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Accurate reactive power control of autonomous microgrids using an adaptive virtual inductance loop

Ramin Moslemi, Javad Mohammadpour*

Complex Systems Control Lab, College of Engineering, The University of Georgia, Athens, GA 30602, United States

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ABSTRACT

In this paper, a new droop-based reactive power control strategy is proposed that is suitable for implementation in autonomous low voltage microgrids. The proposed method exploits the potentials of adding a dynamic virtual inductance loop to compensate for the voltage drop differences caused by line impedances. In addition, it provides a large virtual inductance at the output terminals of a distributed generation (DG) source to eliminate the coupling between the active and reactive powers. Finally, the efficiency of the proposed method to cope with the aforedescribed challenges is examined using comprehensive simulation studies.

1. Introduction

In the last decade, incremental public concerns about environmental issues, persistent growth in the power demands and the need for more efficient and reliable power grids have led to fundamental changes in the power industry. This is done to move towards accommodating higher levels of renewable energy sources (RESs) in the form of distributed generations (DGs) [1]. Relentless increase in the penetration of distributed generations in power distribution networks has initiated the concept of *microgrid*. As described in Ref. [2], a region with enough energy supplies to operate autonomously when it becomes disconnected from the rest of grid could be considered as a microgrid. The microgrids are able to operate in both grid-connected and autonomous (also known as islanded) modes. In autonomous mode, a DG inverter operates like a voltage source and the microgrid dynamics is highly dependent on the connected DGs and the power regulation controls.

A wide variety of methods have been proposed in the literature in order to offer a plug and play capability for DERs. Although communication-based approaches such as master and slave and distributed control (see, e.g.,[3] and the references therein), can provide accurate power sharing control, any failure in master unit or data exchange communication links could bring about whole or partial shut down in the microgrid. Therefore, the decentralized control designs are preferred [4]. However, communication could still be used in higher levels of hierarchical structure of microgrids to control slower dynamics and optimize the operation of autonomous microgrids. Losing communication links, in this architecture, would compromise optimality of the operation; however, the microgrid would still continue to provide power service [5]. Therefore, among the proposed control approaches, a decentralized control, known as droop control, has attracted a lot of attention due to its simplicity and redundancy [6].

Very early droop control techniques were proposed assuming decoupled active and reactive powers in predominantly inductive lines [7]. However, this assumption is not valid for medium or low voltage microgrids, in which the feeders have mixed or even resistive impedances, respectively. To avoid the coupling between active and reactive powers, virtual impedance methods have been proposed to make inverters output impedance highly inductive [8]. The main problem in using virtual impedance method is that the reactive power sharing may exacerbate because of an increase in impedance voltage drops.

As an objective of a plug and play configuration, the active and reactive powers should be shared accurately and proportionally among the DGs. The active power-frequency droop can realize accurate active power sharing [9]. On the other hand, the reactive power sharing accuracy is affected by voltage differences at the inverters' output terminals. To share linear or nonlinear reactive loads in a distributed AC power system, a new approach was proposed in [10] by introducing additional control inputs. However, by applying this method, the line currents may be distorted because of

* Corresponding author. Tel. +1 7065427295.
E-mail address: javadm@uga.edu (J. Mohammadpour).

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an increase in controller complexity. In Ref. [11], a modified version of voltage and reactive power droop was introduced to compensate for the effect of voltage drops caused by feeder impedances through modifying the droop slopes. Although the suggested method could achieve a more accurate reactive power sharing, it would need an online slope estimation, which makes this strategy quite complicated.

In microgrids with several DG inverters operating in parallel, the difference between inverters' output voltages causes circulating current among inverters. The circulating current may lead to inverters overcurrent and also a degradation in droop control efficiency. A modified virtual impedance approach was presented in [12] to mitigate the circulating current among inverters, but the proposed approach could be used only for DGs with the same rating. Furthermore, the method proposed in Ref. [12] could not cope with reactive power sharing problem because of the voltage differences at the outputs of inverters.

In this paper, a new variable virtual inductance control loop, along with a modified energy management system (EMS), is proposed to enhance the performance of the traditional droop controllers to simultaneously cope with the following problems: (1) eliminating active and reactive power coupling in low and medium voltage microgrids; (2) achieving an accurate proportional reactive power sharing; (3) mitigating the circulating current among inverters, without the need for communication between DG units in the primary level.

The remainder of this paper is organized as follows. In Section 2, the principle of conventional droop method is explained and its drawbacks are reviewed. In Section 3, the proposed modified virtual impedance control loop is elaborated to address the conventional droop control issues. In Section 4, simulation results will be presented and the efficiency of the proposed droop control will be evaluated, and finally Section 5 concludes the paper.

2. Traditional droop control technique

The ability to control the inverter output voltage is one of the best ways to realize DG plug and play feature in autonomous microgrids. The droop control method has been devised based on the power flow equations between voltage sources separated by a line impedance given as [7]

$$P_{12} = \frac{E_1}{R^2+X^2}[R(E_1 - E_2\cos\delta) + XE_2\sin\delta] \quad (1)$$

$$Q_{12} = \frac{E_1}{R^2+X^2}[X(E_1 - E_2\cos\delta) - RE_2\sin\delta] \quad (2)$$

where E_1 is the voltage magnitude of the inverter output, E_2 is the bus voltage magnitude, X and R are line inductance and resistance, respectively, and δ is the angle difference between E_1 and E_2. Also, P_{12} and Q_{12} represent active and reactive powers injected by the inverter to the transmission line. Neglecting the line resistance and assuming the phase angle to be sufficiently small, the above equations could be simplified, where the active and reactive powers would be proportional to the phase angle difference δ and the voltage magnitude difference $(E_1 - E_2)$, respectively. Based on these relationships, in autonomous mode, the DG active power can be controlled with changing output voltage frequency and the reactive power can be regulated by modifying DG output voltage magnitude difference. Therefore, the conventional droop control for the microgrids with highly inductive lines takes the following form

$$\omega_i = \omega^* - M_{P_i}(P_i^* - P_i) \quad (3)$$

$$E_i = E^* - M_{Q_i}(Q_i^* - Q_i), \quad (4)$$

where P_i and Q_i are active and reactive power outputs of ith DG, respectively, P_i^* and Q_i^* are the ith DG dispatched powers in the grid-connected mode, ω^* and E^* are frequency and voltage magnitude at the grid-connected mode and M_{P_i}, M_{Q_i} are frequency and voltage droop slopes, respectively. Since it is preferred to make each DG generate active and reactive powers in proportion to its power capacity, the droop slopes are defined as

$$M_{P_i} = \frac{\omega^* - \omega^{\min}}{P_i^* - P_i^{\max}} \quad \text{and} \quad M_{Q_i} = \frac{E_i^* - E^{\min}}{Q_i^* - Q_i^{\max}}, \quad (5)$$

where $P_i^{\max}$ and $Q_i^{\max}$ are the maximum active and reactive power outputs, and $\omega^{\min}$ and $E^{\min}$ are minimum allowable operating frequency and voltage, respectively. Although the droop control strategy is easy to implement due to its simplicity and is also reliable due to its decentralized structure, the conventional droop controllers suffer from several drawbacks reviewed in following section.

2.1. Drawbacks of the conventional droop control methods

As mentioned earlier, the $P-\omega$ and $Q-E$ droops are derived based on the assumption that the lines are highly inductive. This is indeed a valid assumption for conventional power systems with long distance transmission lines; however, in the medium and low voltage (LV) microgrids, the lines and distribution feeders are mixed impedance or even dominantly resistive that introduces a significant coupling between the active and reactive power flows especially during transients. Therefore, the transient response of the conventional droop methods becomes poor [13], especially in LV microgrids. To address this problem in LV microgrids, a large inductance could be added to the output impedance of DGs. The traditional virtual impedance techniques realize this solution by adding a large virtual inductance at the DG output; however, employing virtual impedance could increase the reactive power sharing inaccuracy because of the voltage drops due to the added virtual inductance.

An accurate active power sharing could be easily realized, whereas obtaining an accurate reactive power sharing among inverters is a challenging task due to the difference in voltage magnitude at the DGs output voltages. Fig. 1a shows the schematic of a small microgrid with two DGs that supply active and reactive power to a sensitive load. The $Q-E$ droop works based on the voltage difference between the point of common coupling (PCC) and the DG output to allow an appropriate reactive power flow. For a highly inductive line, the voltage drop on line impedance, i.e., voltage magnitude difference between the DG output voltage and PCC voltage, could be approximated as a linear function of the DG output reactive power by

$$\Delta E_i = E_i - E_{\mathrm{PCC}} \simeq \frac{X_i \times Q_i}{E_i}. \quad (6)$$

Therefore, due to the difference in line impedances or in currents flowing from DGs to the load, the voltage drops on the line impedances will be different. As a result, the DGs output voltages would be different that leads to reactive power sharing errors. Fig. 1b shows an inaccuracy in the reactive power when conventional droop methods are applied for voltage regulation. By considering (6), when the microgrid is fully loaded (voltage at PCC is at minimum acceptable value $E_{\mathrm{PCC}}^{\min}$), DG1 and DG2 operate at points (E_1,Q_1) and (E_2,Q_2), respectively, as seen in Fig. 1b. Therefore, the first unit operates below the minimum acceptable voltage ($E_1^{\min}$) and generates a reactive power higher than its maximum power output ($Q_1^{\max}$), while second DG provides lower than its maximum reactive power ($Q_2^{\max}$), hence violating reactive power sharing requirements. This could lead the DG system to exceed cur-