method of multipliers (ADMM) is an algorithm that is intended to blend the decomposability of dual ascent with the superior convergence properties of the method of multipliers, which is well suited for distributed MGs [23], [51], [80], [89], [90], [92]. The authors in [51] provide an overview of ADMM for optimizing power flow in Section II-C. This algorithm is used in IMMGs to achieve online energy management that does not require forecast data to proceed in [80]. The authors in [92] leverage ADMM for realtime energy management fo IMMGs in data centers. The Lyapunov optimization technique is adopted to resolve the "time-coupling" constraints, and a variant of ADMM leads to a distributed implementation. In [23], ADMM is utilized to achieve a good convergence performance in reaching the optimal power schedule in networked MGs. ADMM is employed in [90] to solve the optimal power flow problem with a completely distributed solution.

In [29], a consensus algorithm is applied to allocate the desired power to support the requests of each MG in a distributed IMMG. The authors in [14] apply an interactive game matrix (IGM) to coordinate the power exchanges among multiple MGs, and between the distribution network and the MGs. Finally the problem is solved by a modified hierarchical genetic algorithm. Distributed adjustable robust optimal scheduling algorithm (DAROSA) is chosen to distributedly achieve the objective of minimizing the total cost, including the fuel cost of DGs, degradation cost of BESSs, net energy trading cost with the main grid, and energy transfer cost among the MGs [69].

VI. PROSPECT AND FUTURE TRENDS IN IMMGS

Considering the growing load demand all over the world and the high requirements on renewable resources across the globe, there is an increasing interest among researchers in studying the IMMGs to satisfy the demands in an economical, stable, and reliable manner. We briefly summarize the future trends on IMMG energy management research in the following.

- Distributed energy management schemes are highly suited for the IMMGs to achieve effective and efficient energy sharing in simple and autonomous ways. We envision such schemes will be the main focus of IMMG research in the near future.
- The spatial correlation of renewable power generation in a small geographical area, and the random arrivals and departures of electric vehicles in IMMGs introduce spatial-temporal uncertainties. Such uncertainties should be consider to improve the accuracy of system modeling, whether in real-time or stochastic models. The realization of energy sharing in this interrelated multivariate environment is still one of the important directions in the future research.
- Since the power-related (renewable resources, load demand) and market-related variables (electricity price) in IMMGs are random, online optimal algorithms are considered to have extensive prospects in energy scheduling. The focus of online algorithm research should be on reducing the computational complexity, achieving an excellent convergence performance between online and offline global results, and so on.
- The demands and interests from users and that from power supply companies are very different. Energy management in IMMGs should consider such differences and satisfy both users and power supply companies' requirements, while protecting their privacy. The optimal strategies developed for the system should achieve fair energy allocation.
- Most of the recently research is mainly focused on active trading and sharing in IMMGs. However, reactive power is also an indispensable part in IMMGs, and should be considered in energy management to improve the robustness and reliability of the entire system. When the active and reactive powers are regulated simultaneously, the optimal strategies should have a low complexity for effective managing and operating the system.

VII. CONCLUSION

This paper reviewed the state-of-the-art in energy management research for IMMGs. We first reviewed the commonly used topology structures of the IMMGs. We then discussed EMS in IMMGs, with regard to the mostly used optimization objectives, the operation timescales, and the scheduling optimization structures. We next focused on distributed optimization approaches for IMMGs, including dual decomposition, game theory, other decentralized strategies. We concluded this survey with a discussion of open problems and future directions.

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HUALEI ZOU (S'18) received the B.E. degree in electrical engineering and automation from the Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2008, and the M.E. degree in power electronics and power drives from Jiangsu University, Zhenjiang, China, in 2011. She is currently pursuing the Ph.D. degree with the Department of Electrical Engineering, NUAA. Her research interests include energy management in smart grid and microgrid, and optimization.

SHIWEN MAO (S'99–M'04–SM'09–F'19) received the Ph.D. degree in electrical and computer engineering from Polytechnic University (now New York University Tandon School of Engineering), Brooklyn, NY, USA.

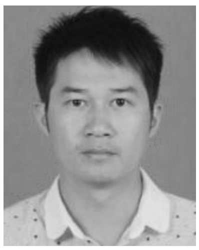
From 2012 to 2015, he was the McWane Associate Professor. He is currently the Samuel Ginn Distinguished Professor with the Department of Electrical and Computer Engineering and also the Director of the Wireless Engineering Research and Education Center, Auburn University, Auburn, AL, USA. His current research interests include wireless networks, multimedia communications, and smart grid.

Dr. Mao is a Distinguished Speaker, from 2018 to 2021 and was a Distinguished Lecturer, from 2014 to 2018 of the IEEE Vehicular Technology Society. He received the IEEE ComSoc TC-CSR Distinguished Technical Achievement Award, in 2019, the IEEE ComSoc MMTC Distinguished Service Award, in 2019, the Auburn University Creative Research & Scholarship Award, in 2018, the 2017 IEEE ComSoc ITC Outstanding Service Award, the 2015 IEEE ComSoc TC-CSR Distinguished Service Award, the 2013 IEEE ComSoc MMTC Outstanding Leadership Award, and the NSF CAREER Award, in 2010. He was a co-recipient of the IEEE ComSoc MMTC Best Journal Paper Award, in 2019, the IEEE ComSoc MMTC Best Conference Paper Award, in 2018, the Best Demo Award from the IEEE SECON 2017, the Best Paper Awards from the IEEE GLOBECOM 2016 and 2015, the IEEE WCNC 2015, and the IEEE ICC 2013, and the 2004 IEEE Communications Society Leonard G. Abraham Prize in the Field of Communications Systems. He is on the Editorial Board of the IEEE Transactions on Network Science and Engineering, the IEEE Transactions on Mobile Computing, the IEEE Transactions on Multimedia, the *IEEE Internet of Things Journal*, the IEEE Multimedia, the IEEE Networking Letters, and ACM GetMobile.

YU WANG (S'13–M'17) received the B.S. and M.S. degrees in instrument and meter engineering from Southeast University, Nanjing, China, in 2008 and 2011, respectively, and the Ph.D. degree in electrical and computer engineering from Auburn University, Auburn, AL, USA, in 2015. He is currently an Assistant Professor with the Department of Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing. His current research interests include smart grid, microgrid, renewable energy power forecasting, management, and optimization.

FANGHUA ZHANG received the B.S. degree in automation and electrical engineering from Jinan University, Jinan, China, in 1999, and the Ph.D. degree in electrical engineering from the Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2004. He joined the College of Automation Engineering, NUAA, in 2004, as a Lecturer, where he became an Associate Professor, in 2006. His current research interests include dc-to-dc converter, high-performance aeronautical static inverter for aerospace applications, and power electronic systems stability and power quality.

XIN CHEN (S'99–M'04) received the B.S. and Ph.D. degrees in electrical engineering from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 1996 and 2001, respectively. From 2001 to 2003, he was a Chief Engineer with the Power Division, ZTE Corporation. From 2010 to 2011, he was an Invited Researcher with the Rensselaer Polytechnic Institute, Troy, USA. He is currently an Associate Professor with the Nanjing University of Aeronautics and Astronautics. His current research interests include power electronic converters, distributed generation, and microgrids.



LONG CHENG (S'18) received the B.S. degree in automation from Tongling University, Tongling, China, in 2011, and the M.S. degree in detection technology and automatic equipment from Anhui University, Hefei, China, in 2015. He is currently pursuing the Ph.D. degree in power electronics and electric drives with the Nanjing University of Aeronautics and Astronautics, Nanjing, China. His current research interests include dc microgrid, bi-directional dc-to-dc converter, distributed control, and hybrid energy storage systems.