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Agent-Based Decentralized Control Method for Islanded Microgrids

Qiang Li, Feixiong Chen, Minyou Chen, *Senior Member, IEEE*, Josep M. Guerrero, *Fellow, IEEE*,
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Abstract—In this paper, an agent-based decentralized control model for islanded microgrids is proposed, which consists of a two-layer control structure. The bottom layer is the electrical distribution microgrid, while the top layer is the communication network composed of agents. An agent is regarded as a local control processor together with communication devices, so agents can collect present states of distributed generators and loads, when communication lines are added between two layers. Moreover, each agent can also exchange information with its neighboring agents of the network. After information is processed according to control laws, agents adjust the production of distributed generators to which they connect. The main contributions of this paper are (i) an agent-based model for decentralized secondary control is introduced and the rules to establish the communication network are given; (ii) a systematic method is presented, which can be used to derive a set of control laws for agents from any given communication network, where only local information is needed. Furthermore, it has been seen that the output power supplied by distributed generators satisfies the load demand in the microgrid, when agents use the proposed control laws. Finally, the simulation results show that frequency and voltage fluctuations are small and meet the requirements.

Index Terms—Distributed control, multi-agent system (MAS), networked control systems, secondary control, microgrids, energy management.

I. INTRODUCTION

The increasing penetration of distributed generators (DGs) on the electrical supply grid, particularly with renewable sources, can meet future energy requirements [1] and can substantially reduce pollution and carbon emission. However, negative impacts on the grid may occur, such as poor power quality and voltage stability. To deal with those problems, the microgrid (MG) concept was introduced as a solution for the effective integration of DGs into the grid. An MG is a cluster of DGs, loads, energy storage systems and other equipment, which can operate in islanded mode or grid-connected mode, and can seamlessly transfer between these two modes [2], [3]. Generally speaking, islanding may occur in case of preplanned scheduling or unplanned disturbances. Moreover, the islanded

mode has found useful applications in a number of remote or rural areas and geographical islands, where the interconnection with a main grid is impossible or not feasible. Note that the control of islanded MGs is generally more demanding compared with grid-connected MGs, because of their low equivalent inertia. Moreover, the voltage and frequency of islanded MGs are no longer dominated by the main grid [3]. Fluctuating power outputs of intermittent DGs may lead to severe deviation in both frequency and voltage, if proper control strategies are not adopted [3].

In recent years, many researchers have focused on control schemes for MGs [4]–[10]. Among them, the hierarchical control seems a promising method [7], [11], [12]. The first level of the hierarchical approach is primary control, which operates local control loops of each DG in an MG by a local controller (LC) independently. The strategies adopted at this level are commonly droop control, active and reactive power control (PQ control) or voltage and frequency control (V/F control). Additionally, secondary control compensates the voltage and frequency deviations produced by the primary control. The secondary control of an MG can be (i) centralized or (ii) decentralized. The centralized control method requires all DGs to communicate with an MG central controller (MGCC) first, and control actions are then broadcasted back to each unit, being highly dependent on this central controller [12], [13]. Once failure of the central controller occurs, the MG may fail, which decreases the reliability of the system. Moreover, the computational burden of the central controller in the centralized control method is high and data sharing is not easy due to its complexity and cost, when the number of DGs in an MG reaches a certain level [12]. Alternatively, decentralized control with a spare communication network does not need a central controller and each unit is controlled by its local control system, which allows the control action to be simply based on local information rather than global information [9], [13], [14]. Thus, large quantities of information manipulated by the MGCC can be distributed among those local control systems that only need to communicate with their neighbors.

Motivated by the idea of decentralized control, researchers have presented several types of distributed control algorithms for MGs. For example, in [15], a decentralized secondary control for droop controlled MGs was proposed, where the impacts of communication system delay and data drop-out on MGs were also considered. On the other hand, to achieve feasible and near-optimal solutions, a Lagrangian relaxation based mechanism in a decentralized fashion was developed for the optimal active and reactive power coordination of

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MGs [16]. For the case of an MG working in islanded mode, Etemadi et al. [17], [18] demonstrated a power-management and decentralized control strategy, in which a new multi-variable decentralized robust servomechanism approach was employed to get the local control of each DG. In addition, cooperative control [19], [20] has also been applied to provide a dynamic and decentralized control mechanism for DGs in MGs [4]–[6], [21]. Xin et al. [4], [5] presented a cooperative control strategy to regulate the active and reactive power outputs of multiple photovoltaic (PV) generators. For the case that DGs were organized within several clusters first, cooperative control can also be used to operate DGs and realize the active power objective [6], [22]. After this, Maknouninejad et al. [23] proposed a cooperative control optimum design and applied it to the control of distributed generators in MGs.

More recently, multi-agent system (MAS) based methods have emerged in decentralized control, optimization and energy management for MGs. In 2005, Dimeas et al. [24] shed light on how an MAS might be used for the control of an MG. Later, further studies were carried out in order to find feasible and reliable control schemes based on the MAS concept. In [25], a decentralized MAS based frequency control strategy was investigated for an islanded MG, when agents were only allowed to exchange information locally. Bidram et al. [26] combined the cooperative control with an MAS and then developed a secondary voltage control for MGs. Later, they presented a distributed secondary control framework for an MG [27]. For the case of a system consisting of multi MGs, a distributed control approach was also studied, where each MG and each power line were treated as agents [28].

In this paper, an agent-based secondary control strategy for an islanded MG is proposed. The control approach is decentralized without an MGCC, in which a two-layer control structure is employed. The MG, called the bottom layer, is a power network, where power flows in the network. In contrast with it, there is a communication network composed of agents for secondary control, also known as the top layer, in which each agent collects the present states of a DG and a load to which it connects through the communication lines between two layers, and then exchanges the information with its neighboring agents. After all the information is processed according to control laws, agents adjust the output power of the DGs at the next time step in order to balance the supplies and demands in the MG.

Further, we formulate the rules for how a communication network is constructed. Once an MG is given, many communication networks may be built in terms of the rules, and apparently the control laws for agents on each communication network are different. Therefore, we present a systematic method to derive a set of control laws for agents from any given communication network, where only local information is needed. Furthermore, we prove a theorem that shows the output power supplied by DGs equals the load demand in the MG, if each agent applies the control law that is derived. To evaluate the performance of our control laws, four cases are designed, in which the illumination intensity, the wind speed or/and the load demand change over time. Finally, simulations are carried out in MATLAB/Simulink and the results show

that the frequency and the voltage satisfy the requirements, and the system remains stable, even in extreme conditions. Compared with a centralized control method, the proposed decentralized method only needs local information, which reduces the communication complexity.

The rest of the paper is organized as follows. In Section II, the two layer control model with an agent-based communication network is introduced in detail. Using the steps and rules given, one can construct an agent-based communication network as the top layer of the control model, and then derive the control laws for agents from the structure of the network according to the theorem that we prove. The structure of the MG and the parameters of DGs for simulations are introduced and listed, and then two sets of control laws are derived from two given communication networks in Section III. Later, four cases are designed and studied in Section IV, where the performance of the control laws is evaluated and the simulation results are analyzed and discussed. Section V concludes the paper.

II. CONTROL MODEL FOR MGs

This Section introduces the two layer control model for MGs, where the electrical structure of the MG and the LCs of units conform the bottom layer, while the agents and the communication network encompass the top layer. After the MG is given, the design rules for the communication network are presented first. Further, a theorem is proved, which provides the formulation to find the control laws for agents according to the structure of the constructed communication network.

A. Topology of a communication network

The communication network is assembled by adding communication devices and processors. Note that the communication network and the electrical network do not have necessarily the same structure (see Fig. 1). If the communication devices together with local control processors are considered as agents and communication lines as edges, the communication network is also a graph according to the definition of a graph in graph theory, where there are no leaders or central agents in the network. Therefore, in the rest of the paper, when the term “communication network” is used, it denotes the graph or the network of agents $G(V, E)$, where V is the set of agents (nodes), E is the set of edges, as shown in Fig. 1.

Additionally, one can notice that there also exist some edges between two layers and each agent in the network connects to a DG and a load through these edges. Thus, the present states of the DG and the load, such as the output power of the DG and the load demand, can be collected by the agent. Besides, each agent communicates with its neighboring agents on the top layer, where the arrows on the solid lines and the dashed lines indicate the information transfer direction.

In an MG, the DGs, such as photovoltaic (PV) systems or wind turbines (WTs), are regarded as *uncontrollable* DGs, because their output power is largely influenced by the environment. On the contrary, other DGs, such as microturbines and small hydropower systems, are regarded as *controllable*

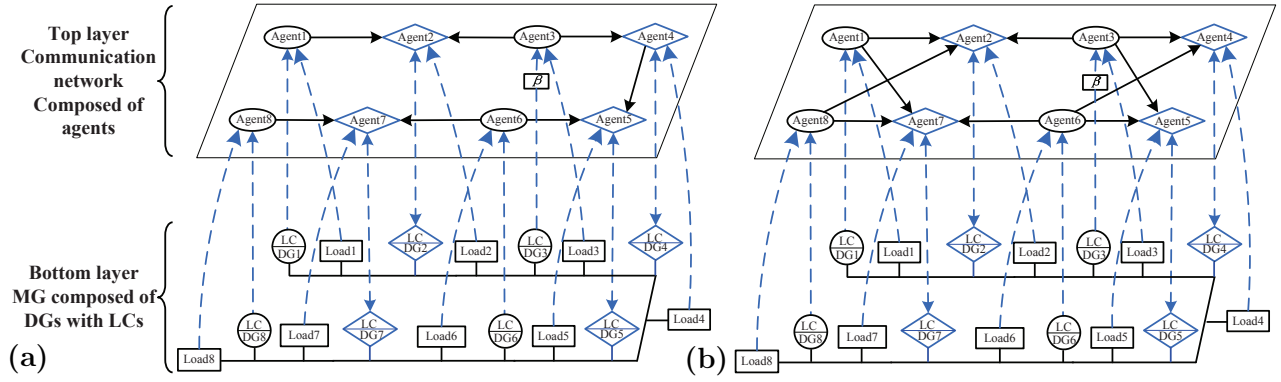


Fig. 1. The two-layer control model for MGs. (a) Network 1: Same electrical and communication topology and (b) Network 2: Different electrical and communication topology, where uncontrollable and partially controllable agents are indicated by circles, while controllable agents are indicated by diamonds. For the same MG, two different communication networks are established and used.

DGs, i.e., their output power can be adjusted by agents according to their control laws. If the MG operates in an islanded mode, a DG working in V/F control mode is needed, which provides the frequency and voltage references for the MG. The V/F DG is regarded as a *partially controllable* DG, because its output cannot be regulated directly by an agent, but can be controlled indirectly, for example, increasing or decreasing the total active or/and reactive power in the system.

Therefore, the agents connecting to uncontrollable and partially controllable DGs are called uncontrollable agents and partially controllable agents, respectively, which are indicated by circles in Fig. 1, while the other controllable agents are indicated by diamonds. Furthermore, on the communication network, uncontrollable and partially controllable agents do not receive any information from other agents, but only send present states of DGs and loads to neighboring agents. On the other hand, controllable agents can not only send, but also receive information to/from neighboring agents. Consequently, note that uncontrollable and partially controllable agents in the communication network only have outgoing edges without any ingoing edges, while controllable agents may have both outgoing and ingoing edges. Thus, the communication network must be a *directed* graph, where the directed graph is a graph in which the edges have a direction associated with nodes in graph theory.

In summary, the following steps can be used to construct a communication network, when an MG is given. *Step 1*: to define n agents as nodes of the network; *Step 2*: to make each agent connect to a DG and a load, which guarantees the agent can acquire the present states of the DG and the load; *Step 3*: agents are labelled as controllable, partially controllable and uncontrollable agents in terms of the type of the DG to which the agent connects; *Step 4*: to add edges between agents according to the above mentioned rules, till no isolated agents are in the network, i.e., it is a connected network.

B. Decentralized control laws of a given communication network

Given an MG, many different communication networks can be constructed according to the steps introduced in the previous subsection. For example, a communication network

that follows the same network as the electrical MG topology is shown in Fig. 1(a). In this way, information may be transmitted through the power lines without additional communication lines. Certainly, if some communication lines are added, a communication network as shown in Fig. 1(b) can be designed. Consequently, different control laws for agents are derived from different communication networks. In this subsection, a systematic method to derive control laws is presented.

When the communication network is established, we can use an adjacency matrix, A , to describe the relationships between nodes (agents). The adjacency matrix A is an $n \times n$ matrix, where the non-diagonal entry $a_{ij} = 1$ means there is an edge from node i to node j , otherwise $a_{ij} = 0$, and the diagonal entry a_{ii} is zero due to no self-loops in the network. Also, A^T denotes the transpose of the adjacency matrix A . Generally, both A and A^T are not symmetric matrices in a directed graph. In addition, there are three types of agents in the network, so that we need an attribute matrix R to indicate the type of each agent. The attribute matrix R is an $n \times n$ and diagonal matrix, where the diagonal entries are zero or one, which depends on the type of the agent. If the agent is a controllable one, then the diagonal entry r_{ii} is one, otherwise, it is zero. Also, because the network is a directed graph, the outdegree and the indegree of each agent are different, where an outdegree of a node is the number of outgoing edges of the node and an indegree is the number of ingoing edges of the node. In our case, an outdegree matrix D is employed, which is also a diagonal matrix and the diagonal entry d_{ii} represents the outdegree of an agent i .

As is mentioned above, there is a V/F DG in an islanded MG. When loads fluctuate dramatically, this DG must provide system losses in order to maintain the frequency and voltage constant in the system. However, the maximal output power of a DG is limited, so that it is often difficult for a V/F DG in an islanded MG to balance the power supply and demand. Alternatively, if other DGs can provide more power, the V/F DG can reduce the delivered power. In other words, if we want to decrease the output power of the V/F DG, while maintaining the frequency and voltage references constant at the same time, we only need to increase the output power of controllable DGs by means of agents.

Following this idea, a new parameter $\beta \in \{-1, 1\}$ is introduced into the system and added between the partially controllable DG and its agent. Thus, the values of active and reactive power produced by the partially controllable DG multiply the coefficient β first and then are sent to the corresponding agent. If $\beta = -1$, the agent connecting to the V/F DG will get the opposite value of the power and send this information to its neighboring agents. For example, the V/F DG has actually increased its output power and injected this power into the system at that moment, but the agent informs neighboring agents its output power decreased. Therefore, the neighboring agents will increase the output power of the DGs to which they connect. As a result, the power supplied increases in the system, so the V/F DG decreases its output power to maintain the frequency and voltage constant. Consequently, the power supplied by other DGs satisfies the load demand, while the output power of the V/F DG decreases to zero. Summarily, the V/F DG provides system losses instantaneously. After that, controllable DGs share the outputs of the V/F DG, so the output of the V/F DG decreases to zero gradually. Conversely, if let $\beta = 1$, then the V/F DG will also provide system losses, but no other controllable DGs can share its heavy burden.

In an MG, if the active and reactive power produced equals the amount of active and reactive power consumed, the system is balanced. Under these requirements, the active and reactive power outputs, $P(t + \tau)$ and $Q(t + \tau)$, provided by controllable DGs at the next time step $t + \tau$, $\tau > 0$ according to control laws plus those of other DGs at this time step t should equal to the total amounts of active and reactive power, $L^P(t)$ and $L^Q(t)$, demanded by all loads at that time. In other words, the outputs of controllable DGs at the next time step should balance the change of power of uncontrollable and partially controllable DGs, and the fluctuation of load demand at this time step. Consequently, the relationship between power supply and load demand can be written as

$$\begin{cases} \sum [R \cdot P(t + \tau)] + \sum [(I - R) \cdot P(t)] = \sum L^P(t), \\ \sum [R \cdot Q(t + \tau)] + \sum [(I - R) \cdot Q(t)] = \sum L^Q(t), \end{cases} \quad (1)$$

where $P(t + \tau) = [P_i(t + \tau)]_{n \times 1}$, $Q(t + \tau) = [Q_i(t + \tau)]_{n \times 1}$, $L^P(t) = [L_i^P(t)]_{n \times 1}$ and $L^Q(t) = [L_i^Q(t)]_{n \times 1}$, while I is an $n \times n$ identity matrix. Note that network losses or line losses are compensated by the V/F DG first, and then they are shared by some controllable DGs in terms of the control laws, so they do not appear in (1) directly. In order to satisfy (1), the control laws of controllable DGs at the next time step can be derived from a given communication network as follows,

$$\begin{cases} R \cdot P(t + \tau) = R \cdot P(t) + (A^T + R) \cdot (D + R)^{-1} \cdot [L^P(t) - P(t)], \\ R \cdot Q(t + \tau) = R \cdot Q(t) + (A^T + R) \cdot (D + R)^{-1} \cdot [L^Q(t) - Q(t)]. \end{cases} \quad (2)$$

As a result, we have determined the *theorem* below.

Theorem: Let $G(V, E)$ be a directed communication network with n agents, where agents are controllable, partially controllable or uncontrollable. Assume the k -th agent is a partially controllable agent. If agents deal with information in terms of the control laws (2), and controllable agents apply the results to adjust the output power of the controllable DGs to which they connect, then the system is balanced, namely, satisfying (1).

Proof: First, the sum of the transpose of the adjacency matrix A^T and the attribute matrix R is calculated

$$A^T + R = \begin{bmatrix} r_{11} & \cdots & a_{k1} & \cdots & a_{n1} \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ a_{1k} & \cdots & r_{kk} & \cdots & a_{nk} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{1n} & \cdots & a_{kn} & \cdots & r_{nn} \end{bmatrix}. \quad (3)$$

Then, we can obtain the inverse of the sum of the outdegree matrix D and the attribute matrix R

$$(D + R)^{-1} = \begin{bmatrix} \frac{1}{d_{11} + r_{11}} & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & \cdots & \frac{1}{d_{kk} + r_{kk}} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & \frac{1}{d_{nn} + r_{nn}} \end{bmatrix}. \quad (4)$$

Therefore, $(A^T + R) \cdot (D + R)^{-1} \cdot [L^P(t) - P(t)]$

$$= \begin{bmatrix} \frac{r_{11}}{d_{11} + r_{11}} & \cdots & \frac{a_{k1}}{d_{kk} + r_{kk}} & \cdots & \frac{a_{n1}}{d_{nn} + r_{nn}} \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ \frac{a_{1k}}{d_{11} + r_{11}} & \cdots & \frac{r_{kk}}{d_{kk} + r_{kk}} & \cdots & \frac{a_{nk}}{d_{nn} + r_{nn}} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{a_{1n}}{d_{11} + r_{11}} & \cdots & \frac{a_{kn}}{d_{kk} + r_{kk}} & \cdots & \frac{r_{nn}}{d_{nn} + r_{nn}} \end{bmatrix} \cdot \begin{bmatrix} L_1^P(t) - P_1(t) \\ \vdots \\ L_k^P(t) - \beta \cdot P_k(t) \\ \vdots \\ L_n^P(t) - P_n(t) \end{bmatrix}. \quad (5)$$

Considering (2), if its left side and its right side are added respectively, we have the following expression,

$$\begin{aligned} & \sum R \cdot P(t + \tau) \\ &= \sum R \cdot P(t) + \sum (A^T + R) \cdot (D + R)^{-1} \cdot [L^P(t) - P(t)] \\ &= (r_{11} \cdot P_1(t) + \cdots + r_{kk} \cdot \beta \cdot P_k(t) + \cdots + r_{nn} \cdot P_n(t)) \\ &+ \frac{r_{11} + \cdots + a_{1k} + \cdots + a_{1n}}{d_{11} + r_{11}} \cdot [L_1^P(t) - P_1(t)] \\ &+ \cdots + \frac{a_{k1} + \cdots + r_{kk} + \cdots + a_{kn}}{d_{kk} + r_{kk}} \cdot [L_k^P(t) - \beta \cdot P_k(t)] \\ &+ \frac{a_{n1} + \cdots + a_{nk} + \cdots + r_{nn}}{d_{nn} + r_{nn}} \cdot [L_n^P(t) - P_n(t)]. \end{aligned} \quad (6)$$

According to graph theory, for the j -th row of the adjacency matrix A , the sum of all elements in the row vector should equal the outdegree of an agent j , so that it yields the following equation

$$\sum_{i=1}^n a_{ji} = d_{jj}. \quad (7)$$

Applying condition (7) to (6), we obtain the final result as follows

$$\begin{aligned} & \sum R \cdot P(t + \tau) \\ &= (r_{11} \cdot P_1(t) + \cdots + r_{kk} \cdot \beta \cdot P_k(t) + \cdots + r_{nn} \cdot P_n(t)) \\ &+ [L_1^P(t) - P_1(t)] + \cdots + [L_k^P(t) - \beta \cdot P_k(t)] + \cdots \\ &+ [L_n^P(t) - P_n(t)] \\ &= ((r_{11} - 1) \cdot P_1(t) + \cdots + (r_{kk} - 1) \cdot \beta \cdot P_k(t) + \cdots \\ &+ (r_{nn} - 1) \cdot P_n(t)) + \sum L^P(t) \\ &= \sum L^P(t) - \sum (I - R) \cdot P(t). \end{aligned} \quad (8)$$

Similarly, we can prove the other expression in (1). ■

From (2), which represents the control laws, it can be found that the dimension of the column vector representing the loads, $L^P(t)$ or $L^Q(t)$, should equal to that of the column vector representing the DGs, $P(t)$ or $Q(t)$. However, in a general case, the number of loads may be greater than that of DGs in an MG. In this case, we can consider several loads nearby as a large load in order to make the number of loads equal the number of DGs. On the contrary, if the number of loads is less than that of DGs, some virtual loads will be added into the network, in which the demand of the virtual load is always zero.

In addition, for a controllable agent i , it is possible that it does not have an outgoing edge, but only an ingoing edge. In this case, d_{ii} is zero, but r_{ii} must be one due to the type of the agent, so that $d_{ii} + r_{ii}$ must be greater than zero. Furthermore, it is worth noting that there is at least one outgoing edge from an uncontrollable or partially controllable agent j to other agents. Otherwise, both d_{jj} and r_{jj} are zeroes, which implies the inverse matrix of $(D + R)$ does not exist. However, this case will never occur, because an uncontrollable or partially controllable agent has no ingoing edges, according to the rules of constructing a communication network. At the same time, if it has no any outgoing edges too, this agent must be an isolated agent, whereas this is not allowed in terms of our rules. Therefore, $(D + R)^{-1}$ always exists.

III. MICROGRID SYSTEM ARCHITECTURE

In this Section, the setup of the MG system under test is introduced first. Later, two sets of control laws corresponding to different communication networks (Fig. 1) are derived according to the model in Section II.

A. MG structure and local controls

An islanded MG with a radial structure is developed in MATLAB/Simulink, as depicted in Fig. 2, which is composed of eight DGs and eight loads, namely $n = 8$. Here, DG₁ is a PV that works in the maximum power point tracking (MPPT) control mode, while DG₃ is a battery energy storage system (BESS), which works in V/F control mode. Moreover, DG₃ offers frequency and voltage references for the MG. In this way, DG₃ can inject or absorb active and reactive power to/from the MG [29]. Furthermore, the coefficient β corresponding to a V/F DG in the control laws is set to $\beta = -1$, which leads the output power of DG₃ to decrease to zero after an instantaneous increase, because its output power is shared by its neighbors. Additionally, DG₆ and DG₈ are two permanent magnet synchronous generator wind turbines (PMSG-WTs), both working in MPPT control mode too.

The other four DGs, DG₂, DG₄, DG₅ and DG₇, are ideal DC voltage sources V_{dc} that can be regarded as the DC-link of microturbines for instance [30]–[32]. They are connected to the MG through DC-AC inverters, all working in PQ control mode. According to the definition of the attribute of a DG, the power production of DG₁, DG₆ and DG₈ depends on the environment, so they are uncontrollable DGs, while DG₂, DG₄, DG₅ and DG₇ are controllable. Also, DG₃ works in V/F

control mode, so it can be seen as a partially controllable DG. In addition, the maximal capacities of DGs and loads, and other parameters are listed in Table I.

TABLE I
SETUP AND PARAMETERS OF DGs AND LOADS

Sources	Capacities	Control	Load	Max. Demand
DG ₁	50 kW, 0 kVar	MPPT	Load ₁	25 kW, 11.5 kVar
DG ₂	50 kW, 40 kVar	PQ	Load ₂	25 kW, 17 kVar
DG ₃	30 Ah	V/F	Load ₃	20 kW, 11.5 kVar
DG ₄	50 kW, 30 kVar	PQ	Load ₄	20 kW, 0 kVar
DG ₅	50 kW, 30 kVar	PQ	Load ₅	30 kW, 11.5 kVar
DG ₆	30 kW, 0 kVar	MPPT	Load ₆	20 kW, 0 kVar
DG ₇	50 kW, 30 kVar	PQ	Load ₇	20 kW, 17.5 kVar
DG ₈	30 kW, 0 kVar	MPPT	Load ₈	25 kW, 11.5 kVar

In the simulation tests, it is assumed that DG₁, DG₆ and DG₈ do not produce any reactive power, namely $Q_1 = Q_6 = Q_8 = 0$, and the line voltage and the frequency are set at 380 V and 50 Hz, respectively. Moreover, the line losses in the MG are considered, when the line impedance is set at $0.169 + j0.07 \Omega/\text{km}$. The sample time is set at $\tau = 0.001$ s for the precision of simulations. In reality, if the presently collected data equals to the previous one, the information transmission will not be necessary. Therefore, asynchronous communication is another choice, which is an efficient way to decrease communication costs, while our model can support both synchronous and asynchronous communication. Initially, the MG system works in a balanced state.

Note that physical constraints are also taken into account during the construction and simulations of the islanded MG in MATLAB/Simulink. For example, the output power of a DG (except a BESS) must be restricted between 0 and its capacity, even if the setting point is beyond the capacity or less than zero. Moreover, the instantaneous output power of the BESS is limited and there is a capacity constraint when the BESS charges or discharges. Other constraints of a battery in reality are also considered. On the other hand, our model in MATLAB/Simulink is scalable, where DGs can be added, deleted and substituted easily, when some interfaces and parameters are modified.

B. Control laws of two communication networks

As mentioned in Section II, many possible communication networks may be considered for a given MG. Moreover, the structure of a communication network is associated with the performance of derived control laws directly. Therefore, we can obtain good control laws by constructing optimal or sub-optimal communication networks. Here, two communication networks with different structures, *Network 1* and *2*, are designed for the same MG, as shown in Fig. 1. It can be seen that the structure of *Network 2* is more complex than that of *Network 1*, i.e., information is shared among more neighbors in *Network 2* due to adding four communication lines.

By following the design rules, in these two networks, there are no ingoing edges for those agents connected to DG₁, DG₃, DG₆ and DG₈, because they are defined as uncontrollable or partially controllable agents, whereas there are ingoing and

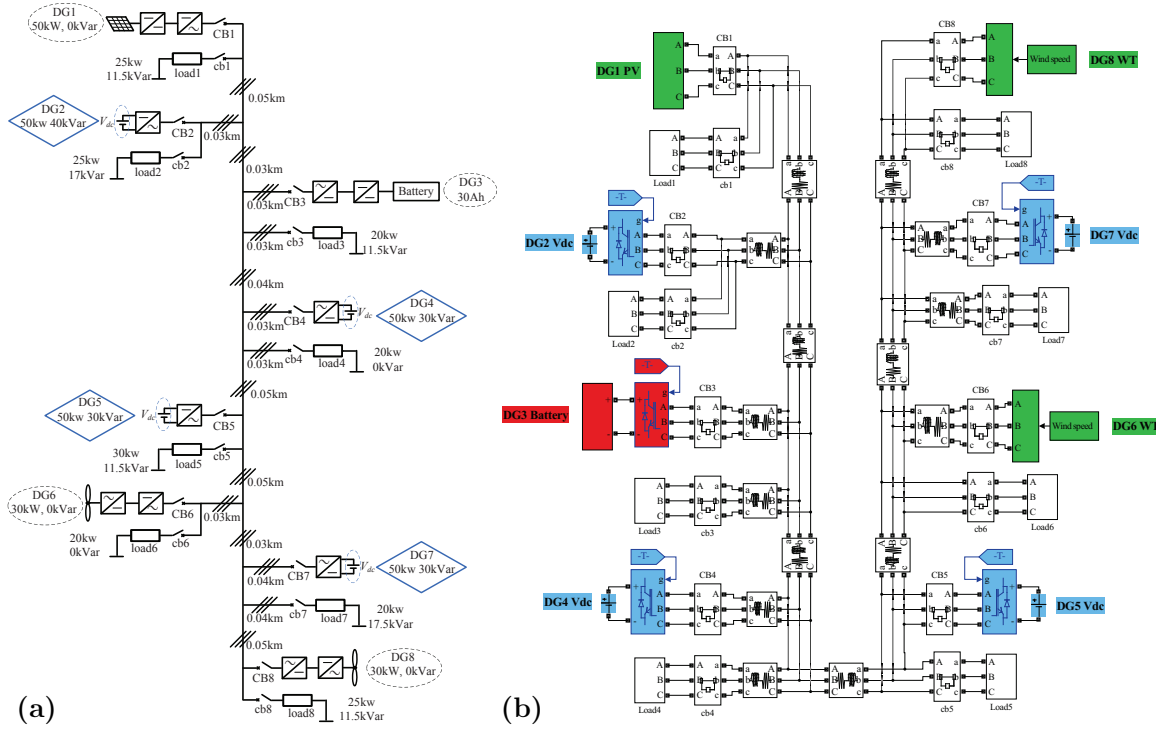


Fig. 2. Islanded MG with a radial structure and its agents. (a) is the radial structure of an islanded MG with parameters of capacity and loads. (b) is the MG established in MATLAB/Simulink.

outgoing edges for other controllable agents. According to the theorem, we can obtain two sets of control laws for the agents of Network 1 and 2, named here the control law I and II, respectively. For example, to obtain the control law I, the adjacency matrix A_1 for Network 1 needs to be written first

$$A_1 = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}. \quad (9)$$

Then, the attribute matrix R_1 and the outdegree matrix D_1 can be given as follows,

$$R_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad (10)$$

$$D_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}. \quad (11)$$

Consequently, the control laws of controllable DGs $R_1 \cdot P(t + \tau)$ from Network 1 can be obtained according to (2), which take the following forms,

$$P_2(t + \tau) = L_1^P(t) + L_2^P(t) + \frac{1}{2}L_3^P(t) - P_1(t) - \frac{1}{2}\beta \cdot P_3(t) \quad (12)$$

$$P_4(t + \tau) = \frac{1}{2}L_3^P(t) + \frac{1}{2}L_4^P(t) - \frac{1}{2}\beta \cdot P_3(t) + \frac{1}{2}P_4(t) \quad (13)$$

$$P_5(t + \tau) = \frac{1}{2}L_4^P(t) + L_5^P(t) + \frac{1}{2}L_6^P(t) - \frac{1}{2}P_4(t) - \frac{1}{2}P_6(t) \quad (14)$$

$$P_7(t + \tau) = \frac{1}{2}L_6^P(t) + L_7^P(t) + L_8^P(t) - \frac{1}{2}P_6(t) - P_8(t). \quad (15)$$

Moreover, $R_1 \cdot Q(t + \tau)$ can be calculated by following the above steps, so we have

$$Q_2(t + \tau) = L_1^Q(t) + L_2^Q(t) + \frac{1}{2}L_3^Q(t) - Q_1(t) - \frac{1}{2}\beta \cdot Q_3(t) \quad (16)$$

$$Q_4(t + \tau) = \frac{1}{2}L_3^Q(t) + \frac{1}{2}L_4^Q(t) - \frac{1}{2}\beta \cdot Q_3(t) + \frac{1}{2}Q_4(t) \quad (17)$$

$$Q_5(t + \tau) = \frac{1}{2}L_4^Q(t) + L_5^Q(t) + \frac{1}{2}L_6^Q(t) - \frac{1}{2}Q_4(t) - \frac{1}{2}Q_6(t) \quad (18)$$

$$Q_7(t + \tau) = \frac{1}{2}L_6^Q(t) + L_7^Q(t) + L_8^Q(t) - \frac{1}{2}Q_6(t) - Q_8(t). \quad (19)$$

It must be emphasized that uncontrollable and partially controllable agents *do not* compute the values of uncontrollable and partially controllable DGs at the next time step and also *do not* regulate the outputs of these DGs, but these agents only collect information from uncontrollable and partially controllable DGs at each time step and send it to neighboring agents as shown in Fig. 1.

Similarly, the control law II for agents on Network 2 is also obtained, after A_2, R_2 and D_2 are given,

$$A_2 = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}, \quad (20)$$

$$D_2 = \begin{bmatrix} 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \end{bmatrix}. \quad (21)$$

Here, R_2 and R_1 are identical because we are using the same MG structure. Hence, $R_2 \cdot P(t + \tau)$ is

$$P_2(t + \tau) = \frac{1}{2}L_1^P(t) + L_2^P(t) + \frac{1}{3}L_3^P(t) + \frac{1}{2}L_8^P(t) - \frac{1}{2}P_1(t) - \frac{1}{3}\beta \cdot P_3(t) - \frac{1}{2}P_8(t) \quad (22)$$

$$P_4(t + \tau) = \frac{1}{3}L_3^P(t) + L_4^P(t) + \frac{1}{3}L_6^P(t) - \frac{1}{3}\beta \cdot P_3(t) - \frac{1}{3}P_6(t) \quad (23)$$

$$P_5(t + \tau) = \frac{1}{3}L_3^P(t) + L_5^P(t) + \frac{1}{3}L_6^P(t) - \frac{1}{3}\beta \cdot P_3(t) - \frac{1}{3}P_6(t) \quad (24)$$

$$P_7(t + \tau) = \frac{1}{2}L_1^P(t) + \frac{1}{3}L_6^P(t) + L_7^P(t) + \frac{1}{2}L_8^P(t) - \frac{1}{2}P_1(t) - \frac{1}{3}P_6(t) - \frac{1}{2}P_8(t). \quad (25)$$

In the same way, we can obtain $R_2 \cdot Q(t + \tau)$, as follows:

$$Q_2(t + \tau) = \frac{1}{2}L_1^Q(t) + L_2^Q(t) + \frac{1}{3}L_3^Q(t) + \frac{1}{2}L_8^Q(t) - \frac{1}{2}Q_1(t) - \frac{1}{3}\beta \cdot Q_3(t) - \frac{1}{2}Q_8(t) \quad (26)$$

$$Q_4(t + \tau) = \frac{1}{3}L_3^Q(t) + L_4^Q(t) + \frac{1}{3}L_6^Q(t) - \frac{1}{3}\beta \cdot Q_3(t) - \frac{1}{3}Q_6(t) \quad (27)$$

$$Q_5(t + \tau) = \frac{1}{3}L_3^Q(t) + L_5^Q(t) + \frac{1}{3}L_6^Q(t) - \frac{1}{3}\beta \cdot Q_3(t) - \frac{1}{3}Q_6(t) \quad (28)$$

$$Q_7(t + \tau) = \frac{1}{2}L_1^Q(t) + \frac{1}{3}L_6^Q(t) + L_7^Q(t) + \frac{1}{2}L_8^Q(t) - \frac{1}{2}Q_1(t) - \frac{1}{3}Q_6(t) - \frac{1}{2}Q_8(t). \quad (29)$$

IV. RESULTS

To evaluate the performance of the control law I and II, four cases are designed in order to test different scenarios. Case 1 focuses on how the control laws respond to the output power fluctuation of uncontrollable DGs due to the change of the environment. For Case 2, it considers the relationship between the load demand and the tolerance of the control laws. In the final cases, Case 3 investigates whether the system keeps stable, when both environmental conditions and the load demand change at the same time, and further in the same settings Case 4 employs time delays. Finally, the results are discussed and explained specifically.

A. Case 1: Environmental conditions fluctuation

As is known, the active power production of DG_1 depends on sunlight, while DG_6 and DG_8 on wind power. In Case 1, the illumination intensity fluctuates between 300 W/m² and 1000 W/m², so that the output power of DG_1 ranges from 15 kW and 50 kW. Moreover, the wind speed also changes with time, which leads to the output power of DG_6 and DG_8 fluctuating in a large range. The fluctuation of the illumination intensity for DG_1 and the wind speed for DG_6 and DG_8 is shown in Fig. 3(a), while the output power of DG_1 , DG_6 and DG_8 that follows the fluctuation and that of DG_3 are drawn in Fig. 3(b). In this case, the control law I from Network 1 are used.

From Fig. 3(b), it can be seen that the active power output of DG_1 increases gradually with the illumination intensity and it reaches a peak at $t = 3$ s, but in this period of time the power generated by DG_3 , DG_6 and DG_8 remain almost unchanged. As shown in Fig. 1(a), the present states of DG_1 and DG_3 are sent to Agent 2 by Agent 1 and Agent 3. Therefore, Agent 2 decreases the output power of DG_2 , after it deals with this information according to (12). In other words, P_1 rises gradually and other items in (12) remain almost constant from $t = 0$ s to 3 s, so the output power of DG_2 , $P_2(t + \tau)$, always drop.

Further, we can analyze the output power of DGs at $t = 6$ s in terms of the structure of Network 1 and the control laws. Apparently, the output power of DG_2 rises according to (12), because the production of DG_1 drops to the minimum at $t = 6$ s, while that of DG_3 is unchanged. On the other hand, the output power of DG_6 reaches the maximum at $t = 6$ s, while that of DG_8 remains constant. According to (15), the output power of DG_7 decreases by about 22% from 36 kW at $t = 3$ to 28 kW at $t = 6$ as shown in Fig. 3(c). Similarly, the output power of DGs after $t = 6$ s can be analyzed as the same way.

As analyzed in Section II, at each time step, the power supplied by all DGs equals to the load demand. Moreover, the voltage and the frequency in the system is expected to remain in a normal range, when the control laws are applied. From Fig. 3(d), it can be found that the line voltages at the head and the tail of the bus, which are represented by the voltages of Load₁ and Load₈ respectively, stay close to 380 V, and the frequency is always around 50 Hz, even if the output power of DGs fluctuates largely due to the fluctuation in environmental conditions.

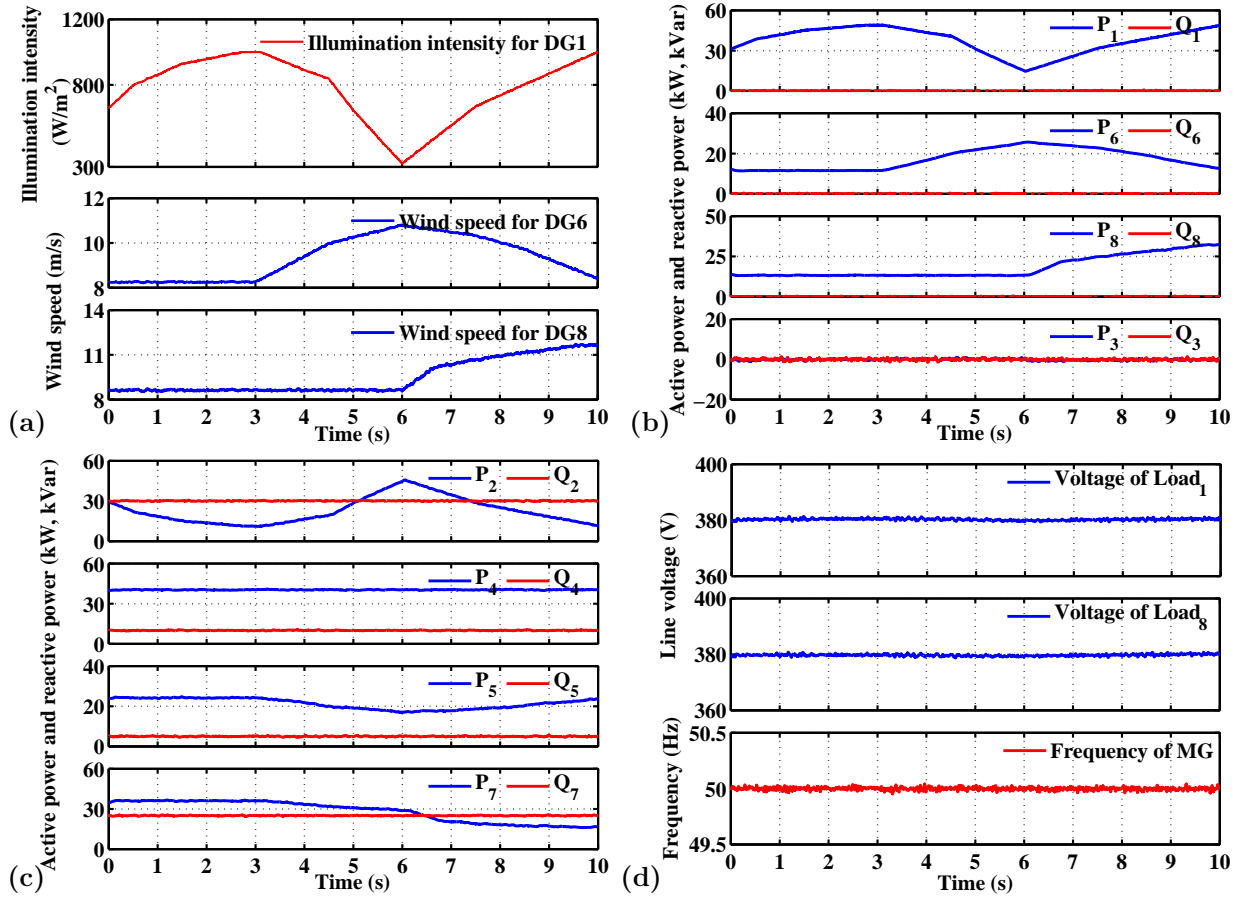


Fig. 3. Simulation results under the control law I, when the environmental conditions change. (a) the illumination intensity and the wind speed fluctuate over time. (b) active and reactive power outputs of uncontrollable and partially controllable DGs, DG₁, DG₃, DG₆ and DG₈. (c) active and reactive power outputs of controllable DGs, DG₂, DG₄, DG₅ and DG₇. (d) line voltage and frequency in the MG.

B. Case 2: Load demand fluctuation

In this case, the load demand changes over time, so the output power of controllable DGs needs to be regulated by controllable agents according to the control law I derived from Network 1 in order to keep the system stable. During simulation tests, the load demand is scheduled as below,

- $t = 3$ s: active power loads decrease by 15% and reactive power loads increase by 15%
- $t = 6$ s: both active and reactive power loads decrease by 15%
- $t = 8$ s: both active and reactive power loads increase by 25%,

while the output power of DG₁, DG₆ and DG₈ is always at 60% of their capacities.

As shown in Fig. 4(b), the power generated by DG₃ increases or decreases with the active and reactive power load demand, because it works in V/F control mode. When the active power load demand decreases sharply at $t = 3$ s, the active power production of DG₁, DG₆ and DG₈ still does not change. At this moment, the output power of DG₃ instantaneously decreases by about 50% to -10 kW, which means BESS is absorbing power from the system, so that the output power of other DGs should be adjusted to the level of current load demand. According to the structure of Network 1,

Agent 3 sends opposite information to Agent 2 and Agent 4 due to $\beta = -1$, i.e., informing Agent 2 and Agent 4 the output power of DG₃ rises. Receiving this instruction, Agent 2 and Agent 4 decrease the active power outputs of DG₂ and DG₄ according to (12) and (13). As such, the surplus of active power drops in the system, while the output power of DG₃ rises, since it does not have to absorb further power. Note that DG₂ and DG₄ will not stop decreasing their active power, until DG₃ ceases absorbing any power from the system, namely, the output power of DG₃ increases to zero.

Similarly, other uncontrollable agents send present states to their neighbors, i.e., Agent 8 sends its information to Agent 7; Agent 6 to Agent 7 and Agent 5. In terms of (14) and (15), the active power supplied by DG₅ and DG₇ drops, because active power loads decrease by 15%, but P_6 and P_8 remain their output power unchanged.

In addition, the reactive power output of DG₃ increases suddenly, when reactive power loads increase by 15% at $t = 3$ s. When calculating $Q_2(t + \tau)$ and $Q_4(t + \tau)$ according to (16) and (17), we can find that DG₂ and DG₄ will increase their reactive power outputs, because of receiving the opposite information from Agent 3 when $\beta = -1$. As a result, the reactive power output of DG₃ returns to zero. Moreover, the reactive power supplied by DG₅ and DG₇ also rises in terms

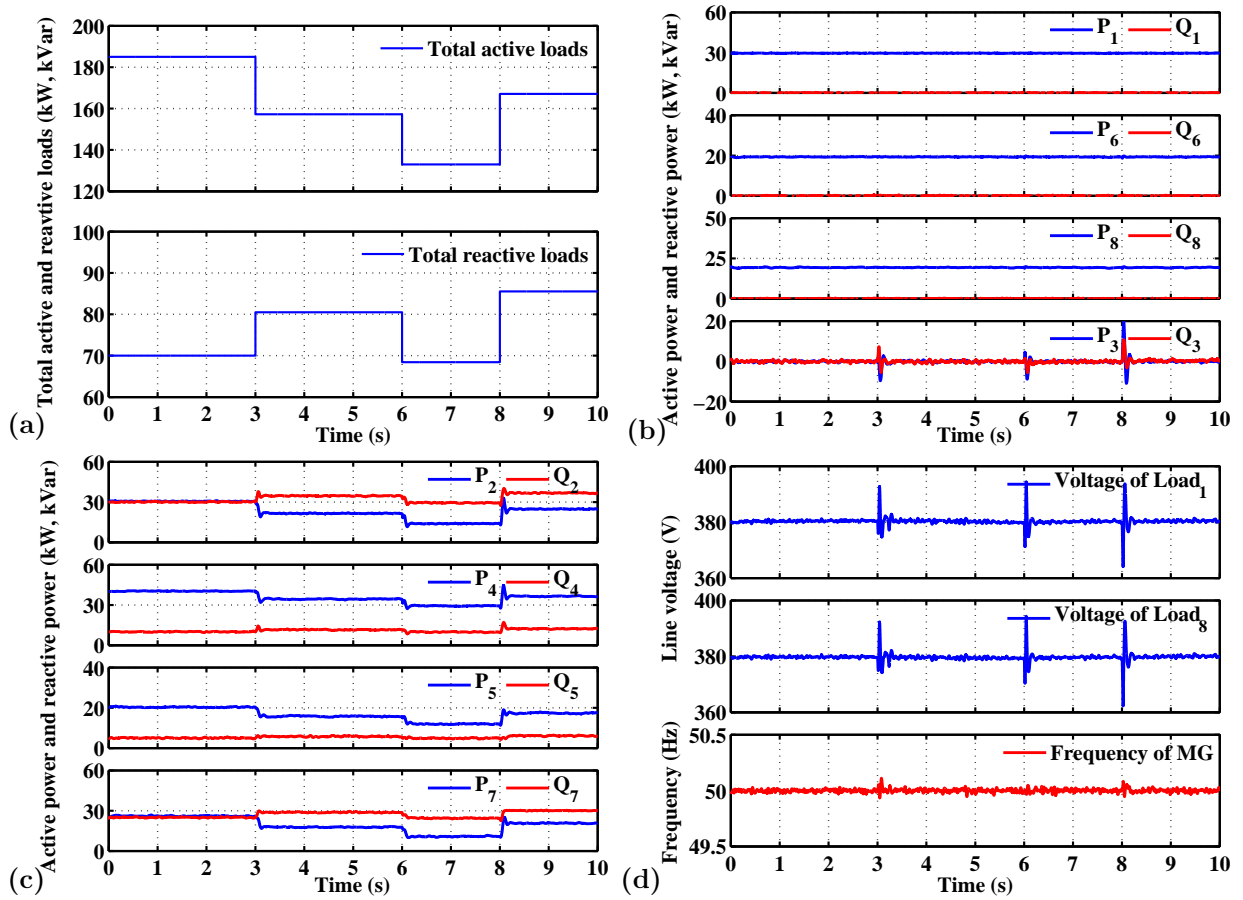


Fig. 4. Simulation results under the control law I, when the load demand changes. (a) active and reactive power load changes over time. (b) active and reactive power outputs of uncontrollable and partially controllable DGs, DG₁, DG₃, DG₆ and DG₈. (c) active and reactive power outputs of controllable DGs, DG₂, DG₄, DG₅ and DG₇. (d) line voltage and frequency in the MG.

of (18) and (19). Similar analyses can be applied to the situations at $t = 6$ s and $t = 8$ s, and the results are shown in Fig. 4(c).

Finally, it is well known that the performance of control laws is directly associated with the voltage and the frequency in the system. In Fig. 4(d), we can find that the voltages fluctuate significantly at $t = 3$ s, $t = 6$ s and $t = 8$ s, but they remain inside an acceptable range and are restored to 380 V quickly. In our case, all loads may change dramatically on occasion. However, generally speaking, these extreme situations occur with a small probability. Hence, voltage fluctuation is much smaller, when loads change gradually. On the other hand, the frequency changes slightly and is always kept around 50 Hz, regardless of the increase or decrease of loads.

C. Case 3: Environmental conditions and load demand fluctuation

In the above two cases, the control laws exhibit good performance, when the environmental conditions or the load demand changes. Here, both aspects, the environmental conditions and the load demand, are considered together to test the performance of two sets of control laws that are derived from Network 1 and 2, where the structure of Network 1 is simpler than that of Network 2. The settings for the environmental

conditions, such as fluctuation of the illumination intensity and the wind speed, in Case 1 are adopted, while the load demand follows the settings in Case 2. The results obtained under the combination of different parameters and control laws are shown in Fig 5.

From Fig 5, it can be found that the voltage and the frequency fluctuate slightly around the setting value during simulations, except that the voltage increases or decreases abruptly at some moments, which still satisfies the requirements in IEEE Standard 1547 [33] for large changes in loads. This means that the system works well no matter which set of control laws is employed. Compared with Case 1 and 2, the active power supplied by DG₂, DG₄, DG₅ and DG₇ in Case 3 fluctuates over a larger range, because the environmental conditions and the load demand need to respond at the same time.

Additionally, in Network 1, each agent only exchanges information with one or two neighbors, which makes the communication network very sparse. However, information is shared among more neighbors in Network 2 due to adding four communication lines, i.e., lines from Agent 1 to Agent 7, from Agent 3 to Agent 5, from Agent 6 to Agent 4 and from Agent 8 to Agent 2. Finally, similar results are obtained, which are drawn in Fig 5, although the control law II derived

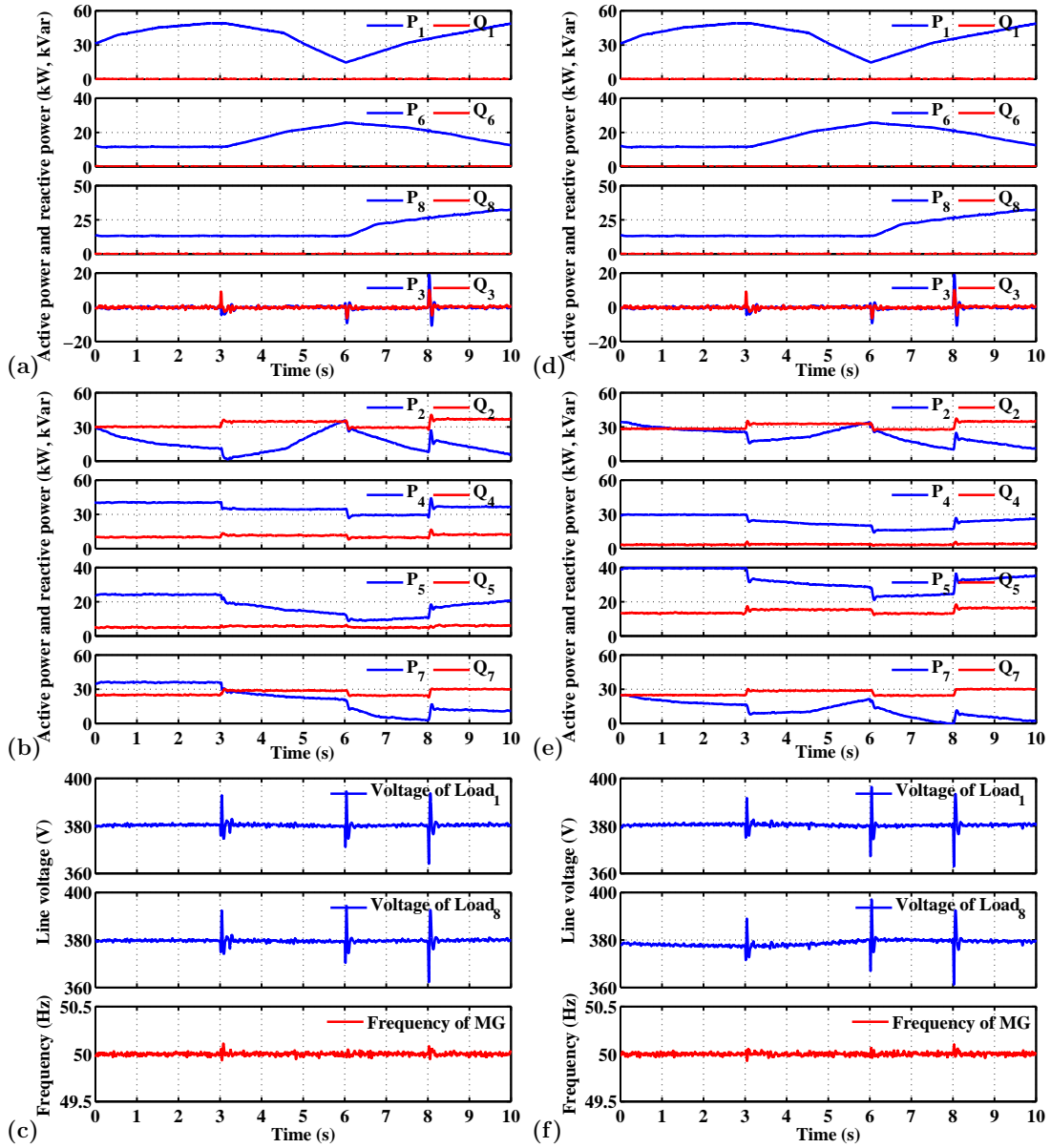


Fig. 5. Simulation results under the control law I and II, when both the environmental conditions and the load demand change. (a) and (d) are active and reactive power outputs of uncontrollable and partially controllable DGs, DG₁, DG₃, DG₆ and DG₈. (b) and (e) are active and reactive power outputs of controllable DGs, DG₂, DG₄, DG₅ and DG₇. (c) and (f) are line voltages and frequency in the MG. (a)-(c) are the results, when the control law I is used. (d)-(f) are the results, when the control law II is used.

from a more complex communication network. This, to some extent, indicates that it is not always true that a more complex communication network results in improved performance, so a simpler network is a better choice, since less communication lines are needed.

D. Case 4: Impacts of time delays when environmental conditions and load demand fluctuation

Information transmission plays a very important role in a decentralized control method. However, in reality, there exist time delays in communication networks due to devices or line failures, etc. In this subsection, the impacts of time delays on the performance of control laws is investigated, when environmental conditions and load demand fluctuate at the

same time, whose settings follow those in Case 3. Moreover, an extreme situation is designed, i.e., for each node, fixed time delays occur at each time step, when the control law I is adopted.

For sake of simplicity, only frequency and voltage responses are shown in Fig. 6, when four fixed time delays t_d are employed, namely $t_d = 0.01, 0.02, 0.03$ and 0.05 s, respectively. From Fig. 6, it can be seen that the frequency and voltages obtained, when the time delay $t_d = 0.01$ s or 0.02 s is involved, are similar to those without any time delay. However, if the longer time delay occurs, the fluctuation of the frequency and voltages lasts longer at the moments when environmental conditions and load demand change largely, but it still stays in a normal range. This is because at time step t agents are

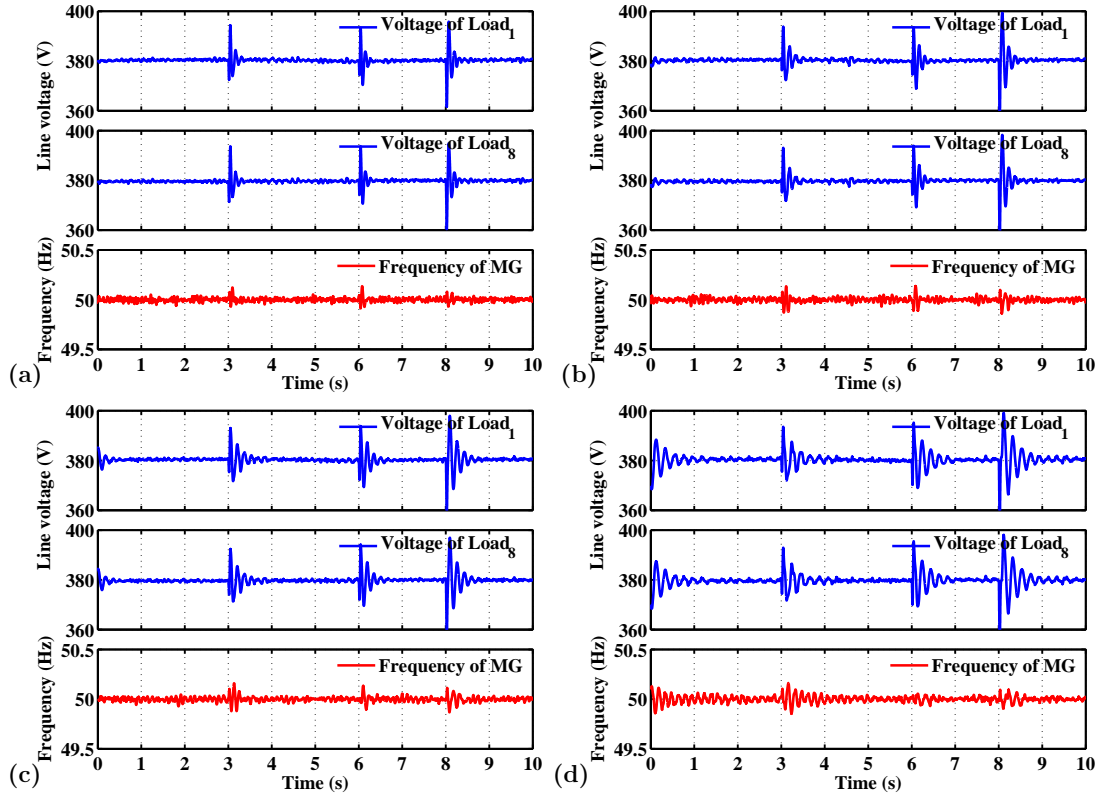


Fig. 6. Simulation results when time delays t_d are involved. Simulations are performed under the control law I, when both the environmental conditions and the load demand change over time. (a) $t_d = 0.01$ s, (b) $t_d = 0.02$ s, (c) $t_d = 0.03$ s, and (d) $t_d = 0.05$ s.

still dealing with data collected at $t - t_d$, which makes control laws hard to respond the change at time step t immediately. Therefore, the bigger the time delay is, the longer the process to restore lasts.

V. CONCLUSION

We have proposed a two-layer, decentralized control model for MGs. In the model, the bottom layer is the MG, where DGs working in PQ control mode or V/F control mode are operated by their LCs. The top layer is the communication network composed of agents, where agents collect present states of DGs and loads to which they connect through the communication lines between the two layers. On the communication network, agents exchange information and then make decisions according to the control laws. After the values of output power of DGs at next time step are calculated, controllable agents send the results to controllable DGs they connect to. Obtaining these instructions, the output power of DGs is regulated by LCs to achieve a balance between production and consumption of energies in the MG.

In this paper, we focus on the establishment of communication networks and the control laws for agents. Therefore, the rules and steps for constructing a communication network have been given. Moreover, a systematic method of how control laws for agents are derived from a given network has been presented. Furthermore, it also has been shown that the power supplied by DGs equals the load demand, if agents apply the derived control laws to adjust the output power of

DGs. To evaluate the performance of control laws, four cases are studied, where Case 1 and Case 2 investigate how the control laws responds to the fluctuation of the environmental conditions and the loads respectively, while in Case 3 these two aspects are combined together to test the control laws and finally time delays are employed in Case 4. From the simulation results, it has been demonstrated that the MG works well, i.e., the voltage and the frequency satisfy the IEEE Standard 1547 requirements under different conditions.

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