International Conference on Information Sciences, Machinery, Materials and Energy (ICISMME 2015)

Multi-agent System based Dynamic Control Framework for Grid-connected Microgrids

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Keywords: Decentralized control, multi-agent system, grid-connected microgrid.

Abstract. This paper presents a multi-agent system (MAS) based dynamic control framework for the grid-connected microgrid (MG), to realise the prescribed interactive power between the MG and the main grid, while managing the output power of distributed generators (DGs) roughly proportional to their capacities. The proposed framework consists of two layers, the grid-connected MG and the MAS communication network. Agents in the communication network acquire the information of DGs and loads in the MG. There exist communication links between agents to facilitate the information exchange. A set of dynamic control strategies were derived from the communication network. Then, agents in the communication network regulate the output power of corresponding DGs at next sampling time, according to the control strategies. Finally, simulation results are provided to show the effectiveness of the proposed framework in the disturbances of intermittent DGs and load changes.

1. Introduction

Nowadays, the MG has earned significant attention, for it is considered as one of the effective solutions for integrating DGs into the main grid[1]. In a grid-connected MG, the shortfall or excess power in the MG can be supplied or absorbed by the main grid respectively. Then, a control framework which manages the interactive power between the MG and the main grid as well as facilitates an economically optimal operation is desired.

The majority of MG control strategies available in the literatures are based on centralized or decentralized structure[2]. The conventionally exploited centralized control approaches depends on a two-way communication network and a central controller (MGCC), for global information acquisition and procession[3]. It notes that, if operating and environment conditions change rapidly and unexpectedly together with the significantly increased number of DGs, the centralized control approach is inadequate to respond in a timely fashion. Instead, decentralized control approach merely requires local information rather than global information of the MG. Therefore, the amount of the exchange information is reduced significantly, which in turn increase reliability and the flexibility of the power supply, furthermore, the MGCC can be obviated[4].

The notion of the MAS has recently been introduced to the MG decentralized control. Generally speaking, a MAS is composed of multiple agents within an environment, where agents interact with others and make decisions, and finally tend to find the solutions for problems, such as consensus[5] and formation[6]. In[7], a MAS based frequency control strategy was developed for an islanded MG, where agents were allowed to exchange information locally. Following this idea, a purely distributed control strategy is proposed for an islanded MG such that the MGCC was obviated while the stability can be guaranteed[8]. As for a grid-connected MG, a multi-agent based hierarchical hybrid control scheme is developed in[10] for the energy management[9].

In this paper, a MAS based dynamic control framework is proposed which only requires local information. Additionally, the simulation results show that, regardless of the disturbances of intermittent DGs and load changes, the proposed control framework keeps the output power of DGs proportional to their capacities, and that the interactive power between the MG and the main grid follows the prescribed reference.

The paper is organized as follows. In Section 2 we provide the details of the control model as well as the dynamic control laws. Section 3 provides the simulation results. Finally, in Section 4, we summarize our work.

2. Control model and dynamic control strategies

2.1 Preliminaries of graph theory

The communication network of the MG is modelled by a directed graph, agents are nodes of the graph and the edges of the graph represent the communication links. The adjacency matrix A is a $n \times n$ matrix, where the entry $a_{ij} = 1$ means there is an edge from node i to node j, otherwise $a_{ij} = 0$. Besides, the out-degree matrix is defined as $D = diag\ d_i$ with d_i denotes the out-degree of node i. Additionally, the weight matrix W is employed to describe the connection strength between nodes, where $w_{ij} = a_{ij} / d_{ii}$.

2.2 Control model of a given communication network

In this paper, each agent in the communication network is assigned with a DG and a load in the MG, note that the communication network and the MG do not have necessarily the same structure as shown in Fig.1. Moreover, through the communication links between two layers, each agent can collect the current states of the DG and the load, such as the output power of the DG and the load demand. Furthermore, information exchanges occurs between agents, to acquire the information that has been acquired by its neighboring agents, where the arrows on the solid lines and the dashed lines indicate the information transfer direction. At last, according to the control laws, the controllable agents regulate the output power of controllable DGs in the MG at next sample time.

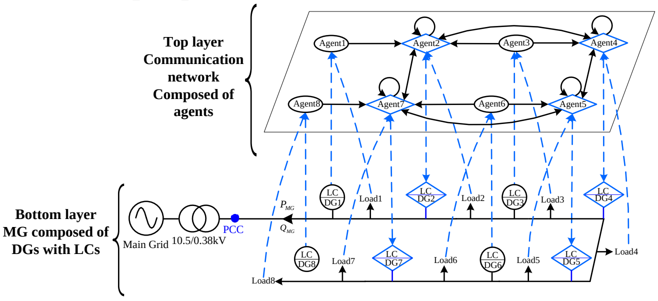

Fig.1: The two-layer control model for the grid-connected MG

It notes that DGs in the MG are mainly categorized into uncontrollable and controllable. Uncontrollable DGs refer to intermittent DGs, and corresponding agents are called uncontrollable agents, which are illustrated by circles in Fig.1. On the contrary, other DGs such as microturbines etc, can be seen as controllable DGs and the corresponding agents are called controllable agents, which are illustrated by diamonds. In addition, an $n \times n$ diagonal attribute matrix R is used to indicate the type of each agent, if Agenti is a controllable one, then the diagonal entry r_{ii} is zero, otherwise, it is one.

2.3 Dynamic control strategies of agents

As for a grid-connected MG, it can be considered as a virtual plant whose output power is the interactive power between the MG and the main grid, which can be dispatched by coordinating the output power of DGs in the MG and the interactive power flow direction is shown in Fig.1. Additionally, the load demand is satisfied simultaneously and it can be written as

$$\sum_{i=1}^{n} P_i(t+\tau) = \sum_{i=1}^{n} L_i^P(t) + P_{grid}(t)$$
$$\sum_{i=1}^{n} Q_i(t+\tau) = \sum_{i=1}^{n} L_i^Q(t) + Q_{grid}(t) \tag{1}$$

where $P_i(t+\tau)$ and $Q_i(t+\tau)$ denote the active and reactive output power of DGi at $t+\tau$ respectively, and the $L_i^p(t)$ and $L_i^Q(t)$ are the active and reactive power demand of Loadi at t respectively, and $P_{grid}(t)$ and $Q_{grid}(t)$ are the interactive power between the MG and the main grid.

In this paper, a decentralized control framework is to be developed such that the output power of DGs are proportional to their capacities and the load demand as well as prescribed interactive power are satisfied simultaneously.

First, the utilization ratio is defined below to describe the utilization profile of controllable DGs, where P_i^{max} is the capacity of DGi, $P_i(t)$ is the output power of DGi at t,

$$a_i(t) = P_i(t) \,/\, P_i^{max}. \tag{2}$$

Additionally, the basic idea of dynamic control laws is that, the utilization ratio of each DG will be compared to that of its neighboring DGs. If the DG has a higher utilization ratio than its neighboring DGs, the agent will decrease the output power of the corresponding DG, while increasing the output of its neighboring DGs. And if the DG has a relative lower level of utilization, the response of DGs and agents can be analyzed in the similar way.

Following this idea, it assumed that Agenti knows the utilization ratios of DG(i+1), DG(i+2), ...DG(i+k), due to the communication links. First, Agenti compares the utilization ratio of DGi to the mean utilization ratio of DG(i+1), DG(i+2), ...DG(i+k). Then, the reference output power of DGi, $P_i^{ref}(t)$ is calculated,

$$P_i^{ref}(t) = \left(\frac{a_{i+1}(t) + a_{i+2}(t) + \cdots + a_{i+k}(t)}{k}\right) \times P_i^{max} \tag{3}$$

After that, the reference output power of DGi, $P_i^{ref}(t)$ is compared with the measured output power of DGi, $P_i(t)$, to obtain the error $P_i^{err}(t)$, as shown in Fig.2. If $P_i^{err}(t) > P_i(t)$, then required power $P_i^{ex1}(t)$ is generated and is sent to Agenti to increase the output power of DGi at next sample time. On the contrary, the required power $P_{i+1}^{ex2}(t)$, $P_{i+2}^{ex2}(t)$... $P_{i+k}^{ex2}(t)$ are generated to decrease the output power of DG(i+1), DG(i+2), ...DG(i+k) at next sample time. If $P_i^{err}(t) \le P_i(t)$, it can be analyzed in the similar way. Finally, in order to satisfy (1) and to gain better utilization ratios of controllable DGs, we have determined the following theorem.

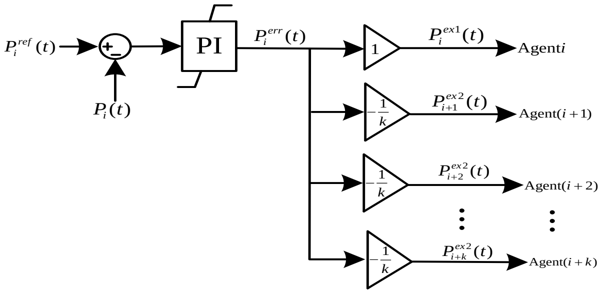

Fig.2: Utilization ratios based PI controller.

Theorem: In a grid-connected MG, if agents deal with the information in terms of the following control strategies to adjust the output power of corresponding DGs, then (1) can be satisfied and the fair utilization ratios of controllable DGs can be achieved.

$$P(t+t) = \underbrace{R \cdot P(t) + W^T \cdot L^p(t) - W^T \cdot R \cdot P(t)}_{power\ balance\ term} + \underbrace{P^{ex1}(t) + P^{ex2}(t)}_{fair\ \ utilization\ ratio\ term} \tag{4}$$

$$Q(t+t) = \underbrace{R \cdot Q(t) + W^T \cdot L^Q(t) - W^T \cdot R \cdot Q(t)}_{power\ balance\ term} + \underbrace{Q^{ex1}(t) + Q^{ex2}(t)}_{fair\ utilization\ ratio\ term} \quad (5)$$

Proof: First, the power balance term, namely, the expression below can be proved,

$$P(t+t) = R \cdot P(t) + W^T \cdot L^p(t) - W^T \cdot R \cdot P(t) \quad (6)$$

Considering (6), if its left side and its right side are added respectively, we have the following expression,

$$\sum_{i=1}^{n} P_i(t+t) = \sum_{i=1}^{n} L_i^P(t) \quad (7)$$

That is, the power balance term is proved. Additionally, it notes that the fair utilization ratio term equals zero, as shown in Fig. 2, that is,

$$P^{ex1}(t) + P^{ex2}(t) = 0 \quad (8)$$

Finally, the expression in (4) is proved, and the expression in (5) can be proved in the similar way, namely, satisfying (1).

3. Architecture of the grid-connected MG

3.1 MG structure and local controllers

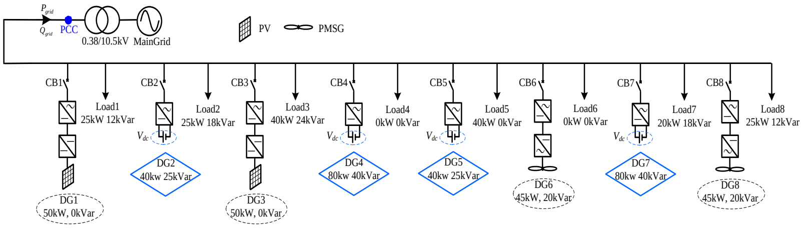

Fig.3: The structure of the grid-connected MG.

The gird-connected MG is developed in MATLAB/Simulink, as depicted in Fig.3. Here, PV and permanent magnet synchronous wind power generator(PMSWG), both working in MPPT mode. Other DGs are represented by ideal dc voltage sources Vdc for simplification and they are all working in PQ mode. According to the definition of the attribute of a DG, PV and PMSWGs are uncontrollable, while other DGs are controllable. In addition, the capacities of DGs and loads, and other parameters are illustrated in Fig. 3. The sample time is τ = 1 ms. Initially, the MG system works in a balanced state.

3.2 Dynamic Control Strategies

Many possible communication networks may be considered for a given MG. Here, network as shown in Fig.1 is designed for the MG in Fig.3. And the control laws from network can be obtained according to (4), which take the following forms,

$$P_1(t+\tau) = P_1(t) \quad (9)$$

$$\begin{aligned} P_2(t+\tau) = {} & L_1^P(t) + \frac{1}{3}L_2^P(t) + \frac{1}{2}L_3^P(t) + \frac{1}{3}L_4^P(t) + \frac{1}{3}L_7^P(t) \\ & - P_1(t) - \frac{1}{2}P_3(t) + P_{MG}(t) + P_2^{ex1}(t) + P_4^{ex2}(t) + P_7^{ex2}(t) \end{aligned} \quad (10)$$

$$P_3(t+\tau) = P_3(t) \quad (11)$$

$$\begin{aligned} P_4(t+\tau) = {} & \frac{1}{3}L_2^P(t) + \frac{1}{2}L_3^P(t) + \frac{1}{3}L_4^P(t) + \frac{1}{3}L_5^P(t) - \frac{1}{2}P_3(t) \\ & + P_4^{ex1}(t) + P_2^{ex2}(t) + P_5^{ex2}(t) \end{aligned} \quad (12)$$

$$P_5(t+\tau) = \frac{1}{3}L_4^P(t) + \frac{1}{3}L_5^P(t) + \frac{1}{2}L_6^P(t) + \frac{1}{3}L_7^P(t) - \frac{1}{2}P_6(t) + P_5^{ex1}(t) + P_4^{ex2}(t) + P_7^{ex2}(t) \tag{13}$$

$$P_6(t+\tau) = P_6(t) \tag{14}$$

$$P_7(t+\tau) = \frac{1}{3}L_2^P(t) + \frac{1}{3}L_5^P(t) + \frac{1}{2}L_6^P(t) + \frac{1}{3}L_7^P(t) + L_8^P(t) - \frac{1}{2}P_6(t) - P_8(t) + P_7^{ex1}(t) + P_2^{ex2}(t) + P_5^{ex2}(t) \tag{15}$$

$$P_8(t+\tau) = P_8(t) \tag{16}$$

Similarly, $Q(t+\tau)$ can be calculated by following the above steps. It notes that, Agent2 is the only agent that receive information of prescribed interactive $P_{MG}(t)$, as illustrated in (10).

4. Result

In this case, the prescribed interactive active and reactive power is set to 50 kW and 15 kVar respectively. The fluctuation of the illumination intensity and the wind speed are shown in Fig. 3(a). Moreover, the load demand is scheduled as below and the total active and reactive loads are illustrated in Fig. 3(b).

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%.

From Fig. 3(c), it can be seen that the active output power of DG1, DG3 and DG8 decrease gradually from t = 0 s to t = 3 s, and the active output power of DG6 remain almost unchanged. As shown in Fig.1, the current state of uncontrollable DGs are sent to controllable Agents by uncontrollable Agents. Then, according to the power balance term in the control laws, controllable agents increase the output power of controllable DGs to guarantee the power balance and the stability of the interactive power.

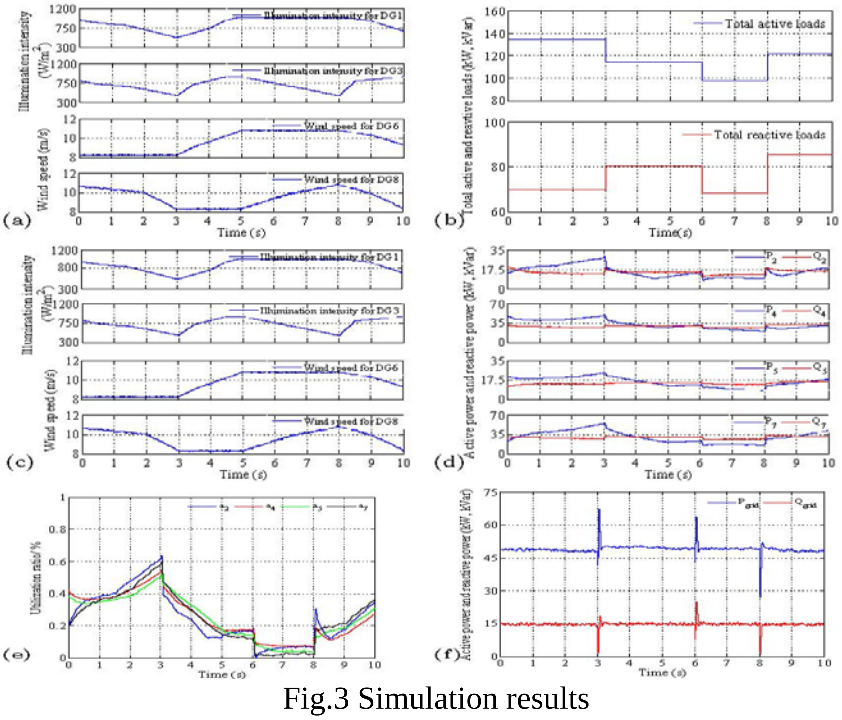

Fig.3 Simulation results

In addition, according to the MAS communication network in Fig.1, Agent2 compares the utilization ratio of DG2 with that of DG4 and DG7, then, the reference output power of DG2 is calculated according to (3). And then $P_2^{ex1}(t)$ is generated and sent to Agent2 to regulate the active output power of DG2, and $P_4^{ex2}(t)$ and $P_7^{ex2}(t)$ are generated and sent to Agent4 and Agent7, to regulate the active power output of DG4 and DG7 respectively, for the fair utilization ratios of controllable DGs. Likewise, the responses of other controllable DGs and agents can be analyzed in this way. Moreover, when load changes occurs, the control framework make the utilization ratio converge to new operating point.

In addition, the utilization ratios of controllable DGs are maintained the same. And it is evident that the interactive active and reactive power remain unchanged in 50 kW and 15 kVar respectively, as illustrated in Fig.3(e) and (f).

Conclusion

This paper presents a MAS based decentralized control framework for a grid-connected MG. Moreover, a set of dynamic control strategies are derived for agents in the communication network and the simulation results show that the prescribed interactive power and fair utilization ratios of controllable DGs are obtained.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant No. 51177177 & No. 61105125) and National “111” Project (Grant No. B08036).

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