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Advanced localized reactive power sharing in microgrids

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ABSTRACT

The droop characteristics have gained much attention for controlling the distributed generation (DG) units in an islanded microgrid, since they obviate the requirements for communication infrastructure and have relatively fast response time. However, inability to properly share the reactive power due to line impedance mismatches is one of the major drawbacks of droop characteristics. In this paper, a method for decreasing the reactive power sharing error is proposed which is based on changing the operating points of the microgrid resources by correcting the voltage droop characteristic. The proposed method consists of three stages, namely, initial load sharing using the conventional droop characteristics, estimating the appropriate amount of correction which in operating point of each source, and applying this correction by changing the y-intercept of voltage droop characteristic. Deployment of this method does not disturb the microgrid voltage and frequency stability and preserves the plug and play attribute of sources. Additionally, the proposed method can be implemented locally at each DG without the requirement of communication infrastructure. Simulation and experimental results are presented to verify the validity of proposed method.

1. Introduction

In the recent years, distributed generators (DGs) have gained much attention to improve the resiliency of power grids, facilitate demand side managements, and address environmental concerns [1,2]. Technological advancements in manufacturing the power electronic equipment, energy storages, small-scale generators, and protective devices have made possible the use of several DG units to supply a part of the utility load as a microgrid. Therefore, in addition to utilization of advantages of DG units and elimination of existent defects in interaction between a DG unit and the grid, possibility of using smart grids is also provided [3,4].

A microgrid can be utilized in grid-connected or islanded modes of operation [5]. In grid-connected mode, the microgrid is a part of the main grid and it operates under the conditions dictated by main grid. On the other hand, in islanded mode, DGs are responsible for supplying the microgrid loads. Because of the design and rating constraints of DGs, proportional sharing of microgrid active and reactive power is of paramount value [6]. Accordingly, appropriate load sharing among the DGs is one of the most important subjects to be considered in control strategies of islanded microgrids [7,8]. Some of these strategies highly rely on communication infrastructures that are more costly and less reliable [9–11]. In an islanded-mode mircrogrid, sharing loads without communication links between controllers is the most desirable capability, especially when the network is gradually becoming complex or spanning over a large geographic area [12]. Alternatively, droop characteristics can be used to minimize the requirement for communication infrastructure. In this method, DGs are controlled locally and are independent of communication infrastructure with increased system reliability and plug and play ability. The conventional active power/frequency (*P–f*) and reactive power/voltage (*Q–V*) droop characteristics are deployed for controlling the active and reactive powers of DG units, respectively. Although the active power is properly shared due to its proportionality with the global parameter of frequency, some factors including line impedance mismatches and different loading patterns can result in inappropriate reactive power sharing, circulating reactive current, and overloading of DGs [13,14].

The improper reactive power sharing of *Q–V* droop characteristic has been addressed in many articles in the literature. In [15], inserting a series inductor into the output terminals of inverters is proposed to compensate the line impedance mismatches. However, the inserted inductance is bulky and expensive. In another approach, a voltage control loop has been proposed to introduce

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a virtual impedance for line impedance mismatch compensation [16–20]. The virtual impedance method also can reduce the reactive power sharing error by correcting the slope of droop characteristics [21]. Virtual impedance method has some limited drawbacks such as high dependency on the microgrid topology and limited response to load changes. Another method for improving the reactive power sharing is to utilize reactive power and rate of change of the output voltage characteristic [22]. Some advantages of this method include reduction of coupling between the active and reactive powers and low dependency on line impedances. However, the response of this method depends on the initial conditions considered for the controller. An adaptive reactive power sharing method is proposed in [23,24] using integral controller for adjusting the common bus voltage. This approach is improved in [25] to be applicable for grids with different ratios of X/R. These methods are independent of the system parameters, but they require the load voltage measurement. A nonlinear optimization method for improving the reactive power sharing and voltage regulation is proposed in [26] which is effective but complicated to implement. In [27], a compensation method is proposed which estimates the reactive power sharing error by injecting a distortion into the real power. Then, the estimated error is removed by adding an integral term to Q–V droop characteristic. This method operates in two stages. First, DGs are controlled by the conventional droop characteristics and, then, corrected characteristics are employed to achieve the ideal power sharing.

This paper proposes a reactive power sharing method to improve the method in [27] based on correcting the Q–V droop characteristic. The proposed method detects the reactive power sharing error using a small and temporary distortion in active power controller and coupling between the active and reactive powers. Then, operating point of each DG unit is corrected by injecting the required amount correction into the voltage droop characteristic until the ideal power sharing is achieved. The salient features of proposed method are:

- This method can remove the reactive power sharing error in islanded microgrids under different loading conditions.
- The grid parameters and their changes have no influence on the performance of the proposed method.
- As opposed to [27], the proposed method is implemented locally and obviates the requirements for a central controller, which in turn increases the system reliability.

The rest of paper is organized as follows: Section 2 discusses the conventional droop characteristics and operation of these controllers for power sharing. Furthermore, due to limitations of the conventional voltage droop characteristic, general approaches to improve the reactive power sharing are briefly studied. A new control strategy is proposed in Section 3 and its different stages are analysed. The validity of the proposed method are verified in Sections 4 and 5 using simulation and experimental results of an implemented laboratory test bed. Section 6 concludes the paper.

2. Power sharing in an islanded microgrid

Conventionally, active and reactive power sharing among the DGs in microgrids is achieved by droop characteristics. Inputs of the droop characteristics are the measured active and reactive powers and their outputs determine the frequency and amplitude references for output voltage of the DGs. In order to achieve proper load sharing based on the DG ratings, slopes of these characteristics are selected inversely proportional to the DG nominal active and reactive powers. Droop characteristics share the load among the DGs in addition to keep the grid voltage and frequency within their acceptable limits. Moreover, they provide the capability of synchronizing the DGs with each other through generating the voltage and frequency references

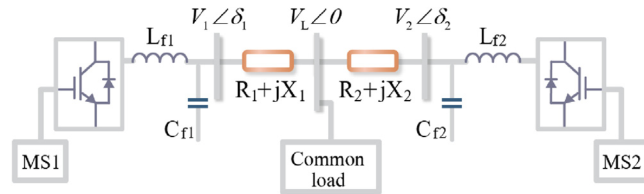

Fig. 1. A simple microgrid consisting of two DGs and a common load.

2.1. Conventional droop characteristics

Fig. 1 shows a simple microgrid containing of two inverter-based DGs with LC filter and output voltage of $V_i\measuredangle\delta_i$ which supply the required power of a common load with voltage of V_l through the impedance $Z_i = R_i + jX_i = |Z_i|\measuredangle-\varphi_i$. Apparent power generated by each DG is:

$$S_i = V_i I_i^* = V_i\angle\delta_i\left(\frac{V_i\angle\delta_i - V_l\angle 0}{Z_i\angle-\varphi_i}\right)^* \tag{1}$$

Separating real and imaginary parts of (1) yields

$$P_i = \frac{V_i}{R_i^2 + X_i^2}\left[R_i\left(V_i - V_l\cos\delta_i\right) + V_l X_i \sin\delta_i\right] \tag{2}$$

$$Q_i = \frac{V_i}{R_i^2 + X_i^2}\left[X_i\left(V_i - V_l\cos\delta_i\right) - V_l R_i \sin\delta_i\right] \tag{3}$$

Neglecting the line resistance and assuming $\cos\delta_i \approx 1$, the following equations are achieved:

$$\delta_i = \frac{X_i P_i}{V_i V_l} \tag{4}$$

$$V_i - V_l = \frac{X_i Q_i}{V_i} \tag{5}$$

Using (4) and (5), the frequency and voltage droop characteristics are extracted as follows:

$$\omega_i = \omega_0 - m_{pi}\cdot P_i \tag{6}$$

$$V_i = V_0 - n_{qi}\cdot Q_i \tag{7}$$

where ω_0 and V_0 are the reference frequency and voltage, and m_{pi} and n_{qi} are the frequency and voltage droop coefficients. These droop characteristics are illustrated in Fig. 2. According to (4), the active power is proportional to δ (or its derivative ω) and, consequently, changing the voltage phase angle of DGs impacts their output active power. In order to share the active power and adjust the frequency, P–f droop characteristic is conventionally utilized. Deploying this characteristic, the generated active powers of DGs are proportional to their active power ratings. As illustrated in Fig. 2(a), the DGs generating more active power have lower frequency and, conversely, the DGs generating less active power have higher frequency. As a result, the DGs with higher frequency have leading-phase respective to other DGs. According to (4), there is a direct relation between the real power and δ; accordingly, the leading-phase of DGs with less active power makes them to generate more real power, and vice versa. Since the frequency has a global nature throughout the microgrid and it is the same for all the sources under steady-state condition, real power is appropriately shared among the DGs by the mentioned mechanism.

On the other hand, for sharing the reactive power and voltage regulation, Q–V droop characteristic is deployed. However, the conventional voltage characteristic results in different contributions of