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Brief Papers

Distributed power control for DERs based on networked multiagent systems with communication delays

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ABSTRACT

This paper develops a distributed secondary cooperative scheme for the current-controlled PWM inverters (CC-PWMIs) based on networked multiagent systems that can guarantee the accurate power sharing among the distributed energy resource (DER) units in microgrids. With the assumption that the communication networks are local, time-varying, and with low bandwidth, two distributed secondary controllers are designed such that all DERs in the microgrid can share their active and reactive powers accurately on the conditions of both fixed and switching topologies with time-varying communication delays. Moreover, delay-dependent sufficient conditions are obtained by using the Lyapunov–Krasovskii stable analysis method. The proposed controllers, allowing each DER unit to receive the current and active/reactive load information intermittently from its neighboring DERs, are then fully distributed. The effectiveness of the proposed control methodology is verified by the simulation of a low-voltage microgrid test system in the MATLAB/SimPowerSystems Toolbox.

1. Introduction

Microgrids are able to achieve the effective integration of a large number of DER units, loads and energy-storage elements connecting to the medium and low voltage grids via DC/AC inverters. They can operate in either a grid-connected or an islanded mode [1–3], then the switching between different modes will naturally lead to the load variations and power imbalance in microgrids. In this situation, the typical droop control technique (i.e., primary control), embedded locally in the inverter of each DER unit, will be applied to adjust their own output powers automatically [4,5]. However, the inaccuracy power sharing is still observed after this control layer [6,7]. Also, the deviations of frequency and voltage amplitude are the attendant problems.

In order to maintain the stability of microgrids, the traditional centralized secondary control is adopted, which will face the high costs of all to all communication and low reliability caused by a single point-of-failure [8,9]. An alternate approach is the distributed secondary control, which needs the communication among all DERs through equipping each DER with a communications equipment. This way, the secondary control problems can be transformed to the so-called network control problems, which can be solved by means of multi-agent system theory [10–13,22].

Due to the advantages of low communication burdens and highly computational efficiency for the distributed control strategies, many researchers began to investigate the secondary control problems of microgrids in a distributed fashion [14]. Specially, by using a low-bandwidth communication network, a distributed control method was proposed [15] for proportional load sharing and enhancement of voltage regulation in DC microgrids. For the microgrids with large number of DER units, a pinning-based distributed cooperative control idea is adopted [16] for autonomous microgrids, by which the number of controllers is greatly reduced. To avoid the communication latency, [17] studied the distributed control for frequency and voltage regulation by using a sparse communication network.

Apart from the frequency and voltage regulation, power sharing problems should be also considered. In [18], a distributed networked control system is used to ensure reactive power sharing and compensation of frequency and voltage amplitude deviations. However, the adopted distributed control scheme requires that each local controller communicate with all the other controllers across the entire system, then the communication costs of which are nearly the same as a centralized controller. In addition, the detailed analysis on the stability of the whole dynamics is missing. Following this line, a distributed averaging proportional integral (PI) controller is proposed for a first-order inverter model

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with coupled oscillators to guarantee the power sharing [19], where the node voltages are assumed to be constants and the reactive power sharing is not considered.

By analyzing the above literatures, most of them did not consider the influences of network variability and communication delays on the system stability. On the one hand, the emergence of a large number of open communication networks (e.g., Internet, GPRS, Power optical fiber or WiFi) will inevitably lead to the problems of dropout and communication delays. On the other hand, the variant topologies of communication networks might be caused by the frequent plug and play operations of DERs in a microgrids. Thus, both the communication delays and switching topologies should be taken into account when designing the secondary control strategies for microgrids.

Besides, a majority of the existing works focused on the microgrids consisting of voltage-controlled voltage source inverters [16–19]. However, it is very important for the DERs based on CC-PWMI to achieve suitable load power dispatches (e.g., photovoltaic arrays, flues cells) [20,21]. For example, the input DC voltage of CC-PWMIs is lower than the peak grid voltage and can vary in a wide range, which is more suitable and reliable for the maximum power point tracking (MPPT) control of photovoltaic arrays. This is in sharp contrast to the MPPT control based on voltage control–voltage source inverters, which might cause the voltage destroyed of DC bus, then reduce the responsibility of microgrids [7,19].

The objective of this paper is to study the distributed secondary control for proportional power sharing of CC-PWMI-based DER units via considering the communication delay effect for microgrids under switching network topologies. The main contributions of this paper lie in the following aspects: Firstly, we investigate the CC-PWMI-based DER units, which are one of the important voltage source inverters and are vital to maintain the stability of microgrids. However, the related works are very rare. Secondly, we design a distributed secondary control algorithm, locally installed in each DER unit, such that all DERs can adjust their own output active/reactive powers based on their power ratings in a distributed way. Then, the accuracy power sharing can be achieved. Thirdly, by Lyapunov–Krasovskii stable analysis technique, sufficient conditions on the requirements for the switching network connectivity, the upper bound of communication delays that can guarantee the stability of the controlled microgrid systems are derived. Finally, the simulation results show that the proposed method is robust to the communication delays and variant communication network topologies even if the considered communication networks are local, and with low bandwidth.

The remaining of the paper is organized as follows: In Section 2, the dynamics of DERs in microgrids and the necessary algebra graph theory are introduced. The distributed secondary controllers for CC-PWMI-based DER units in microgrids are designed in Section 3. Section 4 gives the simulation results by using the MATLAB/SimPowerSystems toolbox. We conclude the work in Section 5.

2. Problem formulation

Consider an islanded operating microgrid with parallel-connected CC-PWMIs-based DERs. The objective of active/reactive power control is to maintain the proportional load power sharing when the load demands or the output powers of DERs change in microgrids. To this end, we first formulate the dynamic model of CC-PWMI-based DERs, and then introduce the basic communication network in Section 2.1 and 2.2, respectively.

2.1. Dynamic model of CC-PWMI-based DERs

We adopt the *d*-*q* reference frame transformation, where the *d*-axis and *q*-axis are rotating at the common reference frequency ω^{com}. Fig. 1 shows the equivalent single-phase representation for a CC-PWMI-based DER. For the *i*th CC-PWMI-based DER, its active power and reactive power can be calculated as

$$\begin{cases} P_i = V_i^{\mathrm{g\_d}} I_i^{\mathrm{g\_d}} + V_i^{\mathrm{g\_q}} I_i^{\mathrm{g\_q}}, \\ Q_i = V_i^{\mathrm{g\_q}} I_i^{\mathrm{g\_d}} - V_i^{\mathrm{g\_d}} I_i^{\mathrm{g\_q}}, \end{cases} \tag{1}$$

where $I_i^{\mathrm{g\_d}}$, $I_i^{\mathrm{g\_q}}$ are chosen from the direct and quadrature (*d*-*q*) components of output current I_i^{g}, and P_i, Q_i are the measured active and reactive powers, respectively.

As usual, the d-axis is aligned to the output voltage vector, then we let $V_i^{\mathrm{g\_d}} = V_i^{\mathrm{g}}$ and $V_i^{\mathrm{g\_q}} = 0$. Rewrite (1) as

$$\begin{cases} P_i = V_i^{\mathrm{g\_d}} I_i^{\mathrm{g\_d}}, \\ Q_i = -V_i^{\mathrm{g\_d}} I_i^{\mathrm{g\_q}}. \end{cases} \tag{2}$$

Since $I_i^{\mathrm{g\_d}}$, $I_i^{\mathrm{g\_q}}$ are controlled by $I_i^{\mathrm{g\_d,ref}}$, $I_i^{\mathrm{g\_q,ref}}$, respectively, then by Eq. (2), we can directly use $I_i^{\mathrm{g\_d,ref}}$, $I_i^{\mathrm{g\_q,ref}}$ to control P_i, Q_i, respectively.

Based on the traditional droop control strategy, the reference voltage of the inverter for the *i*th DER, which is determined by the power control loop, can be abstracted as

$$\begin{cases} \dot{\psi}_i^{\mathrm{g\_d}} = I_i^{\mathrm{g\_d,ref}} - I_i^{\mathrm{g\_d}}, \\ \dot{\psi}_i^{\mathrm{g\_q}} = I_i^{\mathrm{g\_q,ref}} - I_i^{\mathrm{g\_q}}, \\ V_i^{\mathrm{inv\_d,*}} = V_i^{\mathrm{g\_d}} - \omega_i^{\mathrm{com}} L_i^{\mathrm{f}} I_i^{\mathrm{g\_q}} + k_i^{\mathrm{IP}} \left(I_i^{\mathrm{g\_d,ref}} - I_i^{\mathrm{g\_d}} \right) + k_i^{\mathrm{II}} \psi_i^{\mathrm{g\_d}}, \\ V_i^{\mathrm{inv\_q,*}} = V_i^{\mathrm{g\_q}} + \omega_i^{\mathrm{com}} L_i^{\mathrm{f}} I_i^{\mathrm{g\_d}} + k_i^{\mathrm{IP}} \left(I_i^{\mathrm{g\_q,ref}} - I_i^{\mathrm{g\_q}} \right) + k_i^{\mathrm{II}} \psi_i^{\mathrm{g\_q}}, \end{cases} \tag{3}$$

where k_i^{IP} and k_i^{II} are the PI controller coefficients of the current *I*.

Assume that the inverter bridge produces the demanded voltage $V_i^{\mathrm{inv,*}} = V_i^{\mathrm{inv}}$, (i.e., $V_i^{\mathrm{inv\_d,*}} = V_i^{\mathrm{inv\_d}}$ and $V_i^{\mathrm{inv\_q,*}} = V_i^{\mathrm{inv\_q}}$), the dynamics of the output RL filter are then given by

$$\begin{cases} L_i^{\mathrm{f}} \dfrac{dI_i^{\mathrm{g\_d}}}{dt} = -R_i^{\mathrm{f}} I_i^{\mathrm{g\_d}} + \omega_i^{\mathrm{com}} L_i^{\mathrm{f}} I_i^{\mathrm{g\_q}} + V_i^{\mathrm{inv\_d}} - V_i^{\mathrm{g\_d}}, \\ L_i^{\mathrm{f}} \dfrac{dI_i^{\mathrm{g\_q}}}{dt} = -R_i^{\mathrm{f}} I_i^{\mathrm{g\_q}} - \omega_i^{\mathrm{com}} L_i^{\mathrm{f}} I_i^{\mathrm{g\_d}} + V_i^{\mathrm{inv\_q}} - V_i^{\mathrm{g\_d}}. \end{cases} \tag{4}$$

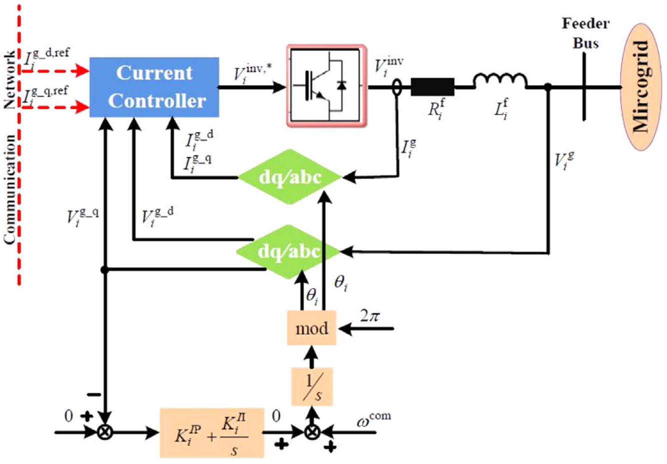

Fig. 1. The block diagram of the *i*th CC-PWMI-based DER, the red dotted lines represent the communication network. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)