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A control strategy for microgrid inverters based on adaptive three-order sliding mode and optimized droop controls

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ABSTRACT

Robust control and seamless formation are the two crucial problems that affect smart microgrids. This paper proposes a new solution for microgrid inverters in terms of circuit topology and control structure. The combined three-phase four-wire inverter, which is composed of three single-phase full-bridge circuits, is adopted in this study. The control structure is based on the inner adaptive three-order sliding-mode closed-loop, the immediate virtual output-impedance loop, and the outer power control loop. Three significant contributions are obtained: (1) the microgrid inverters effectively reject both voltage and load disturbances with the adaptive sliding-mode controllers regardless of whether the inverters are operating in the grid-connected mode, islanding mode, or transition from the grid-connected mode to the islanding mode; (2) the virtual output impedance loop is applied to make a resistive equivalent output impedance of the inverters and to meet the requirements of the inverter parallel operation in the islanding mode; (3) the proposed droop method reduces the line inductive impedance effects and improves the power sharing accuracy by optimizing the droop coefficients. The theoretical analysis and test results validate the effectiveness of the proposed control scheme.

1. Introduction

The installation of distributed generations (DGs) has been given progressive attention not only because of the increasing concern toward environmental emissions from centralized power plants but also because of economic and technical reasons [1–4]. However, the penetration of DGs in a power system is limited because of technical reasons, such as stability constraints. IEEE Standard 1547.4 has recently proposed a clustering concept that uses a microgrid as the building block of DG power systems [5–7]. The microgrid should be able to operate in both the grid connected and islanding modes. Furthermore, the transition between the two modes should be seamless. DGs are usually interfaced through power electronic converters to provide loads. A flexible operation and a robust control of DG interfaces are the major objectives of smart microgrid research [6,7].

The output performance and the robustness of microgrid inverters are mainly affected by the effectiveness of the control strategy used [8–13]. The control strategy is usually composed of the outer power control loop and the inner voltage closed-loop. In the past decade, various closed-loop control techniques (*e.g.*, proportional-resonant control [9], Lyapunov-function-based control [10], two degrees-of-freedom control [11], H∞ control [12], and fuzzy control [13]) have achieved a dynamic characteristic and disturbance rejection under different load types. However, most of these works are only suitable for the grid-connected mode or islanding mode. Some recent works have focused on the sliding-mode control method [14–17]. A robust sliding-mode controller is proposed in Ref. [14] to control the active and reactive powers of a double fed induction generator (DFIG) wind system without involving any synchronous coordinate transformation. However, the DFIG wind system usually operates in the grid-connected mode and stops when a fault occurs or the power quality in the utility decreases. Wai et al. [15] design the adaptive total sliding-mode controllers, which correspond to different operation modes for single-phase inverters. However, the parallel operation has not been considered. Mohamed et al. [16] present a direct-voltage control strategy for a microgrid converter on the basis of the sliding-mode dynamic controller. The method can realize a normal operation in both the grid-connected and isolated modes. However, the output current performance in the grid-connected mode is unimpressive because of the indirect current control. In Ref. [17], a dual-loop controller is proposed for a voltage source inverter control. The inner loop is designed by using the sliding-mode control strategy, and the inner loop generates the pulse-width modulation voltage

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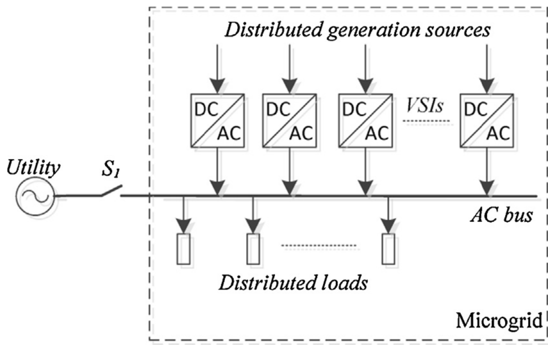

Fig. 1. A simplified microgrid system.

commands to regulate the inverter currents. Nevertheless, previous studies have not considered the chattering phenomenon of the sliding-mode control. The current study designs new closed-loop controllers that correspond to different operation modes on the basis of the adaptive three-order sliding-mode control. The closed-loop adopts direct current control in the grid-connected mode, whereas the islanding mode adopts the direct-voltage control. The voltage and load disturbances are effectively rejected. Furthermore, the dynamic switching process from the grid-connected mode to the islanding mode is smooth. In order to solve the unbalanced problem, the combined three-phase four-wire inverter, which is composed of three single-phase full-bridge circuits, is adopted in the paper.

Another problem for microgrid inverters in the islanding mode is the power sharing accuracy. The inverters should be able to proportionally share the distributed loads to their power ratings. The droop methods, which emulate the behavior of large power generators, are usually adopted to wirelessly perform functions [19–21]. The equivalent output impedance of the inverter should be resistive or inductive, which is the basic prerequisite for the application of the droop method. In the actual system, the output impedance is resistive–inductive and hard to measure or estimate. A possible solution is the addition of an inductor in the series with an inverter output. Nevertheless, this inductor is heavy and bulky and can cause an imbalance among the three phases. Hence, another method that places the virtual output impedance loop into the control structure is adopted [22,23]. This paper adopts a virtual resistive output impedance loop on this basis. Furthermore, an optimized droop controller that considers line impedance is designed. The power sharing accuracy and dynamic response can be effectively improved by controlling the current feedback gain and optimizing the droop coefficients.

Section 2 describes the system, including the circuit topology, the system model, and the basic principle of the decentralized parallel operation. Section 3 presents the proposed control structure and the analysis. Section 4 shows the test results, which demonstrate the effectiveness and the applicability of the proposed control strategies. Section 5 concludes.

2. System descriptions

A simplified microgrid system that consists of DGs, distributed loads, utility, voltage source inverters (VSIs) and AC bus is shown in Fig. 1. VSIs generally operate in the grid-connected mode, and the power is transmitted from the DGs into the utility. When a fault occurs or when the power quality in the utility worsens, the microgrid system disconnects from the utility by cutting off switch S1. The system then enters the intentional islanding mode. DGs and VSIs should be able to proportionally share the variable distributed loads to their power ratings and maintain the consistency of load voltage. If the utility recovers, the microgrid system reconnects to the utility. The dynamic models of the inverter in the grid connected and islanding modes differ according to the operation mode performance.

2.1. Inverter topology

In the actual microgrid, the distributed loads are usually unbalanced, and sometimes the single-phase loads are dominant. So when it comes to the inverter design, the serious load imbalance problem should be considered firstly [18]. Then the VSI topology which is shown in Fig. 2 is adopted in this paper. The topology is composed of three single-phase full-bridge circuits (T1–T12), low-pass filters (L_f and C_f), and an isolated transformer (T). R_f is the LC filter resistance per phase, and Z_{line} is the line impedance between the inverter and bus. u and i are the output voltage and the current of the modular inverter circuit, respectively. v_o and i_o are the output voltage and current of the low-pass filter. Subscripts a, b, and c represent the three phases. Furthermore, each phase in the topology can be controlled independently.

2.2. The model in the grid-connected mode

Before analyzing the model, the following assumptions are made: (1) all switching devices are ideal and delay time is neglected; (2) the isolated transformer T is ideal, its turn ratio is 1:1 and its phase angle shift is not considered. Therefore, when the microgrid operates in the grid-connected mode, the dynamic equation of every phase in the VSI is represented as follows:

$$\frac{di_o}{dt} = \frac{1}{L_f}(K_{PWM}v_{con} - v_s - i_oR_f - v_{sd}), \quad (1)$$

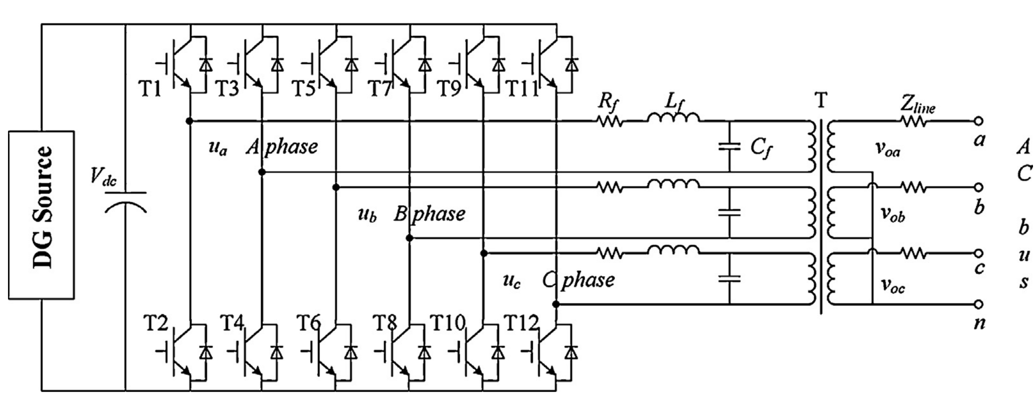

Fig. 2. Topology of the three-phase four-wire inverter.