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Hierarchical frequency control strategy of hybrid droop/VSG-based islanded microgrids

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ABSTRACT

Compared to the conventional centralized power system, in which synchronous generators with speed control offering favorable dynamic behaviors, the islanded microgrid dominated by distributed generators may encounter severe frequency instability. Thus droop control and virtual synchronous generator control have been proposed to design the primary frequency level of the islanded microgrids. In this context, both of these two control strategies will coexist and interact with each other in a microgrid due to their different reaction speed. This paper focuses on the frequency stability of islanded microgrids. The interactions between virtual synchronous generator-based and droop-based parallel inverters are firstly investigated. The small-signal model is used to study the effects of variation of important control parameters. Then the secondary level is also established to compensate the frequency deviation. The internal model control based strategy is used to improve robustness for communication delays of the secondary level. Furthermore, a traditional PI controller is also proposed based on robust $H\infty$ method for comparison. An islanded microgrid test system including four distributed generators dominated by different control strategies is built in PSCAD/EMTDC to verify the proposed control structure.

1. Introduction

With the increased penetration level of distributed generators (DGs), the concept of microgrid is proposed and has received great world-wide attentions. Microgrids, as the basic components of the smart grid, can effectively integrate, control and manage the DGs and distributed energy storages [1]. Normally, a microgrid operates in grid-connected mode where the microgrid is access to the main grid via the point of common coupling (PCC). And it can turn into islanded mode as well when the main grid is in fault or overhaul [2–4].

When operating in islanded mode, the microgrid has to build voltage and frequency references itself. In this context, the hierarchical control structure consisting of three levels is recognized gradually [5,6]. Under this structure, the primary control level is dominated by droop mechanism. Thus each DG can share active and reactive power only using the locally available information and then fast communication can be avoided. To overcome drawbacks of traditional droop control method, the solution such as virtual impedance strategy is also proposed [7,8]. Compared to the conventional centralized power system, where synchronous machines with speed and excitation control offer favorable dynamic behaviors, the islanded microgrids dominated by DGs with power electronic interfaces may encounter severe frequency instability due to their negligible inertia. Hence, a novel concept namely virtual synchronous generator (VSG), which takes advantage of energy storage system and learns from experience of synchronous generator operation, is put forward [9,10]. The VSG can reproduce the dynamic properties of a traditional synchronous generator by mimicking the mechanical rotor and governor. Although no mechanical components exist in reality, it is electrically fully equivalent between an electronmechanical synchronous generator and a VSG from a grid point of view [11]. In this context, DGs with different kinds of control strategies will coexist in a microgrid. Refs. [12] and [13] investigated the relationship between droop control and VSG control. However, the interactions between VSG control and droop control in a microgrid are not considered, especially the interactions due to their different reaction speeds.

In addition, the primary control may cause frequency deviation. Thus the secondary frequency control level is needed to compensate the steady state error. Depending on implementation ways, the secondary control strategy can be classified into distributed control and centralized control. The former does not rely on a central controller. But complex distributed control algorithms are always

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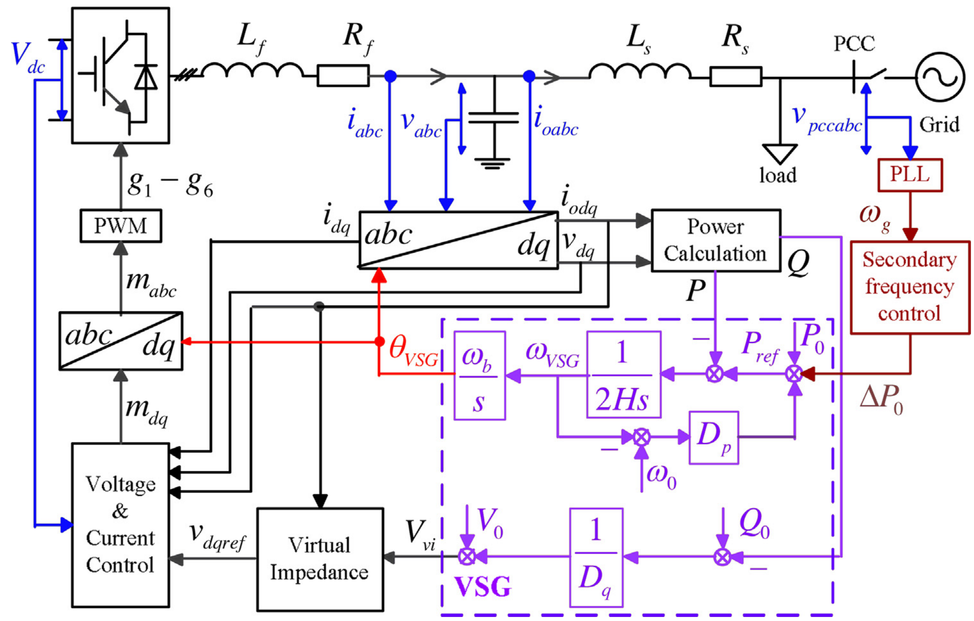

Fig. 1. Topology and control structure of the system.

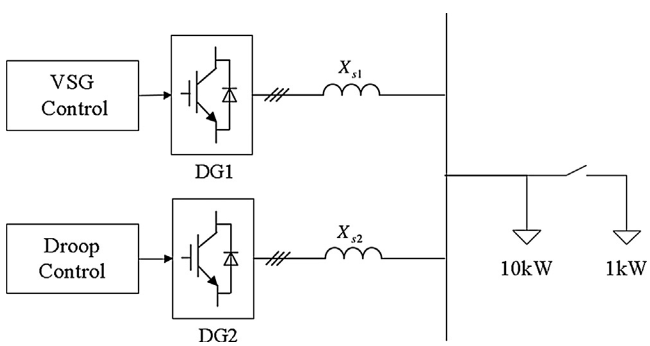

Fig. 2. Structure of two paralleled inverters with different control strategies.

necessary [14–16]. On the contrary, central control structure needs only simple controller such as PI controller. In a microgrid, however, the performance of the traditional PI controller may deteriorate in the presence of communication delays [17,18]. Ref. [19] investigated the impact of communication delays on secondary frequency control and proposed a gain-scheduling methodology. However it depended on the time stamps and should get the offline gains table in advance. Furthermore, it did not consider the VSG. Ref. [20] compared three different kinds of methods considering communication delays while neglecting the primary control due to the fast dynamics of the droop controller. Also the VSG was not considered.

In this paper, a hierarchical frequency control structure for an islanded microgrid is investigated. Some DGs are dominated by VSG control to mimic the dynamics of the synchronous generators with the equivalent inertia of the islanded microgrid being increased. Then interactions between the droop controller and the VSG are investigated. Furthermore, the secondary frequency control considering the communication delays is studied. A secondary frequency control strategy based on the internal model control (IMC) is developed to improve robustness for communication delays. For comparison, a robust H∞ based PI control strategy is also proposed.

The rest of this paper is arranged as follow. Section 2 describes the implementation of the VSG control strategy including inner control and virtual impedance loops. The interactions between VSG and droop control are also discussed in this section, with secondary frequency control structure given in Section 3. Section 4 presents the results using an islanded microgrid test system. This paper is concluded in Section 5.

2. Implementation of virtual synchronous generator in islanded microgrid

The topology and control structure of the system is shown in Fig. 1. The topology includes a three-phase voltage source inverter (VSI) and an LC filter. To implement the control system, filter inductance currents, i_{abc}, filter capacitor voltages, v_{abc}, and output currents, i_{oabc}, are measured and transformed to the *d-q* frame. Thus the output active and reactive powers of VSG can be calculated using the following expressions:

$$P = v_d i_{od} + v_q i_{oq} \tag{1}$$

$$Q = v_q i_{od} - v_d i_{oq} \tag{2}$$

where v_d and v_q are the capacitor voltages in the *d-q* frame, i_{od} and i_{oq} are the output currents of VSG in the *d-q* frame. Besides, the DC-voltage is measured to obtain the modulation signals. Then the modulation signals in the *d-q* frame, m_{dq}, can be generated passing through VSG control, virtual impedance control, inner voltage and current control. In the inner control loop, feed-forward of output current and capacitor voltages is included.

The implementation of the virtual impedance can be shown as

$$v_{dref} = V_{vi} - R_v i_{od} + X_v i_{oq} \tag{3}$$

$$v_{qref} = -R_v i_{oq} - X_v i_{od} \tag{4}$$

where v_{dref} and v_{qref} are the references of the voltage inner control loop, R_v and X_v are the virtual resistor and reactance, V_{vi} is the *d*-axis input of the virtual impedance control and can be derived from *Q-V* droop. The control strategy is based on the angle orientation of the virtual rotor of VSG. Thus the *q*-axis input of the virtual impedance control is zero. The virtual impedance can suppress oscillation of output power and decouple active and reactive power control loops. Then the voltage references of the inverter, e_{dref} and e_{qref}, are derived via the inner voltage and current loops, and are used to PWM.