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Consensus-Based Distributed Control with Communication Time Delays for Virtual Synchronous Generators in Isolate Microgrid

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Abstract

A consensus-based distributed control method of coordinated VSGs with communication time delays in isolate microgrid is proposed. When time delays are considered in communication, there are some effects on frequency restoration and active power output allocation. In the control structure, only local information exchange is needed, while the final frequency can be controlled to the nominal value and the VSGs can automatically share loads according to their rated values. An AC microgrid with three VSGs and some loads is implemented. The proposed control strategy is verified by MATLAB/Simulink simulation results.

Keywords

Virtual Synchronous Generator, Time Delays, Distributed Control, Consensus Algorithm

1. Introduction

Microgrids are active clusters of distributed generators (DG), energy storages and loads [1] [2]. More and more power electronic interfaced DGs are currently being installed in microgrid. However, these DGs cannot provide requisite inertia and damping support. Owing to the insufficient of inertia and damping, serious problems may arise, such as frequency fluctuation [3] [4].

Therefore, virtual synchronous generator (VSG) is proposed to solve those problems mentioned before. Generally, VSG is based on synchronous generator transient model to imitate its operating characteristics [5] [6]. VSGs can provide sufficient inertia and damping, so they are gradually applied in microgrids. In practice, it is necessary for VSGs to cooperate to meet high power requirement of the power supply system [7]. In [8], the mathematic model of VSG is proposed and droop control strategy is designed to share power between VSGs. Since VSGs essentially have droop characteristics, the control of existing microgrid with VSGs actually belongs to the decentralized control [9]. However, as the capacity of VSGs increase, it becomes difficult to coordinate all the VSGs to achieve a common purpose by decentralized control [10].

Compared with the decentralized control, the distributed control can achieve global management through exchanging information between neighbor VSGs [11]. Recently, the consensus-based distributed control scheme for microgrids has been introduced to address complex distributed communication problems [12] [13]. This scheme can help system frequency restoring and active power sharing according to each VSG's nominal ratings.

Nevertheless, when information is exchanged between connected VSGs through communication, time delays from both message transmission and processing should be considered [14]. In [15], average consensus problem for undirected networks of dynamic agents having communication delays is studied. In [16], a novel agreement framework for multiple agents evolving on a directed information graph with non-uniform delays is proposed. However, up to now, few works concentrate on the distributed control with time delays of coordinated VSGs.

Therefore, in this paper, a consensus-based distributed control method considering communication time delays of coordinated VSGs in isolate is designed. With node-to-node distributed communication, the proposed control method only needs several information exchanged between neighbors and the compute is not complex. In addition, the model with time delays has more practical value for engineering application.

The rest of this paper is organized as follows. In Section II, the model of VSG is implemented and the coordinated control structure of VSGs is formed. Furthermore, consensus algorithm with time delays will be presented. In Section III, the consensus-based control with time delays of coordinated VSGs is proposed. In Section IV, some simulations are realized to show the results of coordinated VSGs with different time delays. Finally, conclusion is summarized in section V.

2. Preliminaries

2.1. Control of VSGs

In general, VSG consists of a three phase legs and a three-phase LCL filter. The typical topology of VSG is shown in **Figure 1**.

In **Figure 1**, U_d, L, C and R are DC voltage, the filter inductance, capacitor and resistance, respectively. $u_0 = (u_a, u_b, u_c)^{\mathrm{T}}$ and $i_0 = (i_a, i_b, i_c)^{\mathrm{T}}$ are output three-phase voltage and current, which can be used to compute active and reactive power. The traditional droop control strategy is generally employed in VSGs.

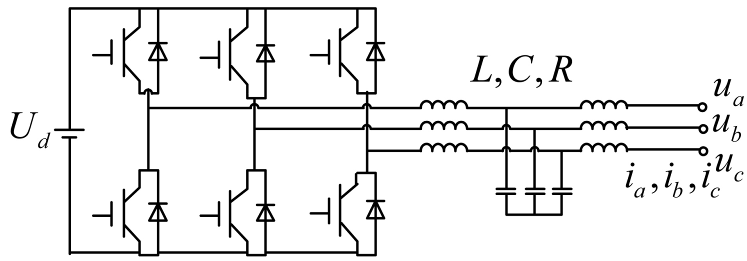

Figure 1. Topology of VSG.

The active power-frequency controller is shown in **Figure 2** and the active power-frequency droop control characteristics of VSG are shown graphically in **Figure 3**.

It is shown in **Figure 2** that P^* and P are rated active power and actual value. J is the imaginary moment of inertia, which can provide VSG with inertia in dynamic process. D is damping coefficient, which is used as feedback gain. ω_0, ω and θ are rated angular frequency, actual angular frequency and angle.

In **Figure 3**, f_a is nominal frequency, P_a is nominal active power output. Firstly the operation node is A. When load power increases to P_b, the operation node moves from A to B, and corresponding frequency is f_b. As we can see from **Figure 3**, there exist frequency deviations for the change of active power output, which should be compensated. In order to solve this problem, the coordinated control structure of VSGs is proposed, as shown in **Figure 4**.

It can be seen from **Figure 4** that the coordinated control structure of VSGs is performed at two levels. Active power-frequency droop control is implemented for primary level. At the second level, the distributed control is utilized to exchange information between neighbor VSGs, thus achieving frequency restoration and reasonably active power sharing.

2.2. Consensus Algorithm Based on Graphs Theory

The consensus algorithm is benefit for distributed cooperative control of VSGs. Consider an undirected graph, the *adjacency* matrix $\boldsymbol{A}$ represents the connection condition of communication topology. Because the nodes are mutually connected, $\boldsymbol{A}$ is a symmetric matrix. Meanwhile, the degree matrix $\boldsymbol{D}$, is a diagonal matrix, where the degree of vertex stands for the number of connected VSGs. The *Laplacian* matrix $\boldsymbol{L}$ of an undirected graph is then defined as

$$\boldsymbol{L} = \boldsymbol{D} - \boldsymbol{A} \tag{1}$$

When the communication topology is satisfied with the demand of a spanning tree, which means each node can reach every node by acertain way, then $\boldsymbol{L}$ is positive semi-definite with one zero eigenvalue [17].

The consensus algorithm can be described as

$$\dot{x}_i = \gamma \sum_{j=1}^{n} l_{ij} (x_i - x_j) \tag{2}$$

where x_i, x_j are control variables of VSG$_i$ and VSG$_j$, n is the number of VSGs, γ is

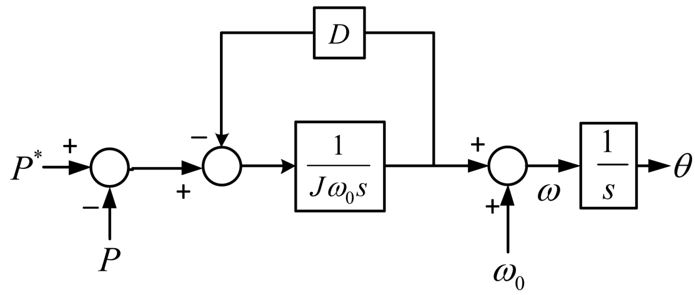

Figure 2. Active power-frequency droop controller.

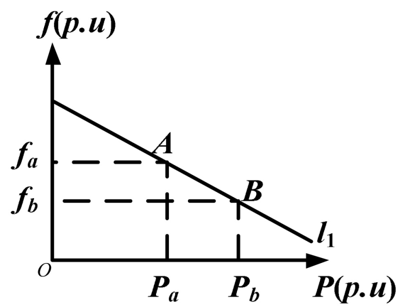

Figure 3. Active power-frequency droop control characteristic.

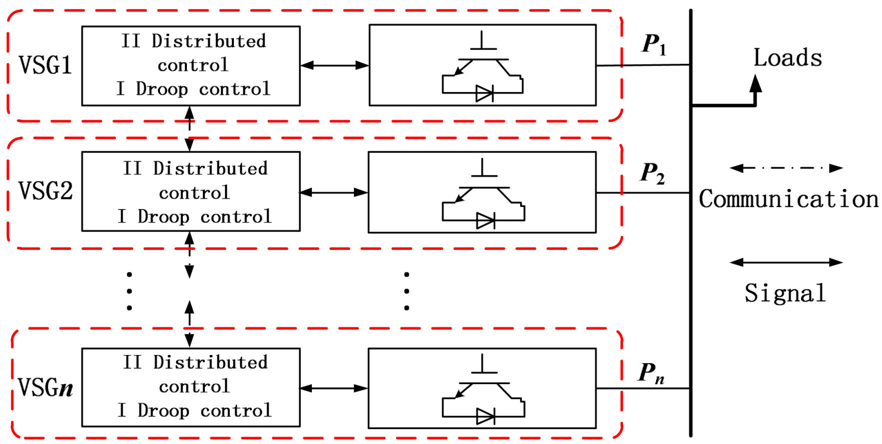

Figure 4. Coordinated control structure of VSGs.

called the diffusion constant and l_{ij} is the element of $\boldsymbol{L}$. If time delays are taken into consideration, formula (2) is modified as

$$\dot{x}_i = \gamma \sum_{j=1}^{n} l_{ij} \left[x_i \left(t - \tau_i \right) - x_j \left(t - \tau_j \right) \right] \tag{3}$$

In the simplest case of $\tau_i = \tau_j = \tau$, it means that transmission and processing time delays of all VSGs are equal. When the system meets the demand of a spanning tree and time delays are in a certain range, all VSGs may globally reach an average-consensus as described below

$$\lim_{t \to +\infty} x_i(t) = \lim_{t \to +\infty} x_j(t) = \frac{1}{n} \sum_{k=1}^{n} x_k(0) \tag{4}$$

In a word, consensus algorithm can be used to reach active power output agreement among VSGs.

3. Consensus-Based Distributed Control Performance

3.1. Consensus-Based Distributed Control

According to the coordinated control structure of VSGs and the consensus algorithm, the control method is depicted as follows

$$J_i \omega_0 \dot{\omega}_i + D_{p,i}(\omega_i - \omega_0) = P_i^{set} - P_i^{inj} - p_i^{reg} \tag{5}$$

$$k_{p,i} \dot{p}_i^{reg} = P_i^{set} - P_i^{inj} - p_i^{reg} + \sum_{j=1}^{n} l_{ij} \left(\frac{p_i^{reg}}{D_{p,i}} - \frac{p_j^{reg}}{D_{p,j}} \right) \tag{6}$$

where P_i^{set} and P_i^{inj} are rated active power and actual value of VSG$_i$ and p_i^{reg} is the regulated value of active power, the subscript i is the serial number of VSGs. $D_{p,i}$, $D_{p,j}$ are the damping coefficient of VSG$_i$ and VSG$_j$. $k_{p,i}$ is the frequency restoration coefficient of VSG*i*. J_i is the imaginary moment of inertia, ω_0 is rated angular frequency.

Neighbor VSGs will exchange the information to achieve consensus. Finally, according to the consensus algorithm, when

$$\frac{D_{p,1}}{P_1^{set}} = \frac{D_{p,2}}{P_2^{set}} = \dots = \frac{D_{p,n}}{P_n^{set}} \tag{7}$$

then

$$\frac{P_1^{inj}}{P_1^{set}} = \frac{P_2^{inj}}{P_2^{set}} = \dots = \frac{P_n^{inj}}{P_n^{set}} \tag{8}$$

According to (8), the active power output of each VSGs are determined by their rated active power [10].

3.2. Consensus-Based Distributed Control with Time Delays

In practice, transmission and processing time delays should be considered. When time delays are introduced, the control method can be described as

$$k_{p,i} \dot{p}_i^{reg} = P_i^{set} - P_i^{inj} - p_i^{reg} + \sum_{j=1}^{n} l_{ij} \left[\frac{p_i^{reg}(t - \tau_i)}{D_{p,i}} - \frac{p_j^{reg}(t - \tau_j)}{D_{p,j}} \right] \tag{9}$$

In accordance with (5) and (9), the control block diagram for each VSG is shown in **Figure 5**.

As is shown in **Figure 5**, there are three main sections, including droop unit, restoration unit and consensus unit. Droop unit and restoration unit can conduct primary frequency regulation and second frequency regulation. Consensus unit exchanges active power regulation information between neighbor VSGs. Time delays, which generally exist in communication, are mainly considered. Thus the consensus-based distributed control with time delays for VSGs is comprehensively built.

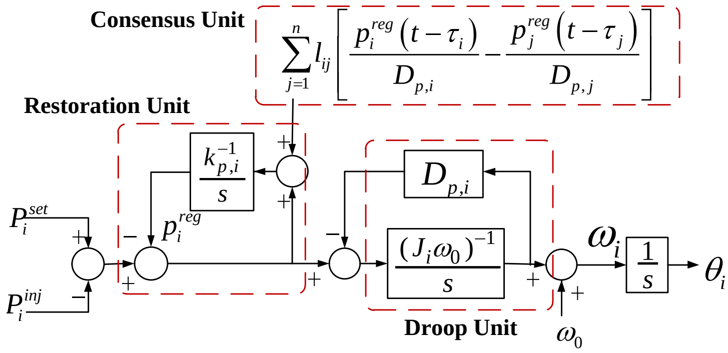

Figure 5. Configuration of VSGs consensus-based distributed control with time delays.

4. Simulation Analysis

An AC microgrid with three VSGs and one aggregate load was implemented to test the effectiveness of the consensus-based distributed control formulation (5) and (9) presented in Section III.

The main parameters of simulation are that P_1^{set} = 10 kW, P_2^{set} = 20 kW, P_3^{set} = 30 kW, D_{p1} = 1000 kW/rad·s^{-1}, D_{p2} = 2000 kW/rad·s^{-1}, D_{p3} = 3000 kW/rad·s^{-1}, $k_{p1} = k_{p2} = k_{p3}$ = 4 s and $J_1 = J_2 = J_3$ = 1.061 kg·m^2. **Figure 6** shows the communication topology.

It can be seen from **Figure 6** that VSG_1 can communicate with VSG_2, while VSG_2 and VSG_3 have communication links.

At 0 s, three VSGs will provide energy to the common load, whose power consumption is 60 kW. Different value of time delays are considered, including $\tau = 0$, it represents no time delay, τ = 0.1 s, τ = 0.2 s, τ = 0.3 s and τ = 0.5 s.

Simulation results of system frequency are shown in **Figure 7** with different time delays.

As is shown in **Figures 7(a)-(c)**, for the increase of load, the system frequency declines and it takes about 1s for frequency to restore to 50 Hz. However, when time delays are chosen to be 0.3 s and 0.5 s, shown in **Figure 7(d)**, **Figure 7(e)**, the frequency oscillates and the system is unstable.

Simulation results of active power output are also shown in **Figure 8** with different time delays.

It can be observed from **Figure 8(a)**, it takes about 1s to achieve stability. Furthermore, P_1^{inj}, P_2^{inj} and P_3^{inj} are about 10 kW, 20 kW and 30 kW, respectively. So the active power output allocation ratio is 1:2:3, which is equal to the scale of the rated value of three VSGs.

In **Figure 8(b)**, the time delay is 0.1 s and the active power output will quickly reach stability, too. Moreover, in **Figure 8(c)**, when the time delay is set to be 0.2 s, the active power output will have slight fluctuations. With time delay being 0.1 s or 0.2 s, the final ratio of active power output can maintain the setting proportion.

However, if the time delay is 0.3 s or 0.5 s, as is shown in **Figure 8(d)** and

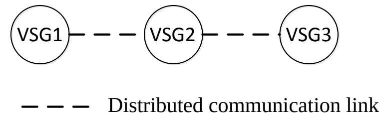

Figure 6. Communication topology.

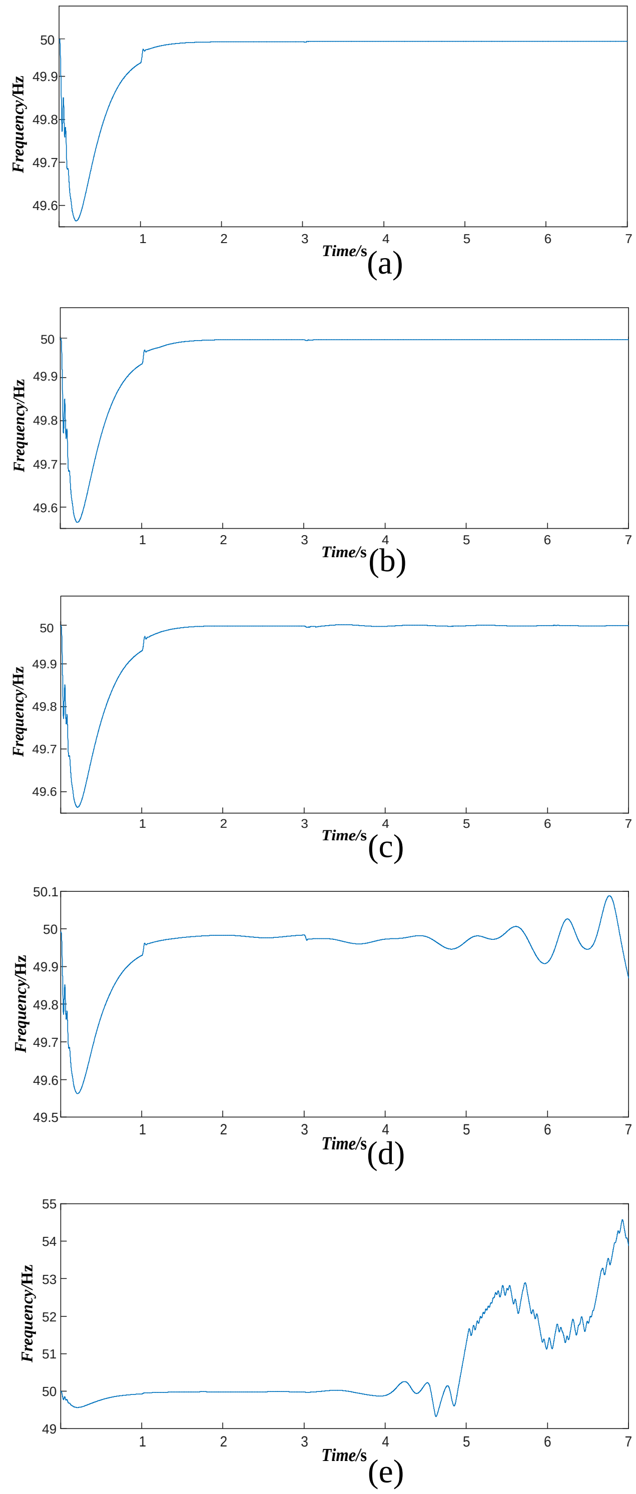

Figure 7. Waveform of frequency, (a) $\tau = 0$, (b) $\tau = 0.1$ s, (c) $\tau = 0.2$ s, (d) $\tau = 0.3$ s, (e) $\tau = 0.5$ s.

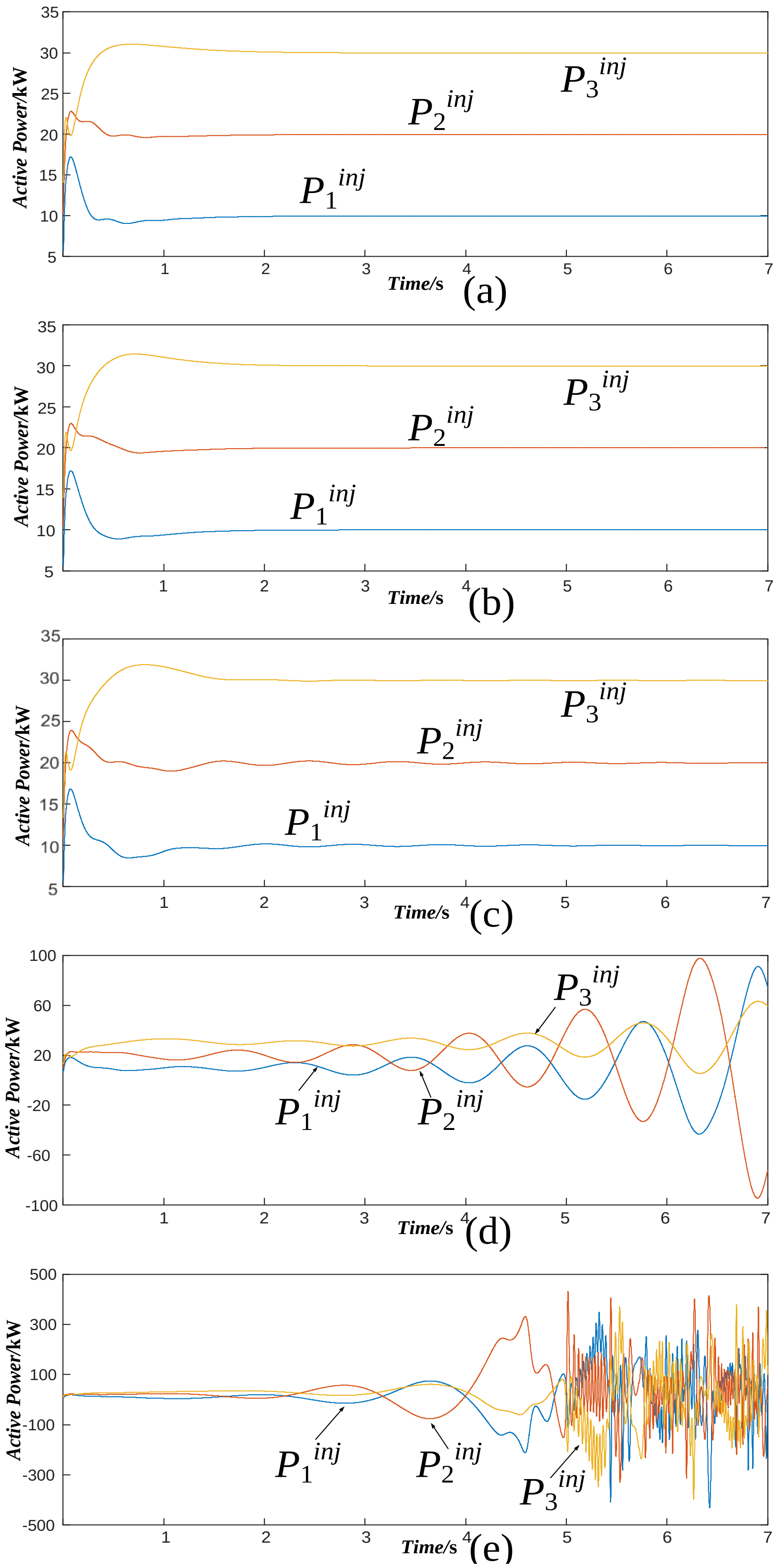

Figure 8. Waveform of active power, (a) $\tau = 0$, (b) $\tau = 0.1$ s, (c) $\tau = 0.2$ s, (d) $\tau = 0.3$ s, (e) $\tau = 0.5$ s.

Figure 8(e), the system will become unstable. In a word, when the communication time delays are in a certain range, the system can keep stable, while the communication time delays is out of this range, the system will get unstable. Therefore it is very important to find a maximum boundary of time delays. Through the improvement of communication technology, time delays should be limited less than the maximum boundary.

5. Conclusion

In this paper, a consensus-based distributed control with time delays for coordinated VSGs is designed. With node-to-node distributed control, the communication cost decreases and the communication stability increases. Under ideal condition, there is no communication time delays and the system performsvery well. However, in practical engineering, time delays cannot be avoided. If the time delays are large enough, the system will not be stable. This research can provide useful reference for the application of VSG in microgrid and active power distribution network. In the future, we will research the maximum boundary of time delays, which can maintain system stability

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