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A power sharing scheme for voltage unbalance and harmonics compensation in an islanded microgrid

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ABSTRACT

In this paper, a hierarchical control structure with voltage unbalanced compensation scheme in ac islanded microgrid is proposed to improve Critical Load Bus (CLB) voltage quality and address inaccurate power sharing problems. The hierarchical scheme includes primary and secondary control levels. The primary control mainly contains the power droop controllers, voltage and current controllers, selective virtual impedance loop, and voltage unbalanced compensation. The virtual impedance loop includes virtual positive- and negative-sequence impedance loops at fundamental frequency and virtual variable harmonic impedance loop at harmonic frequencies. The secondary control is designed to restore frequency and amplitude of the CLB voltage. In order to compensate the CLB voltage, an unbalanced compensation is proposed to change the voltage reference of the distributed generation (DG) units. This strategy also employs the low bandwidth communication (LBC) technique to send the proper signals of the secondary control from the microgrid control center (MGCC) to the primary control. To evaluate the performance of the proposed control strategy, simulations are conducted on two islanded microgrid prototype. The results demonstrate the effectiveness of the proposed control structure in the unbalance and harmonic compensation of the CLB voltage and proper power sharing of reactive, unbalanced and harmonic powers among the DG units.

1. Introduction

Unbalanced and nonlinear load conditions are the common case in low voltage microgrids, where the most of the loads are single phase [1]. The voltage unbalance mainly emerges through the connection of single-phase loads between two phases or between one phase and the neutral [2]. The unbalance and harmonic-distorted voltage have some negative impacts on critical loads that are sensitive to voltage deviations, such as electronic loads, adjustable speed drives and induction motors. Therefore, a control strategy should be designed for the DG units to improve the performance of microgrids under unbalanced and nonlinear load conditions.

One major method for compensation of voltage unbalance and harmonics is the use of series active power filter in series with the distribution line by injecting negative sequence and harmonic voltage [3]. Also, in Refs. [4–6], shunt compensation is provided to mitigate voltage unbalanced and harmonic distortion. In this method, unbalanced load voltage is compensated by balancing the line currents. However, for the islanded microgrid conditions, it is uneconomic to install extra series/parallels active power filter for each of the DG.

Several control strategies have been presented to improve the quality of ac microgrid. In Ref. [7] a control strategy based on droop control method is proposed for a microgrid. The method improves the power quality and proper power sharing in the presence of unbalanced and nonlinear loads. In Refs. [8–12], the virtual impedance is proposed to balance load voltage and share the nonlinear load among DG units. However, in this study, the unbalanced voltage drop of the virtual impedance is not considered, which eventually lead to unbalance of the output voltage. In Refs. [13–15], hierarchical control structure is proposed for voltage unbalance compensation at sensitive loads. However, in most proposed methods, the compensation of voltage harmonics at the DG terminal is investigated, while the power quality at PCC is usually the main concern due to critical loads, which may be connected to PCC [16]. Furthermore, power quality problems under unbalanced and nonlinear loads and power sharing problems with mismatch feeder impedance are scarcely considered. Therefore, in this paper, a hierarchical control structure consisting of several electronically-interfaced three-wire DG units is proposed for an islanded microgrid that includes primary and secondary control levels. It has been supposed that DG capacities can be different. In

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the primary control, the P–f/Q–V droop method has been used. In order to compensate the CLB voltage, a voltage unbalance compensation is proposed to change the voltage reference of the distributed generation (DG) units. In this method, voltage drop across the feeders is estimated for each phase and added to voltage reference generated by the Q–V droop control method. The reactive power sharing is sensitive to the impacts of mismatched feeder impedance. In the proposed control strategy, the mismatch in voltage drops across feeders is compensated. Moreover, in order to avoid the active and reactive power control coupling and also, due to reduction of the fundamental negative sequence circulating current, the virtual positive- and negative-sequence impedance loops with voltage and current control loops have been utilized. Also, the virtual variable harmonic impedance loop at specific harmonic frequency has been used for proper sharing of harmonic power among all the DGs. Furthermore, for performance improvement of the Q–V droop control method; the voltage drop of the virtual positive sequence impedance has been considered. The second order generalized integrator (SOGI) has been implemented to extract the fundamental positive- and negative-sequence currents in order to calculate voltage drop on the fundamental positive- and negative-sequence virtual impedance. The secondary control is designed to restore frequency and amplitude of CLB voltage. The performance of the proposed strategy in microgrids with two parallel DGs is evaluated and reported in this paper. The main novelties of this paper are summarized as follows.

1) Balance of the CLB voltage by voltage drop estimation across the feeder impedance. In order to compensate the CLB voltage, a voltage unbalance compensation is proposed to change the voltage reference of the distributed generation (DG) units.
2) Enhancement of the accuracy of reactive power sharing of the islanded microgrid. In the proposed control strategy, the mismatch in voltage drops across feeders is compensated.
3) Improvement performance of the Q–V droop control method by considering the voltage drop of the virtual positive sequence impedance.

The rest of this paper is organized as follows. The structure of the proposed hierarchical control strategy is analyzed in detail in Section 2, including calculation of the active and reactive power for each phase, P–f/Q–V droop control method, voltage unbalanced compensation, voltage and current control loops and secondary control. The controller performance with/without control strategy is evaluated and compared in Section 3. Finally, conclusions are drawn in Section 4.

2. Microgrid hierarchical control strategy

The hierarchical control structure consists of two control levels: primary and secondary level. The primary control comprises DG local controllers. The local controllers, including power droop controllers, voltage and current controllers, selective virtual impedance loop and unbalance voltage compensators, balance the PCC voltage and share power load between DGs based on their capacity. Furthermore, unbalance voltage compensators can compensate the mismatch in voltage drops across feeders by voltage drop estimation without requiring knowledge of the feeder impedances. The central secondary control level is designed to restore the PCC frequency and voltage amplitude deviations by sending proper reference signals to each of the DGs. The LBC is used for sending the data communication of the secondary controllers and active and reactive power references from the MGCC to the local controller. The MGCC provides the individual power and voltage reference for each local controller. If communication is disrupted, the primary control autonomously compensates voltage unbalance and harmonics and properly share the active and reactive power according to the local measurements unless total load changes, in the case of which, the sharing accuracy is reduced, but the proposed control method still outperforms the traditional droop control method. In this paper, a three-phase three-wire islanded microgrid is considered. The proposed control strategy of an individual DG unit is shown in Fig. 2.

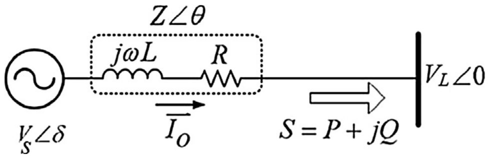

Fig. 1. Equivalent circuit of a DG connected to a load bus.

2.1. The primary control

The primary control is designed to: (1) satisfy decentralized adjustment of the voltage and frequency of the microgrid and properly shared power load between DGs based on its capacity in islanding mode, (2) compensate voltage unbalance and harmonics, (3) minimize the fundamental and harmonic circulating current between DG units, and (4) compensate the mismatch in voltage drops across feeders.

2.1.1. The P–f/Q–V droop control method

The droop control method can be studied by considering an equivalent circuit of a DG connected to load bus, as shown in Fig. 1. The DG unit modeled as an AC source, with the voltage of $V_S\angle\delta$. The load bus voltage is $V_L\angle 0$.

The real and reactive power delivered to load bus is given by

$$P = \frac{V_S^2}{Z}\cos\theta - \frac{V_S V_L}{Z}\cos\left(\theta + \delta\right) \tag{1}$$

$$Q = \frac{V_S^2}{Z}\sin\theta - \frac{V_S V_L}{Z}\sin\left(\theta + \delta\right) \tag{2}$$

If the effective line impedance is purely inductive, $\theta = 90^\circ$ and Z = jX, then (1), (2) can be reduce to

$$P = \frac{V_S V_L}{X}\sin(\delta) \tag{3}$$

$$Q = \frac{V_S^2}{X} - \frac{V_S V_L}{X}\cos(\delta) \tag{4}$$

If the phase difference between the DG output voltage and load bus, δ, is small, it is reasonable to suppose, $\cos\delta \approx 1$ and $\sin\delta \approx \delta$. Then, the frequency and amplitude of the DG output voltage reference can be expressed as follows:

$$f = f_0 - D_p(P_0 - P) \tag{5}$$

$$V = V_0 - D_q(Q_0 - Q) \tag{6}$$

where f_0, V_0 are the frequency and voltage magnitude references, D_p, D_q are droop coefficients and P_0 and Q_0 represent the real and reactive power references. The P_0 and Q_0 from each DG are set by the MGCC. For determining the Q–V droop coefficient, the voltage drop across virtual impedance should also be taken into consideration [17]. As a result, droop coefficient is modified as follows

$$D_{qi}{}^{new} = \frac{V_{0i}{}^{new} - V_{i\,\min}{}^{new} - I_{o\,\max}|Z_{vi}|}{Q_{0i} - Q_{i\,\max}} \tag{7}$$

where $|Z_v|$ is virtual positive-sequence impedance and I_{omax} is output current at full load.