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Han, Yang; Zhang, Ke; Hong, Li; Coelho, Ernane A. A.; Guerrero, Josep M.

Published in:
I E E E Transactions on Power Electronics

DOI (link to publication from Publisher):
10.1109/TPEL.2017.2761438

Publication date:
2018

Document Version
Early version, also known as pre-print

Citation for published version (APA):
Han, Y., Zhang, K., Hong, L., Coelho, E. A. A., & Guerrero, J. M. (2018). MAS-based Distributed Coordinated Control and Optimization in Microgrid and Microgrid Clusters: A Comprehensive Overview. *I E E E Transactions on Power Electronics*, *33*(8), 6488-6508. https://doi.org/10.1109/TPEL.2017.2761438

MAS-based Distributed Coordinated Control and Optimization in Microgrid and Microgrid Clusters: A Comprehensive Overview

Yang Han, *Senior Member, IEEE*, Ke Zhang, Hong Li, Ernane A.A. Coelho, and Josep M. Guerrero, *Fellow, IEEE*

***Abstract*— The increasing integration of the distributed renewable energy sources highlights the requirement to design various control strategies for microgrids (MGs) and microgrid clusters (MGCs). The multi-agent system (MAS)-based distributed coordinated control strategies shows the benefits to balance the power and energy, stabilize voltage and frequency, achieve economic and coordinated operation among the MGs and MGCs. However, the complex and diverse combinations of distributed generations in multi-agent system increase the complexity of system control and operation. In order to design the optimized configuration and control strategy using MAS, the topology models and mathematic models such as the graph topology model, non-cooperative game model, the genetic algorithm and particle swarm optimization algorithm are summarized. The merits and drawbacks of these control methods are compared. Moreover, since the consensus is a vital problem in the complex dynamical systems, the distributed MAS-based consensus protocols are systematically reviewed. On the other hand, the communication delay issue, which is inevitable no matter in the low- or high-bandwidth communication networks, is crucial to maintain stability of the MGs and MGCs with fixed and random delays. Various control strategies to compensate the effect of communication delays have been reviewed, such as the neural network-based predictive control, the weighted average predictive control, the gain scheduling scheme and synchronization schemes based on the multi-timer model for the case of fixed communication delay, and the generalized predictive control, networked predictive control, model predictive control, smith predictor, H_∞-based control, sliding mode control for the random communication delay scenarios. Furthermore, various control methods have been summarized to describe switching topologies in MAS with different objectives, such as the plug-in or plug-out of distributed generations (DGs) in a MG, and the plug-in or plug-out of MGs in a MGC, and multi-agent-based energy coordination and the economic dispatch of the MGC. Finally, the future research directions of the multi-agent-based distributed coordinated control and optimization in MGs and MGCs are also presented.**

***Index Terms*—Microgrids, microgrid clusters, hierarchical control, multi-agent system, consensus, communication delay.**

NOMENCLATURE

Abbreviations

RES	Renewable energy sources
MG	Microgrid
MGC	Microgrid clusters
MAS	Multi-agent system
DG	Distributed generation
ESS	Energy storage system
BESS	Battery energy storage system
GPC	Generalized predictive control
Wi-Fi	Wireless fidelity
WiMAX	Worldwide interoperability for microwave access
MGCC	Microgrid central controller
EMS	Energy management system
PSO	Particle swarm optimization
NPC	Network predictive control
MPC	Model predictive controller
SP	Smith predictor
ULC	Upper-level control
ARE	Algebraic Riccati equation
QoS	Quality of the network service
MOA	Microgrid operation agent
MMA	Microgrid market agent
BA	Battery energy storage system agent
RA	Renewable distributed generators agent
SOA	Service oriented architecture
DA	Distributed generators agent

Variables

ω_{MG}	Frequency of output voltage
E_{MG}	Amplitude of output voltage
P	Active power
Q	Reactive power
m	Active droop coefficient
n	Reactive droop coefficient
$\Delta\omega/E$	Errors processed through the compensators
$\Delta\omega_S$	Synchronization term
x_i	DG$_i$ in a weighted graph model
a_{ij}	Edge lines between nodes
$r_i[t]$	Incremental cost of component i
a_i	Fuel cost coefficients in MAS
b_i	Fuel cost coefficients in MAS
ε	Step size of two level control of an agent
$P_{D,i}[t]$	Local estimation of the global supply-demand mismatch
d_{ij}	Communication coefficient
$u_i(k)$	Consensus protocol of agent i
$x_i(k)$	State of agent i
$\mathbf{K}$	Constant feedback gain matrix with suitable dimensions
$\tau(k)$	Time-varying delays
J_C	Cost function for discrete-time MAS
J_{Cx}	Consensus regulation performance of discrete-time MAS
J_{Cu}	Control energy consumption of discrete-time MAS
$\mathbf{Q_x}$	Symmetric matrices
$\mathbf{Q_u}$	Positive definite matrices
N	Number of agents
$p_i(t)$	Position of agent i
$ve_i(t)$	Velocity of agent i
b_i	Interconnection weight
$\bar{c}_{b,ij}$	Edge betweenness centrality between agents i and j
P_{ij}	Path from node i to node j

Manuscript received June 03, 2017; revised August 29, 2017; accepted October 04, 2017. Date of publication *******; date of current version *******. This work was supported by Sichuan Province Key Research and Development Project under grant No.2017GZ0347. Recommended for publication by Associate Editor *****.

Y. Han, K. Zhang and H. Li are with the Department of Power Electronics, School of Mechatronics Engineering, University of Electronic Science and Technology of China (UESTC), No.2006, Xiyuan Avenue, West Hi-Tech Zone, Chengdu 611731, China (e-mail: hanyang@uestc.edu.cn; 451532007@qq.com; Li_Hong01@126.com).

Ernane A.A. Coelho is with the Universidade Federal de Uberlandia, Uberlandia 38400-902, Brazil (ernane@ufu.br).

J. M. Guerrero is with Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark (e-mail: joz@et.aau.dk).

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Digital Object Identifier ******/TPEL.*******

	graph
$g_{kl}(p_{ij})$	Number of shortest paths which passes p_{ij}
v_i	Measured voltage at agent i
v_i^{avg}	Estimate of the average voltage provided by the estimator at agent i
v_j^{avg}	Estimation of voltage received from the agent j
G_c	Delay transfer function of *PI* controllers
G_p	Delay transfer function of MPC
$e^{-s\tau}$	Transfer function of communication delay
H	*PLL* transfer function
t_1	Command delay time of Smith predictor
t_2	Feedback delay time of Smith predictor
$\hat{G}_P$	Nominal system model without time delay
$u(k)$	Actuator input in gain scheduling method
$u_c(k)$	Output signal in gain scheduling method
$x(k)$	Sensor output in gain scheduling method
L_q	State feedback gain of the controller in gain scheduling method
M	Random number in gain scheduling method
C_{total}	Energy cost in MGC
C_{PV}	Cost of energy supply from photovoltaics
C_{MT}	Cost of energy supply form micro-turbines
C_{grid}	Cost of energy supply from electricity grid
$P_j^{grid}(k)$	Amount of power transferred from electricity grid to MG_j.
$C^{grid}(k)$	Electricity price of the electricity grid
$D_j(k)$	Total amount of power required by MGC
$P_{i,j}^{\max}$	Maximum power to be transferred from MG_i to MG_j

I. INTRODUCTION

During the last decades, the distributed generation (DG) technologies have been applied for grid-integration of the photovoltaic, wind power and other renewable energy sources (RES) [1, 2]. The distributed RESs, which are more scalable than the central power plants and can be used locally or flexibly connected to the power system [3], is gradually replacing the conventional generations and playing an important role in future smart grids [4, 5]. In order to coordinate the contradiction between the large power grid and DGs, and fully exploit the value and benefit of DGs, the concept of microgrid (MG) has emerged at the beginning of this century [6]. A MG is capable of operating in the grid-connected mode and islanded mode, and handling the transitions between these two operation modes. In the gird-connected mode, the power deficit of the local loads can be supplied by the main grid, and excess power generated in the MG can provide ancillary services with the network operator. In the islanded mode, the active and reactive power generated within the MG would be in balance with the demand of local loads to ensure system stability [7, 8].

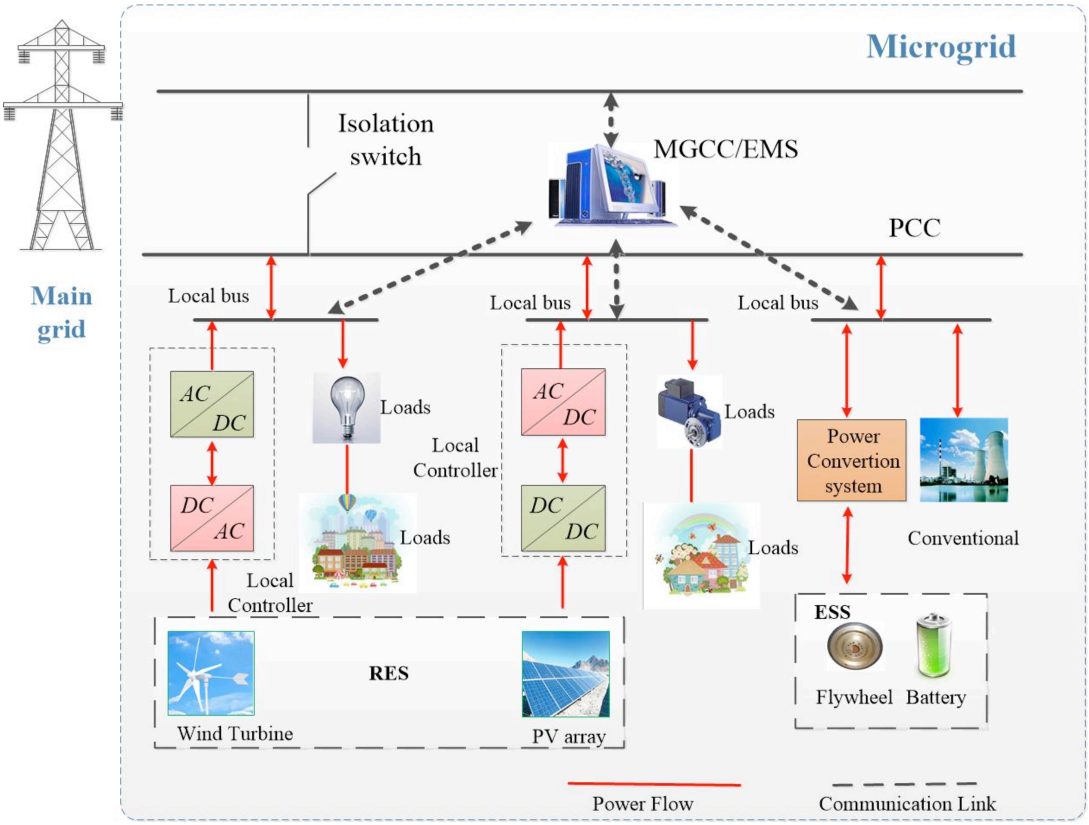


Fig.1 Microgrid structure [9-14, 17, 18].

A structure of MG, as shown in Fig. 1, is controlled by the microgrid central controller (MGCC) or the energy management system (EMS). A basic MG structure integrates RES [9, 10], traditional generators, loads and energy storage systems (ESS) [11, 12], thus forming a more flexible, self-sufficient and environmental friendly system than the individual DG units [13]. The RES, such as wind turbines or photovoltaic, through local controllers to send energy to the grid or communicate with the MGCC and energy management system (EMS). The emergence of the MG has fundamentally changed the conventional way of dealing with load growth [14]. It has numerous merits such as plug and play, reduced cost, and the enhanced power quality solved effectively, and the consequences due to accidents of the large-scale blackout can be avoided, thus the security, flexibility and reliability of the grid can be significantly improved [16].

Although the development of MG has become more and more consummate, there are still some challenges. Such as the lack of absorptive capacity for the large-scale renewable energy, especially under weak distribution network conditions. Meanwhile, the development of the electric vehicles and energy storage technologies has an urgent demand for smart microgrid technology [19]. The requirement for connecting the multiple MGs, enhancing stability, improving energy management, optimization and promoting the ancillary services has received

Microgrid clusters (MGC), which consist of multiple MGs, have received considerable attention recently [21-24]. The essence and goal of the MGC is to increase the penetration ratio of MG in the conventional distribution network, achieve the efficient and stable operation of the renewable energy, and friendly interaction with the grid [25]. As an efficient method to cope with the intermittence and randomness of renewable energy, the MGC have been discussed in [26]. A basic structure of MGC, which contains three MGs, is shown in Fig. 2. Each MG consists the battery energy storage systems (BESS), the controllable distributed generators, the renewable distributed generators and the electrical loads [27]. Moreover, the MGC can be utilized to cope with the distributed coordination issues, while guarantees the stable operation of the system.

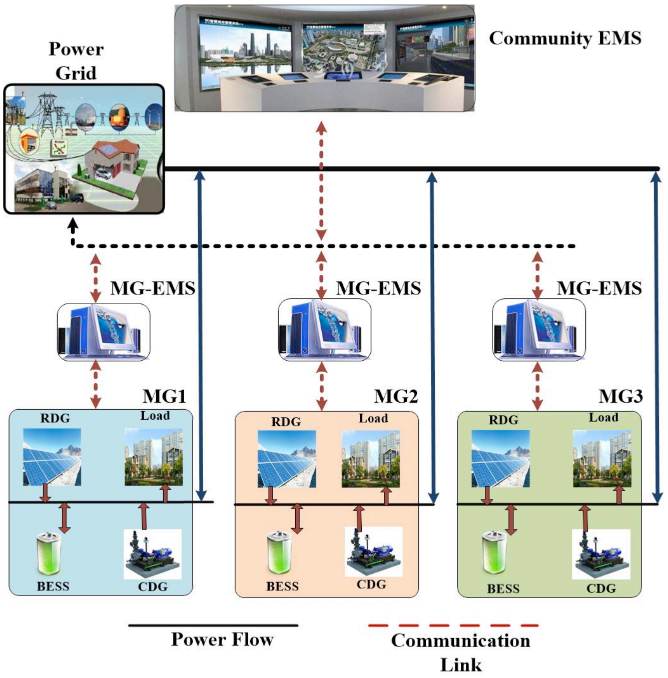


Fig.2 The structrue of microgrid cluster (MGC) [21, 25, 27].

As for the coordinated control strategies for the MGC, there are three main categories, i.e., the master-slave control [28-30], peer-to-peer control [31-33] and hierarchical control [34-36]. In the master-slave control strategy, one of the converters is known to be the master while the others are the slaves, there is a transfer of information between the master controller and the slave controllers [37]. The technical difficulty and risk of master-slave control is relatively low. However, in case of failure of the master controller, the whole MGC system cannot continue operating. Besides, the reliability of the MGC will be damaged if the system rely on master controller overly [38]. In [39], the peer-to-peer control is proposed for the plug and play MGC, which avoids the communication links and has a good expansion capability with a reduced cost. However, the system power will be oscillated and energy utilization would be decreased with the increasing number of RESs.

Notably, the master-slave control scheme is usually used in the islanded mode and the peer-to-peer control scheme is mainly used in the gird-connected mode. To solve the switching stability problem, a hierarchical control strategy is proposed [40]. Hierarchical control is the most commonly used method in MG and MGC, which is suitable for complex MG and MGC systems [41, 42].

Recently, the multi-agent system (MAS) in the hierarchical control, has been applied in MG and MGC [43]. Bidirectional information and energy interaction in the MGs can be achieved by using the distinct features of MAS, such as autonomy, communication and coordination. Moreover, combining MAS with the graph theory and dynamic consensus control to solve the problems of the hierarchical coordination control in MG and MGC is a promising approach. Distributed multi-agent control method has been widely used to establish optimal model to enhance reliability and energy management, optimization, and improve the performance of ancillary services [44]. Various methods for system modelling, including topology models and mathematic models, in MAS have been reviewed in this paper, such as the graph topology model [45-51], non-cooperative game model [52-54], genetic algorithm [55-57] and particle swarm optimization (PSO) [58-61], etc. Moreover, consensus protocol is the rule of interaction among multiple agents in the complex systems, which describes the process of information interaction among agents and their neighbors. The realization of consensus in MAS is one of the most important direction to achieve the coordinated control. In this paper, the MAS-based consensus control schemes are systematically reviewed [62-77].

The operation of MAS relies on the communication links, which inevitably causes delay-introduced stability problems. As the open communication infrastructures, Ethernet, worldwide interoperability for microwave access (WiMAX) and wireless fidelity (Wi-Fi) can be used for communication links of smart grid [78-81]. Each layer in hierarchical usually performs its own tasks independently, and interact with others via communication channels. However, the operation of different control layers has different time scales. In general, the operation time of primary layer, the secondary and tertiary level is in the time scale of microseconds, seconds and minutes [82]. The communication delay can vary from tens to several hundred milliseconds, the power control and measurement signals may be delayed or lost in the communication network. The multiple time-scale property of the hierarchical control causes communication delays among devices, or between equipment and upper control level [83]. It is worth mentioning that, delays are mainly divided into the fixed communication delays and random communication delays, and various delay compensation schemes for fixed communication delays are compared in this paper, such as the neural network predictive control [96], weighted average predictive control [97, 98], the gain scheduling [99-106] and synchronization schemes using multi-timer model [114]. Moreover, some compensation methods for random communication delays are also discussed, such as the generalized predictive control (GPC) [84, 85], networked predictive control (NPC) [86-89], model predictive control (MPC) [90-93], Smith predictor (SP) [90, 94, 95], H_∞ control [107-109] and sliding mode control [110-113], etc. In addition, if one microgrid plugs in or plug out from the microgrid clusters, the topology and structure of the system will be inevitably different. Due to the access of DG system, the study of the switching characteristics for the communication topologies in MAS is a critical problem to be solved [115-121].

The wide application of the multi-agent system has received much attention, and extensive discussions on the multi-agent systems have been presented. The overviews of the application of multi-agent system in power systems are proposed in [122, 123]. The distributed security of the multi-agent systems is presented in [124]. In [125], a review of multi-agent system is carried out along with the demand response and power system operation. In [126], a short review of several multi-agent systems is presented for grid energy management. In [127], the modeling methods, such as graph theory and stochastic matrices are introduced, and the consensus issue is discussed. However, this approach is mainly applied in the area of unmanned aerial vehicles, unmanned ground vehicles, and unmanned underwater vehicles. Moreover, some modelling methods, including Boids model, Vicsek model, Couzin-Levin model and various complex dynamical network models, are proposed in [128]. However, the comparison of advantages and disadvantages on these methods is missing. The reference [129] presents an overview of the very

Detailed introductions about the multi-agent system in many aspects are overviewed in these papers, including the modeling, consensus issues and applications. However, the discussion on MAS of the existing literature are still incomplete. In this paper, an elaborate analysis on the MAS-based distributed coordinated control and optimization is presented, which can be applied in the MGs and MGC, such as the modelling methods, consensus control, communication delays, switching topologies, energy coordination and economic dispatch issues.

The rest of this paper is organized as follows. Section II analyzes the conventional hierarchical control for MG and MGC. Furthermore, the MAS based distributed coordination control on MG and MGC is presented. Section III gives a survey on the model establishment, including topology models and mathematic models, and the MAS-based consensus control algorithms. Section IV generalizes the communication delay compensation schemes and the time-varying characteristics in the MAS. Section V emphasizes on the energy coordination and economic dispatch methods based on the MAS in MGC. Section VI presents the future trends of the MAS-based MG and MGC, and Section VII concludes this paper.

II. HIERARCHICAL CONTROL FRAMEWORK OF MICROGRID AND MICROGRID CLUSTERS

The power electronic converter in a microgrid (MG) has the characteristics of small inertia, fast response and low over-current capacity, which makes the operation and control of MG and MGC very different from the conventional power systems. Meanwhile, whether in the grid-connected mode or islanded mode, the operation of MG must achieve a balance between supply and demand to maintain the stability of voltage and frequency of the MG. Notably, MG is a complex multi-objective control system, which shows multiple time-scale property, deals with the issues of load power sharing, voltage/frequency and power quality regulation in different time scales. In order to cope with these issues properly, hierarchical control methods, as a frequently-used solution for the effective management of the distributed generators, have been widely recognized [18].

A. The Classical Hierarchical Control Strategies for Microgrid and Microgrid Clusters

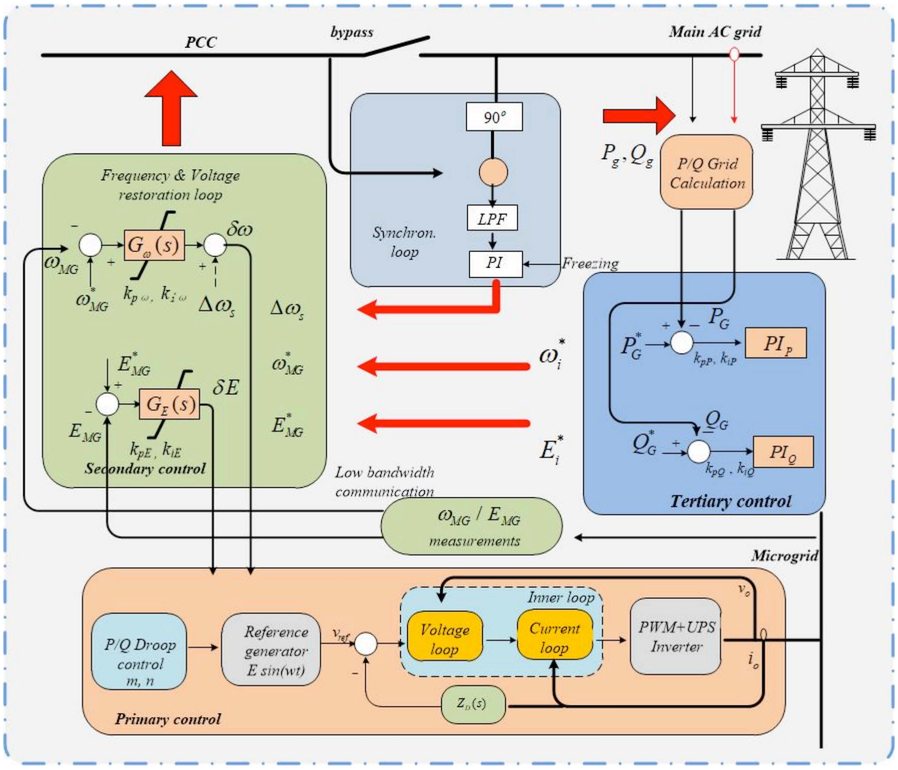


Fig.3. Block diagrams of the hierarchical control of MG [130, 134, 136, 140].

Fig. 3 shows the classical hierarchical control structure, which contains the primary, secondary and tertiary control. The primary control loop mainly adopts droop control, in order to regulate the local power, voltage and current, and avoid the voltage and frequency instability, and solve the problems of power sharing among the multiple DGs [18, 131]. This principle can be achieved by using the well-known *P/Q* droop method:

$$\omega_{MG}=\omega^* - m\cdot(P-P^*) \tag{1}$$

$$E_{MG}=E^* - n\cdot(Q-Q^*) \tag{2}$$

where ω_{MG} and E_{MG} are the frequency and amplitude of the output voltage reference, ω^* and E^* are reference frequency and voltage amplitude, P and Q are the active and reactive power, P^* and Q^* are active and reactive power references, m and n are the droop coefficients. The primary control can be used to balance the energy between the DG units and energy-storage elements.

The secondary control, which can be centralized [132-136] or decentralized [137-141], is used to eliminate the deviation of output voltage and frequency in the primary control. In case of an AC MG, the frequency and amplitude restoration controllers G_ω and G_E can be denoted as follows:

$$\delta\omega=k_{p\omega}(\omega^*_{MG}-\omega_{MG})+k_{i\omega}\int(\omega^*_{MG}-\omega_{MG})dt+\Delta\omega_s \tag{3}$$

$$\delta E=k_{pE}(E^*_{MG}-E_{MG})+k_{iE}\int(E^*_{MG}-E_{MG})dt \tag{4}$$

where $k_{p\omega,}$ $k_{i\omega,}$ k_{pE} and k_{iE} are the control parameters of the secondary control compensator and $\Delta\omega_S$ is a synchronization term which remains to be zero when the gird is not present. ω_{MG} and E_{MG} are sensed and compared with the references $\omega^*{}_{MG}$ and $E^*{}_{MG}$. The parameters $\delta\omega$ and δE are the errors processed through the compensators, which are sent to all the units to restore the output voltage frequency and amplitude. Normally, $\delta\omega$ and δE are limited in order not to exceed the maximum frequency and amplitude deviations [130].

In general, centralized control and decentralized control are two common methods in secondary control. For the centralized control, the biggest problem is the excessive dependence on MGCC, which causes a lot of challenges when the MGCC undergoes faulty conditions. Moreover, bidirectional communication architecture is needed in the centralized control architecture. The characteristics of these time delays can be constant, bounded, or random, depending on the inner mechanisms of the communication systems adopted. Furthermore, the sampling rates of the communication systems are very fast, in contrast, the data volume of the centralized control signals in secondary control is much lower [99]. There will always be communication delay issue, the measurement and control signals may be delayed or lost in the communication channels. Under this circumstance, the cost of the MG will be increased and the stability of system can be undermined [142].

Therefore, decentralized control strategy have been proposed to solve the problems in the centralized control [143]. The decentralized control does not rely on a MGCC and droop mechanism, so the error of a DG unit will not produce the failure of the entire system. Compared with the centralized control, these strategies have higher ability to tolerate the communication errors, and better plug-and-play performance, and can be easily extended to more DG units, which makes the system more scalable [144]. Nevertheless, there are still many problems that have not been effectively solved in the existing literatures. By using the decentralized control scheme, each DG controller needs to measure the information of voltage and frequency at PCC. Therefore, for a large capacity MG, it is necessary to use a high bandwidth bidirectional communication link. In some practical applications [145], the synchronization signals must be provided among all the DG units, which deteriorates system robustness. On the other hand, the frequency in MG is a global signal [90, 144], if different controllers try to regulate the grid frequency simultaneously, the system stability would be deteriorated.

The tertiary control can be applied for one or more MGs, and the operation status of MG can be optimized according to the economic dispatching rules [146]. What's more, tertiary control is the highest level in the MG control, long term optimal decision can be achieved according to the system status, market signal and demand forecast [147]. When the MG operates in the grid-connected mode, the power flow can be controlled by adjusting the frequency and amplitude of the voltage inside the MG. As can be seen in the tertiary control block diagram of Fig. 3, by measuring the *P/Q* through the static bypass switch, P_G and Q_G can be compared with the desired P^*_G and Q^*_G. The control laws can be expressed as:

$$\omega^*_{MG}=k_{pP}(P^*_G-P_G)+k_{iP}\int(P^*_G-P_G)dt \tag{5}$$

$$E^*_{MG}=k_{pQ}(Q^*_G-Q_G)+k_{iQ}\int(Q^*_G-Q_G)dt \tag{6}$$

where k_{pP}, k_{iP}, k_{pQ} and k_{iQ} are the control parameters of the tertiary control compensator. Depending on the sign of P^*_G and Q^*_G, the active and reactive power flows of the MG can be exported or imported independently [130].

By implementing the hierarchical control architecture, the electrical control, power quality regulation and economic operation control can be achieved simultaneously in different time scales, which is helpful to realize the standardization and improve the intelligence and flexibility of the MG [148]. In addition, the MGCC is used in hierarchical control to unify and coordinate all kinds of DGs and loads, and achieve safe and reliable operation of the multiple MGs. Power generation systems based on different technologies and power levels are interrelated in a MG. In this way, it is necessary to implement the hierarchical control scheme to reduce the operation cost, improve efficiency, achieve reliability and controllability [149].

B. *MAS-based Distributed Coordination Control of the Microgrid and Microgrid Clusters*

The performance of high intelligence, strong scalability, high redundancy and reliability adjustment of the voltage, frequency and power in MG cannot be realized by classical hierarchical control strategy. As an intelligent control method, multi-agent control method is gradually applied to the MG. The main idea of multi-agent control method is dividing the complex large-scale system into several subsystems, which have the features of autonomy and communicating with each other. An agent has several characteristics to be intelligent [150, 151]:

(a) Reactivity: Every agent is able to perceive and respond to the changes in the environment.

(b) Pro-activeness: Each agent does not perceive and respond to changes simply in their environment, but must have an ability to take the initiative.

(c) Social ability: An agent can use communication protocol for passing information or data with other agents, and it also has the ability to negotiate in compliant mode.

Coordinated operation of system can be achieved by using the multi-agent strategy through intelligent characteristics of the subsystems, thus information utilization and coordinated control in the distributed environment can be realized [152].

In recent literatures, the MAS has been widely used in MG and MGC. In [153], a decentralized secondary control for the MAS model is proposed to establish the appropriate rules under any kinds of communication networks. Hence, the output of voltage, frequency and power can be stabilized under the uncontrollable renewable energy resources conditions with the changing environment and load. A multi-agent strategy is proposed in [154] to achieve power sharing among distributed heterogeneous energy storage devices in MG. Meanwhile, a decentralized coordinated control strategy based on MAS is established in [155, 156], and a distributed automatic generation control method of MAS is designed in [157], which can solve the defects of droop control, restore the voltage and frequency, and achieve reactive power sharing among the DG units. A distributed MAS with frequency control scheme is presented in [158], each agent only communicates with the neighboring agents, by adopting the optimal average consensus strategy, all the information can be shared by the distributed control method. In [159], the MAS has been applied to the power management of the islanded MG.

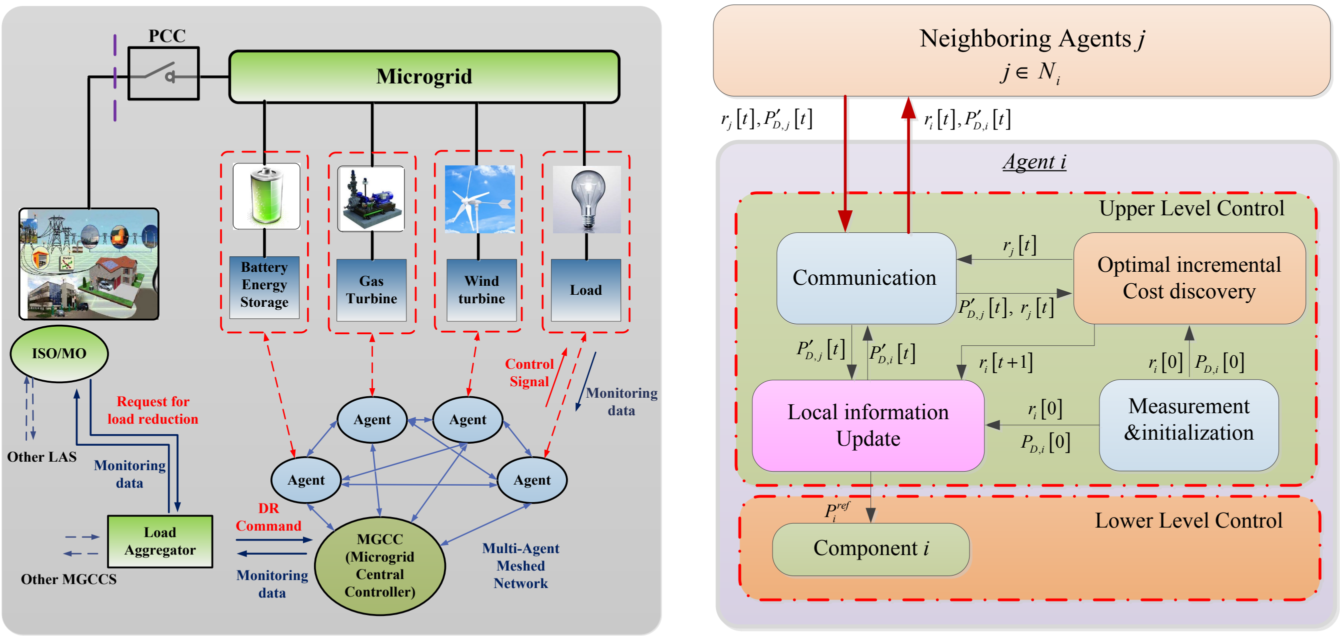
Fig. 4(a) shows the framework of the MAS-based MG. The various types of electrical equipment are authorized to agents such as the battery energy storage, gas turbine, wind turbine and loads. These agents are at the lowest level to monitor the status and control operations of these electrical devices. All of these agents can be coordinated by MGCC, when the load agent sends a command signal, the MGCC informs the related agents in the MG [160]. During the whole process, the communication and coordination are the most important factors and the whole decision-making process follows the contact net protocol [161]. Two level control block diagram of an agent is shown in Fig. 4(b). In the control block diagram of an agent, the upper level control (ULC) calculates the desired optimal incremental cost and determine the power reference of supply and demand.

The ULC block consists of four modules, including the local information updating module, communication module, optimal incremental cost discovery unit, measurement and initialization module. The local information updating module is responsible for updating the participant power reference according to (7) and (8):

$$r_i[t+1]=\sum_{j\in N_i} d_{ij}r_j[t]+\varepsilon\cdot P_{D,i}[t] \tag{7}$$

$$P_{D,i}[t+1]=\sum_{j\in N_i} d_{ij}P'_{D,j}[t] \tag{8}$$

where $r_i[t]$ is the incremental cost of the component *i* at iteration *t*, *ε* is the step-size that is adjusted to control the convergence speed, $P_{D,i}[t]$ is the local estimation of the global mismatch on supply and demand, and d_{ij} is the communication coefficient.



(a) (b)

Fig. 4 Multi-agent based structure and control diagram. (a) The framework of MAS architecture [160]. (b) Two level control diagram of an agent [162].

The communication module exchanges information, such as the incremental cost and local net power estimation, with its neighboring agents. What's more, the optimal incremental cost discovery module updates the data from (9) and (10):

$$P_i[t+1]=\frac{r_i[t+1]-b_i}{a_i} \tag{9}$$

$$P'_{D,i}[t]=P_{D,i}[t]+(P_i[t+1]-P_i[t]) \tag{10}$$

where nonnegative a_i and b_i are the fuel cost coefficients, $P_i[t]$ is used to represent the power of energy storage, generation supply, or load demand of the i_{th} participant.

The measurement and initialization unit, as shown in Fig. 4(b), measures the local generation/load conditions, initializes the local incremental cost and net power estimation as follows:

$$r_i[0]=a_iP_i[0]+b_i \tag{11}$$

$$P_{D,i}[0]=P_i[0] \tag{12}$$

where $r_i[0]$, $P_{D,i}[0]$ and $P_i[0]$ are the initial value of $r_i[t]$, $P_{D,i}[t]$ and $P_i[t]$, respectively.

The lower level control implements the power reference tracking of the associated components [162]. As mentioned earlier, an agent is assigned to each participant in the MG. Each agent obtains local generation and load conditions, updates local information, and exchanges with the neighboring agents. The supporting communication system can be designed to be independent of the network topology [163].

With the development of multi-agent theory, the cooperative problem in the distributed system can be solved, due to its autonomy among the multiple DG agents, the consensus control and bidirectional information and energy interaction between power grid and MGs [164, 165]. The complex and diverse combination modes among the DG units result in significant difficulties for the real-time control implementation of the MGC. Meanwhile, the complexity of system operation is remarkably increased [166]. In order to realize the optimal operation of MAS, an appropriate scheduling optimization model needs to be established, which is closely related to the architecture and operation mode of MGC [167].

III Modeling and Control Strategies for Distributed Multi-Agent System

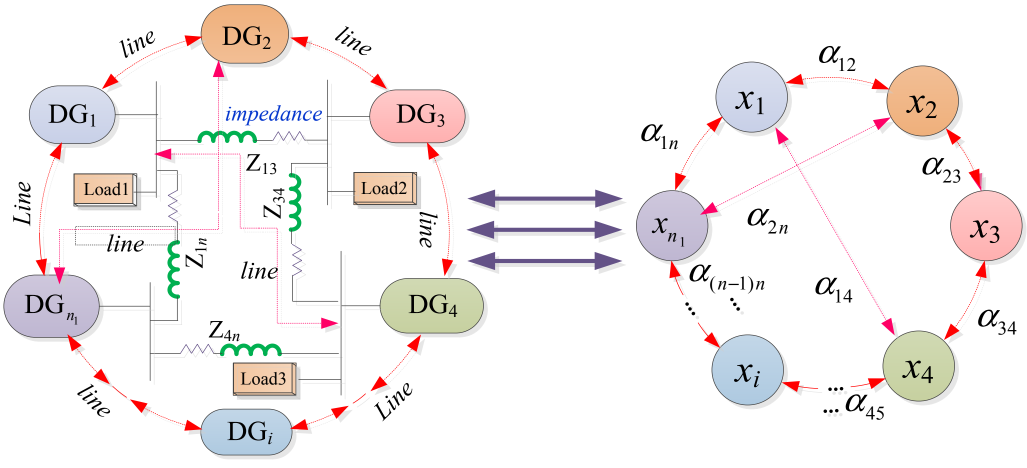
Since the complex and diverse combinations of distributed and also increase the complexity of system operation. In order to design the optimal configuration and control strategy using MAS approach, a suitable model, including topology models and mathematic models, needs to be designed. Meanwhile, the consensus is a vital problem in the complex dynamical systems, which means, as time goes on, the states of all agents can eventually reach the equal value. The realization of consensus in MAS is the most important way to achieve the coordinated control for MG system.

A. Modeling Methods for Distributed Multi-Agent System.

At present, the graph model is a widely accepted method in MAS-based topology modeling. In [45], a decentralized graph reconstruction scheme is presented to build a powerful MAS. A distributed non-periodic predictive control method based on the graph theory for MAS is designed in [46. 47], the model can simplify the number of nodes in the graph and generate a reduced order for the MAS. In [48-50], a model based on graph theory applied in MAS is established, which is the future trend of the large-scale MGCs owing to its high redundancy and easy expansion characteristics. In [51], a weighted graph model for DGs connected with actual communication links is devised, as shown in Fig. 5. The x_i represents DG$_i$, each x_i can be seen as an agent, and the edge line between nodes (a_{ij} corresponds to the bidirectional arrow dashed line) indicates that there is an interaction between two DGs. Z_{ij} represents the impedance between DGs. The advantages of this method is simple structure, high redundancy and easy expansion capabilities.

Therefore, in order to realize overall optimization of the MAS, a large amount of data communication is needed between the system states and the remote control inputs, which leads to the high cost of the communication networks [52]. Thus, under this circumstance, a non-cooperative game model based on the distributed energy system for coordinated operation in the MGC is presented in [53, 54], the optimal balanced state of each agent can be achieved. Moreover, the non-cooperative game model cannot be applied to the large-scale computing and simulation analysis scenario for the dynamic game process of the MGC.

Apart from the above methods, other mathematic models such as genetic algorithm and particle swarm optimization (PSO) algorithm have been proposed to apply to MAS. In [55-57], a genetic algorithm based on the distributed MAS is presented, speed of MAS can be improved by the genetic algorithm (GA). Moreover, the genetic algorithm is scalable and easy to be combined with other algorithms, and it can be compared with a number of agents synchronously. However, the control parameters of genetic algorithm are based on prior knowledge, and the genetic algorithm has a slow dynamic response and high computational burden. Dynamic scheduling model of the MGC with reliability and economic indicators is designed in [58], which is combined with PSO algorithm based on the Monte Carlo simulation. By adopting this method, the optimization scheduling scheme can be greatly improved under the uncertain environment in MGC. In [59], a PSO algorithm applied in MAS is presented, which improves the frequency and voltage of MG in islanded mode. Furthermore, a PSO algorithm for MAS is presented in [60, 61]. Each particle represents an agent, which shows the advantage of realizing the optimal state rapidly so as to share the information with the global agents. Although PSO algorithm avoids the disadvantages of the existing optimization methods, such as complex model and slow computation speed, the solution of the discrete optimization problems is challenging and PSO is easy to be trapped in a local optimum.



(a) (b)

Fig. 5 The physical connection graph of *N* distributed generators and the corresponding graph model of agents. (a). Physical connection diagram of *N* distributed generators; (b). Corresponding communication diagram of DG agent network [51].

Thus, the appropriate establishment of MAS model in MGC is the premise to coordinate control and analyze system stability. By using these methods, the friendly interaction between the MGC and grid, and completely absorption of new energy can be realized [168]. In order to analyze the merits and drawbacks for topology and mathematic models of the MAS comprehensively, various kinds of modeling methods for MGC are summarized in Table I.

TABLE I.
MERITS AND DRAWBACKS OF MAS-BASED MODELING METHODS IN MGC

Model and algorithm of MAS structure	**Merits**	**Drawbacks**
Graph theoretic topology model [45-51]	·Simple model structure ·High redundancy and easy to expand	·Robustness is greatly affected by graph
Non-cooperative dynamic game model [52-54]	·Each agent can achieve the optimal balanced state	·Algorithm is complex and time-consuming
Genetic algorithm [55-57]	·High prediction accuracy ·Fast convergence ·Scalability and parallelism operation	·Most of the parameters depend on experience ·Slow dynamic response
PSO algorithm [58-61]	·Simple model structure ·Fast computation speed ·Efficient economic scheduling ·Improve the frequency and voltage of MG	·Not handling the discrete optimization problems

To conclude, the graph model is topology model, however, the non-cooperative dynamic game model, genetic algorithm and PSO algorithm are mathematic models. It is well known that, due to the simple model structure and high redundancy, the graph model is a widely used topology modeling method for MAS. In addition, the energy coordination problem in MG and MGC can be solved effectively by genetic algorithm and PSO algorithm. Genetic algorithm is more suitable for solving the discrete mathematical problems and the PSO algorithm has the simpler rules compared with the genetic algorithm. As for the non-cooperative feature in interactive operation among multiple MGs, non-cooperative dynamic game model is widely adopted.

B. Control Strategies for Distributed Multi-Agent System

Consensus protocol is the rule of interaction among the multiple agents in the complex systems, which describes the process of information interaction among agents and their neighbors. In the last decades, the consensus of MAS has been widely discussed [169], such as consensus over network 172], optimal consensus [173, 174], sampled-data consensus [170, 175, 176], adaptive consensus [177], second-order consensus [178, 179, 180], consensus of generic linear agents [181, 182] and consensus with the multiple leaders [183]. In addition, a number of consensus algorithms have been proposed in [184], including the average-consensus, max-consensus and min-consensus.

In general, the consensus problems are usually handled by the distributed protocols [178]. In [62], a consensus protocol based on observer is proposed to isolate the abrupt adaptive coupling gain. A linear consensus protocol under communication delay is proposed to solve the problem of parameter uncertainty and time delay in MAS [63]. In this method, the consensus protocol is used for agent *i* as follows:

$$u_i(k)=\mathbf{K}\sum_{j\in N_i} a_{ij}(x_j(k-\tau(k))-x_i(k-\tau(k))) \tag{13}$$

where $u_i(k)$ and $x_i(k)$ are the consensus protocol and the state of agent *i*, respectively. **K** is a constant feedback gain matrix with suitable dimensions. $0\le\tau(k)$ represents the time varying delays

Let $\delta_{ij}(k) = x_j(k) - x_i(k)$ denote the state error between agents j and i. Define a cost function J_C for discrete-time MAS as follows:

$$J_C = J_{Cx} + J_{Cu} \tag{14}$$

$$J_{Cx} = \sum_{k=0}^{\infty}\sum_{i=1}^{N}\sum_{j=1}^{N} a_{ij}\delta_{ij}^{T}(k)\mathbf{Q_x}\delta_{ij}(k) \tag{15}$$

$$J_{Cu} = \sum_{k=0}^{\infty}\sum_{i=1}^{N} u_i^{T}(k)\mathbf{Q_u}u_i(k) \tag{16}$$

where J_{Cx} and J_{Cu} are the consensus regulation performance and control energy consumption of discrete-time MAS, respectively. $\mathbf{Q_x}$ and $\mathbf{Q_u}$ are symmetric and positive definite matrices. For a given feedback gain matrix $\mathbf{K}$, the discrete-time MAS would reach robustness guaranteed cost consensus in the event of any given bounded initial condition [63].

In [64], two kinds of consensus protocols are presented. One is the state feedback control, which assumes each agent has access to its own and its neighbors. Another is output feedback control, each agent measures its own position and the relative neighbor positions. In [65, 66], a MAS-based distributed control strategy is established to ensure the consensus, coordination of distributed agents and improve the frequency stability of the autonomous MG. A distributed output feedback control scheme based on state observer is presented in [67], which guarantees the consensus in MAS. Moreover, a state feedback control is designed to handle the consensus problem in MAS [68]. In [69], a weighted consensus protocol is applied to improve the robustness of the multi-agent system. The main idea is briefly reviewed herein. Let us consider the weighted consensus protocol constructed as follows:

$$\begin{aligned} u_i(t) = \sum_{j=1, j\neq i}^{N} \Big(\frac{\bar{c}_{b,ij}}{\sum_{k=1,k\neq i}^{N}\bar{c}_{b,ik}}\Big) a_{ij}(k)[p_j(t_k) - p_i(t_k) \\ + ve_j(t_k) - ve_i(t_k)] - b_i[(p_i(t) - p_o(t)) + ve_i(t) - ve_o(t)] \end{aligned} \tag{17}$$

$$\bar{c}_{b,ij} = \sum_{k=1}^{N}\sum_{l=1,l\neq k}^{N}\frac{g_{kl}(p_{ij})}{s_{kl}} \tag{18}$$

where N is the number of agents, $p_i(t)$, $ve_i(t)$ and $u_i(t)$ are the position, the velocity and the consensus protocol of agent i, respectively. a_{ij} and b_i are the interconnection weight, if agent i is connected to agent j so $a_{ij}>0$, otherwise $a_{ij}=0$. If the leader is connected to agent i so $b_i=1$, otherwise $b_i=0$. $\bar{c}_{b,ij}$ is the edge betweenness centrality between agents i and j. Here, p_{ij} denotes the path from node i to node j, s_{kl} is the number of shortest paths from node k to l in the graph, and $g_{kl}(p_{ij})$ is the number of these shortest paths which passes p_{ij}. The weighted consensus protocol is weighted by both the local information and the effect of the intermediary between each agent of edges [69].

However, most of the existing control protocols only adopts the present information to generate the distributed control laws, some researchers propose to use predictive control to predict the future actions of neighboring agents [70]. In [71-74], a model predictive control is presented to accelerate the convergence speed to realize dynamic consensus of the MAS. In [75], a distributed secondary voltage control strategy based on the dynamic consensus protocol is established. In this method, the distributed protocol at each agent is expressed as:

$$v_i^{avg}(t) = \sum_{j\in N_i} a_{ij}(v_j^{avg}(t) - v_i^{avg}(t)) + v_i(t) \tag{19}$$

where $v_i(t)$ is the measured voltage at agent i, $v_i^{avg}(t)$ is the estimate of the average voltage provided by the estimator from agent i, and $v_j^{avg}(t)$ is the estimation of voltage received from the neighbor agent j. The local voltage $v_i(t)$ is used in the estimation process, any voltage variation at any agent would affect the estimation accuracy at $v_i^{avg}(t)$ immediately. Each agent uses dynamic consensus protocol to estimate the average voltages

Moreover, a group consensus for multiple interacting clusters is investigated in [76], providing an analysis based on Lyapunov method, which is effective in specifying a sufficient condition in terms of structure and strength of the coupling that guarantees the group consensus. In [77], by developing tools from algebraic graph theory, matrix analysis as well as the Lyapunuv stability theory, a H_∞ group consensus is presented.

For the MG and MGC systems, the dynamic consensus protocols based on the distributed MAS have been extensively recognized. The voltage and frequency stability of each MG can be ensured, and active and reactive powers can be effectively regulated. Meanwhile, the power quality of the MG can also be improved under complex conditions, such as unbalanced line impedance, unbalanced and nonlinear load scenarios.

IV. ANALYSIS OF COMMUNICATION DELAY AND SWITCHING TOPOLOGIES OF MULTI-AGENT SYSTEM

The future development of MGC requires the support from the communication networks. However, there will always be communication delay issue, no matter in a low or high bandwidth communication network. Therefore, it is important to maintain the stability of MGC under the fixed delay and random delay scenarios. The open communication infrastructures, such as Ethernet, WiMAX and Wi-Fi networks can be used to realize the communications of smart grid gradually [78-82]. However, the measurement and control signals may be delayed or lost in the transmission channels. The communication delay is the main obstacle in the practical application of the hierarchical control. How to optimize the cost and increase the delay margin is a prominent research direction [185]. The development of the communication technology becomes more and more important under ever increasing demands on MAS in MG [186].

A. *Communication Mechanism of the Multi-Agent System in Microgrid*

Communication delay is the inherent characteristics of the actual MG system, which is ubiquitous in the process of data transmission. However, the existence of communication delay in the MG hinders the transmission of information among the different agents, also causes disturbance and instability [187]. A variety of protocols in MG system can be adopted to realize the efficient communication between power system and intelligent electronic devices.

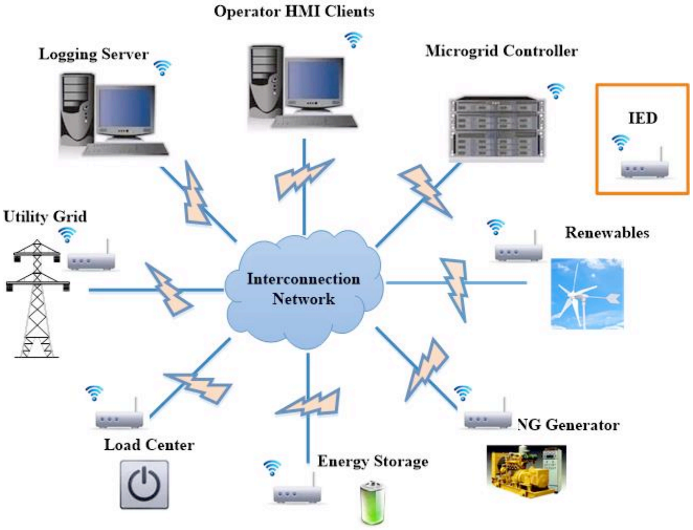


Fig. 6 The communication system architecture of a MG system [187].

Fig. 6 shows the architecture of the communication system in MG, the intelligent electronic devices (IED) acquire information from sensors, and sent the command signals to the distributed energy resources (DER), the energy storage devices, the loads and interconnection switches. Man machine interface (HMI) is used for monitoring and control, logging server and records system data regularly. IED receives data from the DER and sends it back to the microcontroller as a feedback signal. The collected data, including the voltage, frequency, active and reactive power control signals are transmitted to the IED through the MG controller, then IED sends the control signals to the loads and distributed generators [188].

Due to the hierarchical and decentralized nature of the distributed energy systems, their stable operation relies on the communication links. The upper layer is required to provide the parameter information for the lower layer and receive the control signal from the upper layer, so as to carry out effective energy management and scheduling [189]. The delays may be constant or random [190], with the application of hierarchical control and consensus-based control in the MG system, the delay issue caused by the low bandwidth communication cannot be ignored [188, 191]. It is worth mentioning that, time delays are mainly divided into the fixed communication delays and random communication delays [85]. There are three kinds of fixed communication delays, one is the sending and processing delay, which depends on software and hardware performance of source equipment. The second is the receiving and processing delay, which depends on software and hardware performance of the destination equipment. The third is the transmission delay, which relies on the communication network bandwidth and the transmission distance. On the other hand, the random delay is mainly the waiting delay, which is determined by the protocol in MAS layer, connection type and network load. It's important to consider how to maintain MGC stability under the conditions of the fixed delays and random delays. This is also the main obstacle to apply the hierarchical control and MAS theory to solve the practical engineering problems [192].

B. Fixed Communication Delay

In order to mitigate the problems of the fixed communication delay, the predictive control methods have been widely applied. An adaptive networked control system based on neural network delay prediction scheme is presented in [96]. The delay model can be linearized, and the system robustness can be improved by adopting model reference adaptive control method. Furthermore, by adopting the weighted average predictive control, the system robustness under communication delay can be improved and convergence speed can be remarkably increased [97, 98].

On the other hand, in [114], multi-timer model, which unifies the time synchronization part and the embedded system part of the sensor networks, is established. Then two synchronization schemes based on this multi-timer model are proposed to avoid the effect of communication delay. One is an infinite-time event synchronization scheme, and another is a finite-time event synchronization scheme. Several examples are shown in [114], which shows that the schemes can reduce the costs and improve the network robustness while guarantees event synchronization. However, this scheme is rather complex, which cannot handle the random delay determined by the protocol in MAS layer.

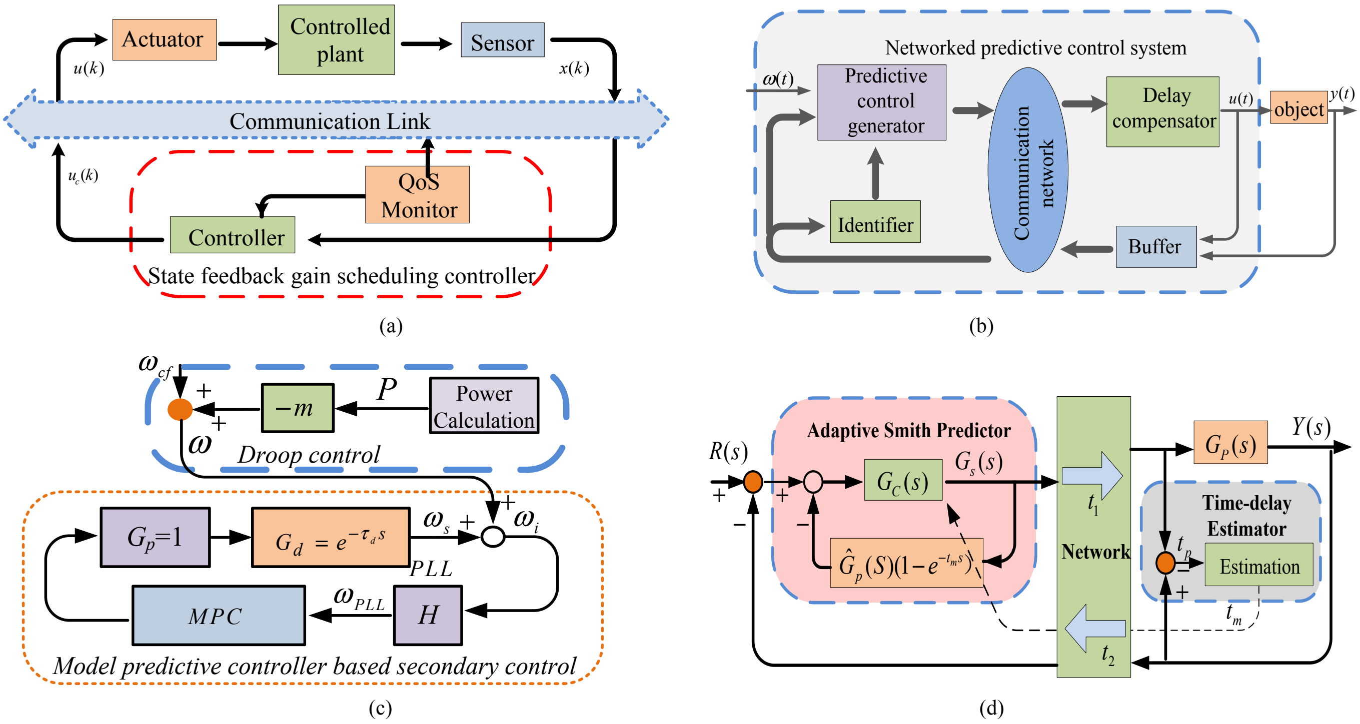

(a)
(b)
(c)
(d)

Fig. 7 The block diagrams of communication delay compensations. (a) The structure of network controller based on states feedback gain scheduling [98]. (b) The block diagram of networked predictive control (NPC). (c) The block diagram of model predictive control (MPC) [192]. (d) The block diagram of SP [89].

Gain scheduling method is widely adopted for the communication delay compensation. In [99], a gain scheduling method is presented to enhance the frequency delay margin by adding delay scheduling in the secondary control. Moreover, a gain scheduling controller is constructed to reduce the effect of the exogenous signal and compensate input delay [100]. In [101], a gain scheduling strategy is employed to improve the control performance of networked control system. In [102], the delay issue in MG is solved by designing the gain scheduling method. An algebra Riccati equation (ARE) method is adopted to design control gain in [103]. Moreover, a gain adaptive modification scheme is established in [104] to reduce the control gains without sacrificing the convergence speed of consensus algorithm. In [105], the gain and phase margin are considered for delay compensation.

Fig. 7(a) shows the control block of the gain scheduling controller, where the packet loss rate is used as a parameter of the network for its stability in a period of time [106]. The quality of the network service (QoS) is changing with time, hence the network status is monitored and can be estimated by the packet loss rate. The controller can schedule different control parameters based on the different QoS. If the packet sampled at the (k-N-1)th instant is effective, the input value affecting on the actuator in the kth instant can be denoted as:

$$u(k) = u_c(k-N-1) = -L_q x(k-N-1) \tag{20}$$

where $u(k)$ is the input of actuator, and $u_c(k)$ is the output of controller, $x(k)$ is the output of sensor. L_q is the state feedback gain of the controller. N can be any number in the natural numbers set. Delays can be compensated by the gain scheduling algorithm reasonably so as to realize the demands of the flexible access and interactive for the large-scale MGs and MGCs.

C. Random Communication Delay

For random communication delays, there are several methods to compensate, such as the generalized predictive control (GPC), networked predictive control (NPC), model predictive control (MPC), etc. The GPC has the benefit of great adaptability, low requirement on the model precision, strong robustness under the structure and parameter variations, and immunity under time delay. Under this circumstance, the GPC has been widely used in industrial process control [84]. A time delay compensation controller based on the GPC is proposed in [85], which is composed of a network predictor and the delay compensator, thus system performance can be improved by providing control parameters with random delay.

The networked predictive control (NPC), as shown in Fig. 7(b), combines the traditional predictive control scheme with the networked control system. NPC shows a strong robustness, which is independent of the model accuracy. Meanwhile, NPC breaks through the traditional control method with single data stream transmission control, which makes full utilization of the network characteristics such as transmission of vector data streams, and compensates the effects of communication delay or data loss. The effect of NPC is identical to the system without any communication delay. The NPC can be used to compensate communication delay, thus ensure system stability by using the distributed protocol, graph theory and matrix theory [86-88]. In [89], a NPC based on an improved GPC scheme is presented, where the delay compensator is designed to compensate the fixed and random communication delays, and the adverse effect of the communication delay is effectively eliminated. The model predictive controller (MPC), as shown in Fig. 7 (c), can be used to compensate the influence of the communication delays among the power devices in MGs or between the devices and upper level control, and reduce data loss [110-113]. When the control systems are decoupled, the characteristic equation of secondary control can be described as [192]:

$$1+e^{-s\tau} G_p G_c H = 0 \tag{21}$$

where H is the *PLL* transfer function. $e^{-s\tau}$ is the transfer function of communication delay. G_c is the delay transfer function of *PI* controllers and G_p is the delay transfer function of the system device to be controlled. Notably, the random delay can be handled by the MAS, which achieves a good robustness under large control delays. However, for the system with a large time constant, the calculation and execution of control algorithm will be huge and dynamic response of the system would be sluggish. The adaptive smith predictor (SP), as shown in Fig. 7(d), is established in [90, 94, 95] to avoid a wide range of time delays. The transfer function from input $R(s)$ to output $Y(s)$ can be denoted as follows:

$$\frac{Y(s)}{R(s)} = \frac{G_C(s)G_P(s)e^{-t_1 s}}{1+G_C(s)\hat{G}_P(s)-G_C(s)\hat{G}_P(s)e^{-t_m s}+G_C(s)G_P(s)e^{-t_p s}} \tag{22}$$

where $\hat{G}_P$ is the nominal model of the system without the delay time, and t_1 is the command delay time and t_2 the feedback delay time, $t_p=t_1+t_2$. The adaptive SP can deal with random delays and has a fast dynamic response. However, since the model of the SP is uncertain and has external disturbance, which would affect robustness of the system.

TABLE II.
MERITS AND DRAWBACKS OF COMMUNICATION DELAY COMPENSATIONS STRATEGIES

Communication delay compensations strategies		**Merits**	**Drawbacks**
` Predictive control method	Generalized predictive control [84, 85]	·Robustness under variable parameters, variable structure and time-varying delay scenarios. ·Can handle fixed delay and random delay ·Fast tracking speed ·Strong anti-interference ability	·Large computation burden ·High demand for mathematical model
	Networked predictive control [86-89]	·Can handle fixed and random delay ·Mathematical models free ·High robustness	·Influence of practical factors on prediction are not considered
	Model predictive control [90-93]	·Reduce data loss ·Good robustness at large delay error ·Can handle fixed and random delay	·Complex algorithm ·Large computation load ·Low dynamic response
	Smith predictor [90, 94, 95]	·Fast dynamic response ·Can handle fixed delay and random delay	·Model uncertainties and external disturbances are existed
	Neural network predictive control [96]	·Linearized ·High robustness	·Not handling random delay
	Weighted average predictive control [97, 98]	·Improve consensus convergence ·Fast tracking speed ·Strong anti-interference ability	·Influence of practical factors on prediction are not considered ·Not handling random delay
Gain scheduling method [99-106]		·Provide a general modeling approach ·Cost reduction ·Good power sharing performance in delay margin ·High robustness	·Gain coefficient and integral term are difficult to be selected ·Not handling random delay
H_∞ control method [107-109]		·Handle fixed and random delay	·Large computation ·Complex algorithm ·Low robustness
Sliding mode control [110-113]		·Simple implementation ·Handle fixed and random delay ·Fast dynamic response ·Robustness under parameter variation and disturbance	·Chattering exists
Synchronization schemes based on multi-timer model [114]		·Cost reduction ·High robustness	·Not handling random delay ·Complex algorithm

It is noteworthy that, many other compensation strategies for dealing with the random communication delay issues have been proposed. In [107], a H_∞ dynamic output feedback control is presented to handle random communication delays. In [108], a associate with communication delay and data loss. Moreover, a H_∞ state feedback control is proposed in [109] to improve the system stability with random delays. Nevertheless, H_∞ control method has a large amount of computation burden due to the

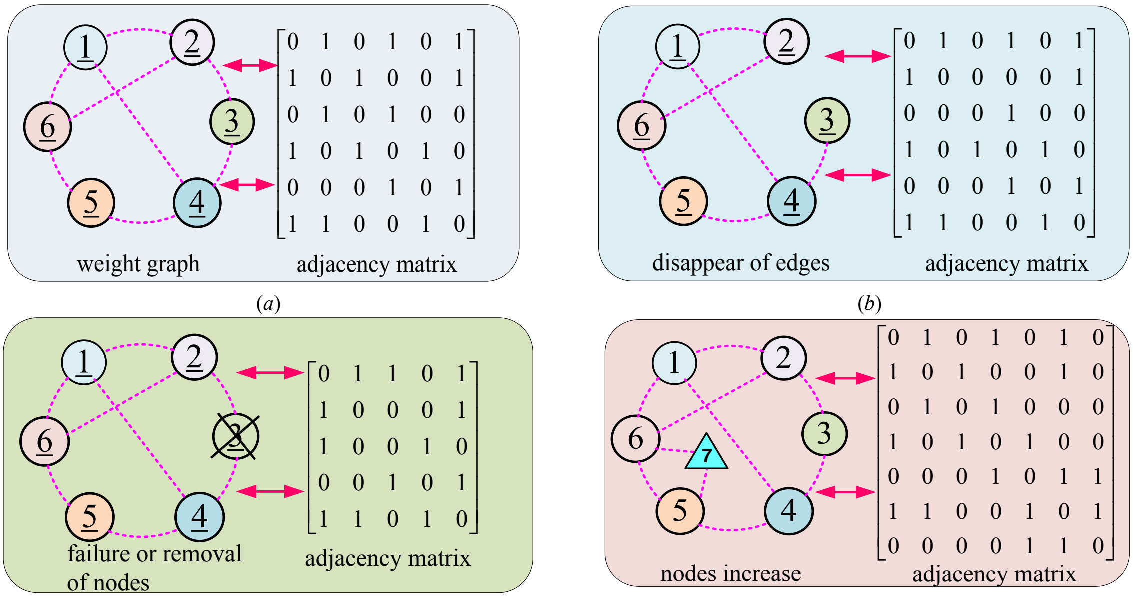
the state prediction and second order sliding mode control has been applied to tackle the random communication delay issues in MAS [110], which eliminates the influence of parameter uncertainties and the external disturbances. In [111, 112], a robust discrete sliding mode control is used to deal with the random communication delays in the discrete-time networked systems. In [113], a sliding mode observer (SMO) is designed to overcome the influence of random communication delay in the feedback loop. Although the sliding mode control method has several advantages such as simple implementation, fast response, and immunity under the random communication delay, it shows the inherent drawback of chattering.

From the aforementioned literatures, a number of research works with different optimization methods are systematically reviewed. A comprehensive comparison is conducted to show the merits and drawbacks of these methods implemented for dealing with communication delay issue, as shown in Table II.

D. Switching Topologies in Multi-Agent System

In practical applications, if one MG plugs in or plug out in MGC, the topology and structure of the MGC system will be inevitably different. Therefore, it is crucial to take into account influence of the switching topologies on the convergence of MAS [193]. Various control methods have been proposed to describe the switching topologies in MAS with different control objectives, including external random disturbance, parameter uncertainties, link failure or outage uncertainties [194, 195].

In order to describe the switching characteristics of the topologies in MAS, the graph theory is widely adopted to represent the communication topologies [115, 116], and the communication links among agents are bidirectional and weighted in a graph model [117]. Meanwhile, the Algebraic Riccati Equation (ARE) based on the graph theory is used to analyze the characteristics of the time-varying effects in the MAS [118, 119]. In [120], a distributed control method combined with a spanning tree using communication graph is applied to describe the time-varying communication topologies.



(*a*) (*b*) (*c*) (*d*)

Fig. 8 The diagram of time-varying topology characteristics and adjacency matrix in MAS. (a) Normal weight graph; (b) The condition of disappearing of graph edges; (c) The condition of failure and removal of graph nodes; (d) The condition of nodes increasing in MAS [121].

Fig. 8 shows the diagram of the time-varying topology characteristics and adjacency matrix in MAS. There are four kinds of topologies in the weighted graph. Fig. 8(a) is a normal weighted graph. Fig. 8(b) represents disconnection of network edges, namely, part of the communication links among agents breakdown. Fig. 8(c) indicates the failure or removal of nodes, which describes the phenomenon of the partial DGs failure or requirement of the temporary maintenance. Fig. 8(d) shows an increase of nodes, namely, part of the DGs are inserted into the MG, or recovery from failure to normal operation.

From Fig. 8, it can be deduced that, the insertion, excision and mode conversion can be equivalent to the change of an adjacency matrix in the MAS. When the topology of MG is constantly changing with the increasing penetration level of DGs, the stability of MGC can be ensured even if there are a large number of DG units and extensive communication links in MG and MGC.

It can be inferred from recent literature that, the study on characteristics for the time-varying communication in the MAS topology is still immature. Moreover, since the insertion, excision and mode conversion in MG systems are common problems encountered in the practical systems, it is necessary to implement further in-depth research on the time-varying characteristics in MAS.

V. OPTIMAL SCHEDULING METHODS FOR MAS-BASED MICROGRID CLUSTERS

In general, the hierarchical structure is normally adopted to coordinate the multiple DGs. Furthermore, the hierarchical structure is also needed to take into account the power allocation between MGC and main grid [196]. It is worth mentioning that, the energy scheduling and power management schemes based on the hierarchical control have been discussed in [197-201]. A self-organized and decentralized energy management strategy of the MGC is devised in [198]. And a unified dispatching and hierarchical energy management scheme is designed and evaluated to effectively optimize and manage the MGC [198-200]. In [201], a two-level optimization model for the coordinated energy managements in MGC is established.

Furthermore, the MAS-based hierarchical control structure has been extensively applied to control MGC recently in order to improve the operating efficiency, reduce costs and enhance system redundancy. During the last decades, a large number of MAS related research in MGC have been proposed [27, 202-207]. For instance, in [27], an energy management strategy based on MAS is established and applied in MGC. Each part is perceived as an autonomous agent, which can communicate easier for system management. Moreover, with the development of hierarchical control system, the burden of communication networks can be reduced and the operating cost can be reduced. In [202], a MAS for energy coordination in MGC is proposed. In [203], a MAS is used to handle the power balance of each MG, and the MGC participates in the operation of the upper network. A service oriented architecture (SOA) based on MAS is constructed to adapt to the changing operating environment of the MGC [204]. Besides, a MAS combined with a model-based optimization algorithm is designed in [205], which guarantees the balance of continuous power at the minimum cost in MGC. A multi-agent adaptive mechanism is applied in MGC [206, 207], which ensures that each DG agent has autonomous ability to execute the individual tasks.

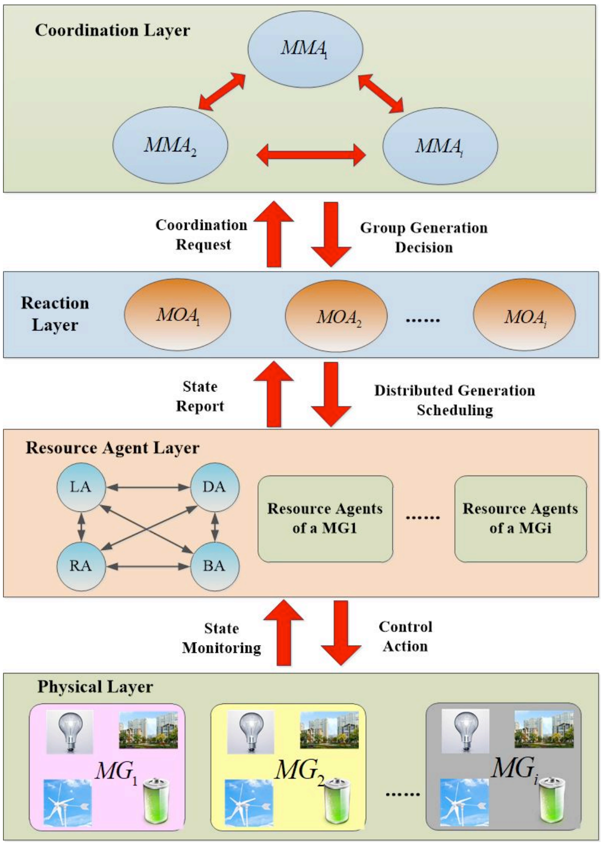


Fig. 9. Hierarchical framework of MAS in the MGC [206].

Fig. 9 shows the hierarchical framework of MAS in MGC, which contains four layers, and the electrical equipments of the MGs are located in the physical layer. The responsibility of resource agent layer is to monitor the resource states and perform control actions. In the reaction layer, when the MG operation agent (MOA) receives the predicted load demands and detects power deficit events, it activates the local agents to balance the load demands using optimized scheduling strategies. If the energy balance cannot be realized locally, the coordination layer is activated. The MG market agent (MMA) coordinates the neighboring MMAs to launch a negotiation process about purchasing energy from other MGs, which is dynamic and autonomous. Under the extreme circumstances, all the MGs will be involved to tackle the energy imbalance problem. After the negotiation process, all the coalition members reach an agreement on energy trading. The decisions will be forwarded to the reaction layer, and the MOA sends the control commands to the resource agent layer, where the load agent (LA), battery storage system agent (BA), renewable distributed generators agent agent (RA) and distributed agent (DA) are activated to perform control actions [206].

The main objective of the proposed hierarchical framework of MAS in MGC is to maintain the power balance for each time of the optimization is to minimize the energy cost as [205]:

$$C_{total} = C_{PV} + C_{MT} + C_{grid} \tag{23}$$

$$C_{PV} = \sum_{i=1}^{N}\sum_{j=1}^{N}[\Delta T \cdot P_{i,j}^{PV}(k) \cdot C_i^{PV}(k)] \tag{24}$$

$$C_{MT} = C_i^{MT}[\sum_{i=1}^{N}\sum_{j=1}^{N}\Delta T \cdot P_{i,j}^{MT}(k)] \tag{25}$$

$$C_{grid} = \sum_{j=1}^{N}[\Delta T \cdot P_j^{grid}(k) \cdot C^{grid}(k)] \tag{26}$$

subject to the following conditions:

$$\sum_{i=1}^{N}\sum_{j=1}^{N}[P_{i,j}^{PV}(k) + P_{i,j}^{MT}(k)] + \sum_{j=1}^{N}P_j^{grid}(k) = \sum_{j=1}^{N}D_j(k) \tag{27}$$

$$0 \le P_{i,j}^{PV}(k) + P_{i,j}^{MT}(k) \le P_{i,j}^{\max} \tag{28}$$

where C_{PV}, C_{MT} and C_{grid} are the cost of energy supply from photovoltaics, microsturbines and electricity grid respectively, N is the total number of MGs in the MGC system, and k is the index for different time interval. $P_{i,j}{}^{PV}(k)$ or $P_{i,j}{}^{MT}(k)$ are the total amount of power transferred from MG_i to the MG_j at time interval k, and $P_j{}^{grid}(k)$ is the amount of power transferred from electricity grid to MG_j at time interval k. $C_{grid}(k)$ is the electricity price of the grid at time interval k, $D_j(k)$ is the total amount of power required by the MGC system at the time interval k. $P_{i,j}{}^{max}$ is the maximum power that is allowed to be transferred from MG_i to MG_j due to transmission line power limit. The cost which is given in (23) is achieved by minimizing C_{PV}, C_{MT} and C_{grid}. Power balance (27) is to ensure that the sum of power transfer from each MG is able to meet the total load demand of MGC, and constraint (28) is to ensure that the power cable transmission limit of the line connection form MG_i to MG_j [205].

Furthermore, a market clearing price λ is the base unit price for maintaining power balance of the MGC system for energy trading, which is calculated based on the total power supplied and C_{total} as given by [205]:

$$\lambda = \frac{C_{total}}{\Delta T(\sum_{i=1}^{N}\sum_{j=1}^{N}[P_{i,j}^{PV}(k) + P_{i,j}^{MT}(k)] + \sum_{j=1}^{N}P_j^{grid}(k))} \tag{29}$$

In summary, analysis of the effects caused by time delay of MAS in MG and MGC has the following distinctive features:

(a) When a local error occurs in the control system, it can be isolated effectively by the hierarchical structure in MAS. The errors will be treated locally, so the MAS is easier to ensure the reliability of the whole system.

(b) It is easier to cope with the change and expansion of the local systems. Hence, the MAS has the flexibility to adapt to the expansion and development of the MG system.

(c) If there are too many levels of the hierarchical system, the time delays would affect the efficiency of the whole system.

(d) Each level of MAS-based hierarchical control strategies contains the autonomous unit for independent decision making, thus the dependence on the main control is reduced. Therefore, the reliability of MG and MGC can be remarkably improved.

VI. FUTURE TRENDS

Although the research on MAS-based MG and MGC control strategies have been discussed [208, 209], the interaction among sub-MGs, power allocation, voltage and frequency regulation in MGC still have a lot of problems that need to be resolved. The research on MAS model, communication delays and switching topologies is still lacking. At present, the research trend of MAS in MG and MGC mainly focus on the following aspects:

A. Impact of Communication Delay.

Communication delay is one of the inherent characteristics of the actual MG and MGC system, which is ubiquitous in the process of information transmission among different agents, and may cause system disturbance and instability [187]. However, the future development of the MG and MGC systems would inevitably require the support from the communication links.

Decreasing the cost and increasing the delay margin are essential research directions of MG and MGC in the future. Therefore, it's urgent to put forward an enhanced solution to maintain the stability of MG and MGC with fixed delay and random delay.

B. Switching Topologies in MG and MGC.

The research on the time-varying characteristics of the MAS topology is still lacking, nevertheless, the insertion, excision and mode conversion in MG are the common problems in practical applications. In order to understand communication topologies in MAS [210], the graph theory is introduced into mathematical modeling of MGC, which promotes the development of MGC, and would be the main research trend for designing optimized architecture and control scheme of MG and MGC in the future [211].

C. Energy Management and Economic Scheduling

Research on energy coordination and economic scheduling in MGC should not only consider their self-characteristics, but also the different interaction and influence among the multiple MGs. Although the issue of energy coordination and economic scheduling in MGC has been extensively discussed in recent literatures. The systematic design guidelines for the specific simulation model establishment and control strategy synthesis have not been fully explored.

To conclude, the properties of the MGC are complex multiple objective, multi-time scale, multi-constraint and high-dimension in nature, hence, the management schemes to obtain optimal operational modes is still one of important research directions in the future [212].

VII. CONCLUSION

This paper presents an overview of MAS-based distributed coordinated control method and optimization in MG and MGC. In order to improve the reliability, energy complementarity and management of MG and MGC, the topology and mathematic models of MAS are established, such as the graph model, non-cooperative game model, genetic algorithm, particle swarm optimization algorithm, etc. The merits and drawbacks of the MAS-based modeling methods in MGC and communication delay compensation strategies are also summarized.

Furthermore, the operation of hierarchical control and MAS relies on the communication links, which inevitably cause delay problem thus degrades system performance. Therefore, the communication delay compensation is of vital importance. The communication delay issue, which is inevitable no matter in the low- or high- bandwidth communication networks, is crucial to maintain the stability of MGs and MGCs with the fixed delays and random delays. Various control strategies to compensate the effect of communication delay have been reviewed, such as the neural network-based predictive control, weighted average predictive control, gain scheduling scheme and synchronization schemes based on multi-timer model for the case of fixed communication delay, and the generalized predictive control, networked predictive control, model predictive control, smith predictor, H_∞-based control, sliding mode control in case of random communication delay scenarios. In addition, since the plug-in or plug-out of the distributed generation system in MG and MGC might be randomly varying, and with a huge number of interactive information, thus the study of the time-varying characteristics for the switching topologies in MAS is a critical

Finally, due to the complicated operation modes of the MAS-based MGs, various methods on energy coordination and economic dispatch strategies for the MGC are systematically reviewed. In the existing literatures, only the description of the functions and communication framework have been studied, hence, the management schemes to obtain optimal operational modes are the important research directions for the MAS-based MG and MGC in the future.

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Yang Han (S'08-M'10-SM'17) received the Ph.D. in Electrical Engineering from Shanghai Jiaotong University (SJTU), Shanghai, China, in 2010. He joined the Department of Power Electronics, School of Mechatronics Engineering, University of Electronic Science and Technology of China (UESTC) in 2010, and has been an Associate Professor since 2013. From March 2014 to March 2015, he was a visiting scholar (guest postdoc) in the area of renewable energy and microgrids at the Department of Energy Technology, Aalborg University, Aalborg, Denmark. His research interests include AC/DC microgrids, grid-connected converters for renewable energy systems and DGs, phase-locked loop (PLL), power quality, active power filters and static synchronous compensators (STATCOMs).

He has authored more than 20 ISI-indexed journal papers and one book chapter in the area of power electronics, power quality conditioners, and smart grid. He has served as the Session Chair in "Microgrid Optimization and Scheduling" Session in the 2nd International Conference on Power and Renewable Energy (ICPRE) in Chengdu in 2017, and in "Power Quality Mitigation and Application" Session in the 5th National Conference on Power Quality in Xi'an in 2017, and in "AC/DC, DC/AC Power Converter" Session in the 2016 IPEMC ECCE-Asia in Hefei, China. He was awarded "Baekhyun Award" by the Korean Institute of Power Electronics (KIPE) in 2016. He received the Best Paper Awards from the 6th Asia International Symposium on Mechatronics in 2017, the 5th National Conference on Power Quality in 2017, the Annual Conference of HVDC and Power Electronics Committee of Chinese Society of Electrical Engineers (CSEE) in 2013, and the 4th International Conference on Power Quality in 2008. He has eighteen issued and ten pending patents.

Ke Zhang was born in Hubei province, China, in 1993. She received her B.S. degree in Electrical Engineering from Hubei University of Technology, Wuhan, China in 2015. She is currently working towards the M.S. degree in Power Electronics and Electric Drives at University of Electronic Science and Technology of China (UESTC), Chengdu, China. Her current research interests include the optimization of ac/dc microgrids, power management, hierarchical and cooperative control, multi-agent control and grid-integration of renewable energy resources.

Hong Li received the B.S. degree in Electrical Engineering and Automation from University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2015. He is currently working towards the M.S. degree in Power Electronics and Electric Drives at UESTC, Chengdu, China. His current research interests include the optimization of ac microgrids, power management, hierarchical and cooperative control, and grid-integration of renewable energy resources.

Ernane Antônio Alves Coelho received the B.S. degree in electrical engineering from the Federal University of Minas Gerais, Belo Horizonte, Brazil, the M.S. degree from the Federal University of Santa Catarina, Florianopolis, Brazil, and the Ph.D. degree from the Federal University of Minas Gerais in 1987, 1989, and 2000, respectively. In 1989, he joined the Electrical Engineering Faculty at Federal University of Uberlandia, where he is currently a Full Professor. His research interests are Power-factor Correction, PV and Fuel Cell Systems, Microgrid Modelling and Digital Control by microcontrollers and DSP's.

Josep M. Guerrero (S'01-M'04-SM'08-FM'15) received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics from the Technical University of Catalonia, Barcelona, in 1997, 2000 and 2003, respectively. Since 2011, he has been a Full Professor with the Department of Energy Technology, Aalborg University, Denmark, where he is responsible for the Microgrid Research Program. From 2012 he is a guest Professor at the Chinese Academy of Science and the Nanjing University of Aeronautics and Astronautics; from 2014 he is chair Professor in Shandong University; from 2015 he is a distinguished guest Professor in Hunan University; and from 2016 he is a visiting professor fellow at Aston University, UK.

His research interests are oriented to different microgrid aspects, including power electronics, distributed energy-storage systems, hierarchical and cooperative control, energy management systems, smart metering and the internet of things for AC/DC microgrid clusters and islanded minigrids; recently specially focused on maritime microgrids for electrical ships, vessels, ferries and seaports. Prof. Guerrero is an Associate Editor for the IEEE TRANSACTIONS ON POWER ELECTRONICS, the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, and the IEEE Industrial Electronics Magazine, and an Editor for the IEEE TRANSACTIONS on SMART GRID and IEEE TRANSACTIONS on ENERGY CONVERSION. He has been Guest Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS Special Issues: Power Electronics for Wind Energy Conversion and Power Electronics for Microgrids; the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS Special Sections: Uninterruptible Power Supplies systems, Renewable Energy Systems, Distributed Generation and Microgrids, and Industrial Applications and Implementation Issues of the Kalman Filter; the IEEE TRANSACTIONS on SMART GRID Special Issues: Smart DC Distribution Systems and Power Quality in Smart Grids; the IEEE TRANSACTIONS on ENERGY CONVERSION Special Issue on Energy Conversion in Next-generation Electric Ships. He was the chair of the Renewable Energy Systems Technical Committee of the IEEE Industrial Electronics Society. He received the best paper award of the IEEE Transactions on Energy Conversion for the period 2014-2015. In 2014 and 2015 he was awarded by Thomson Reuters as Highly Cited Researcher, and in 2015 he was elevated as IEEE Fellow for his contributions on "distributed power systems and microgrids."