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An enhanced decentralized reactive power sharing strategy for inverter-based microgrid

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ABSTRACT

The conventional droop methods can not accurately share reactive power among DG units in an islanded Micro-Grid (MG) because of the mismatched line impedances. This paper proposes an enhanced decentralized control strategy for an MG with inverter-based voltage sources to improve reactive power sharing accuracy. This method is based on the conventional droop curves corrected following a change in the DGs' operating points. Thus, first, any significant load change, DG switching or mode-transfer of the MG as the main reasons for operating point variation is monitored to trigger the local correction process. Next, for each DG units, according to the injected real power disturbance, the reactive power sharing error is estimated. Simultaneously, an integration term is added to voltage droop control to eliminate the error within a transient period. The proposed local correction procedure modifies the slope or y-intercept of the $Q-V$ curve to cancel the impedance mismatch effects and lead DGs to proper active and reactive power sharing. The simulations and experimental tests prove the accuracy of the proposed method. The MGs can easily be equipped with this technique to affordably improve the power quality and reliability of the network.

1. Introduction

A Micro-Grid is a small-scale power system that consists of a group of interconnected loads and Distributed Generators (DG). One of the key features of the MG is the ability to operate in both grid-connected and islanded modes. Islanding capability improves the reliability of MG in term of supplying critical loads during grid outages. In an islanded MG, the DGs are in charge of the voltage and frequency of the system. For this purpose, two conventional frequency-active power ($P-\omega$) and voltage-reactive power ($Q-V$) droop methods have been widely utilized for active and reactive power sharing, respectively [1,2]. The key feature of droop control methods is their independency on communication links among DGs.

Since frequency is a global quantity in the system, the $P-\omega$ droop method can precisely share the real power among DGs according to their power ratings. However, the $Q-V$ droop method fails to appropriately share the reactive power due to the following reasons:

- In contrast to frequency, voltage is a local parameter [3].
- Reactive power requirement of the network is related not only to loads, but also to network configuration and line parameters [3,4].
- The resistive nature of lines in distribution systems makes the active and reactive powers mutually dependent [5].

Improper reactive power sharing among DGs in an islanded microgrid can yield to voltage and frequency deviations, unexpected load curtailment, deteriorated power quality, and DGs' protection mal-operation which in turn affects the MG stability. DG outages and unexpected load curtailment can also result in severe economic losses. Therefore, correcting conventional droop methods to properly share reactive power among DG units reflects a noticeable value of paramount [6].

So far, various methods have been proposed to improve reactive power sharing among DGs in an islanded MG. For instance, in [7], the difference between local and common bus voltages is integrated by an integrator added at the output of Q-V droop block. This method needs the access to common bus by all DG units which is not affordable. The local load and voltage drop in the connecting line are used to choose proper Q-V droop parameters in [8]. This method needs real-time estimation of local load and voltage drop and also it only leads to the optimum sharing of the common load. Similarly, in [9], some new terms, related to the square and cube of active and reactive powers, are

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added to $Q-V$ droop equation. Compared to traditional droop methods, these terms increase the slope of $Q-V$ equation in heavy loading conditions and hence improve reactive power sharing. However, the drawback of this method is the low voltage profile in heavy loading conditions. Ref. [9] also proposes an optimization method to minimize circulating reactive power among DGs and improve the voltage profile by finding the best coefficients of $Q-V$ equation. Although the proper reactive power sharing and suitable voltage regulation can be achieved, solving the optimization problem is a complicated process which needs the detailed network information.

Another reactive power droop control strategy is the virtual impedance methods proposed in [10–12]. These approaches aim to reduce the difference among the output impedances of DGs. In fact, virtual impedance makes controller sense a virtual voltage drop which is not available in reality. In this way, this strategy is able to compensate voltage variations due to load or droop effect [11]. Obtaining the optimal virtual impedance is dependent on real-time information of the MG configuration (the structure of MG network) which is difficult to be obtained in practical situations.

An adaptive voltage droop control is investigated in [13] to achieve accurate reactive power sharing. This method modifies the voltage droop curves of DG units to solve the impedance mismatches of feeders. To do so, the exact values of voltage drops across the feeders are simultaneously collected in a controller, which commands DG units to correct their curves according to the data collected. Therefore, this method necessarily needs a central controller and two-way communication links.

Ref. [14] proposes an enhanced reactive power sharing technique to decrease operation dependency on communication links. It uses the infrequent measurement of point of common coupling (PCC) voltage to estimate the mismatch output impedances among different feeders. Accordingly, the voltage droop gains are readjusted to solve mismatch problem. Next, using the recent calculated gains, the controller reverts to a conventional droop curve. This reversion makes this method immune to any loss in the communication links.

An approach is presented in [15] to properly share reactive power by modifying the droop controller parameters upon a change in the system operating point. This approach is implemented in two steps, namely, error reduction and voltage recovery. The first step changes the y-intercept of the $Q-V$ droop controller curve periodically, which is activated by the low-bandwidth synchronization signals. The second step restores the voltage magnitude to its nominal value. These two steps make this method independent of MG line parameters. On the other hand, the control strategy can easily be integrated into conventional droop methods. As a result, the approach has become so popular and frequently used method in wide variety of practical applications.

To improve the reactive power sharing accuracy, an enhanced control strategy is proposed in [16], which estimates the reactive power control error by injecting a small real power disturbance which is activated by low-bandwidth synchronization signals from the central controller. Also, a slow integration term is added to the conventional reactive power droop control in order to eliminate reactive power sharing error. This control strategy is realized by two stages. The conventional droop method is used in the first stage, and the averaged real power in the steady-state should be measured for use in the second stage. In the last stage, the reactive power sharing error is compensated by introducing a real-reactive power coupling and using an integral voltage magnitude term. Like [15], this method is not sensitive to X/R ratio and therefore it is a common technique among researchers.

Generally, given [15] and [16] only modify the common-used droop control strategy and do not need any new complex controller, they benefit from applicability to the current-used practical controllers as well as less investment costs. However, there are some practical challenges to these solutions:

- First, using communication links decreases the reliability of the solution. That is, any failure or unplanned delay in data transmission deteriorates the performance of the proposed methods.
- Second, the correction procedure of droop curve has an inappropriate and slow dynamic causing output fluctuation across DGs. This issue impacts the operation of the MG under some operational conditions, especially when there is a noticeable change in load or network topology. This paper improves the reactive power sharing method of [16] with the following salient features.
- The compensation control of each DG unit is triggered according to a local decision-making method without any communication link.
- The local decision-making method rightly triggers the controller against any change in DGs' operating points which can be due to load variation, DG switching or mode-transfer of the MG.

This paper is organized as follows:

In Section 2, the conventional droop control methods are reviewed. Section 3 presents the synchronized reactive power compensation techniques. In Section 4, the novel localized droop control scheme is proposed. Simulation results are given in Section 5. In this section six case studies are designed and simulated to verify the proposed method performance against different aspects. Section 6 gives the experimental results, and finally, Section 7 concludes the paper.

2. Conventional frequency and voltage droop controller

Fig. 1a shows how two different operating points of a DG unit would have different frequencies according to the conventional $P-\omega$ droop.

According to Fig. 1a, any increase in output active power of a DG yields to a corresponding decrease in its frequency. As a result, if the load is not equally shared among DGs, their frequency will not be similar. The relation between the frequencies of several DGs can be written as Eq. (1):

$$\omega_i = \omega_j + \Delta\omega_{ij} \tag{1}$$

where ω_i and ω_j are the angular frequency of two selected DGs (i^{th} and j^{th} DGs) and $\Delta\omega_{ij}$ is the amount of difference between ω_i and ω_j. According to the fact that usually the allowable range of ω is limited to a very small region, it is assumed that $\Delta\omega_{ij}$ is negligibly small. Hence, for a limited period of time, it is possible to assume V_i as a phasor with a frequency of ω_j and angle of $\Delta\omega_{ij}t$. So, V_i is a linear function of time

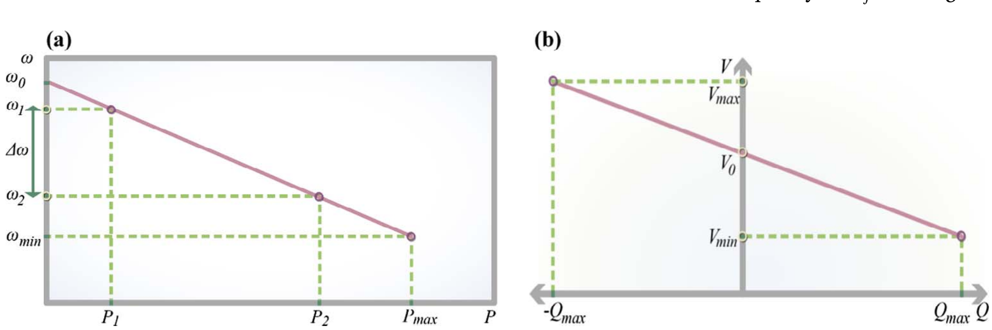

Fig. 1. Conventional droop characteristics: (a) the frequency-active power, (b) the voltage-reactive power.