An Accurate Power Control Strategy for Power-Electronics-Interfaced Distributed Generation Units Operating in a Low-Voltage Multibus Microgrid

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***Abstract*—In this paper, a power control strategy is proposed for a low-voltage microgrid, where the mainly resistive line impedance, the unequal impedance among distributed generation (DG) units, and the microgrid load locations make the conventional frequency and voltage droop method unpractical. The proposed power control strategy contains a virtual inductor at the interfacing inverter output and an accurate power control and sharing algorithm with consideration of both impedance voltage drop effect and DG local load effect. Specifically, the virtual inductance can effectively prevent the coupling between the real and reactive powers by introducing a predominantly inductive impedance even in a low-voltage network with resistive line impedances. On the other hand, based on the predominantly inductive impedance, the proposed accurate reactive power sharing algorithm functions by estimating the impedance voltage drops and significantly improves the reactive power control and sharing accuracy. Finally, considering the different locations of loads in a multibus microgrid, the reactive power control accuracy is further improved by employing an online estimated reactive power offset to compensate the effects of DG local load power demands. The proposed power control strategy has been tested in simulation and experimentally on a low-voltage microgrid prototype.**

***Index Terms*—Distributed generation (DG), droop control method, microgrid, parallel inverter, power control, power sharing, renewable energy resource (RES).**

I. Introduction

WITH the increased concerns on environment and cost of energy, the power industry is experiencing fundamental changes with more renewable energy sources (RESs) or microsources such as photovoltaic cells, small wind turbines, and microturbines being integrated into the power grid in the form of distributed generation (DG). These RES-based DG systems are normally interfaced to the grid through power electronics and energy storage systems [1].

A systematic organization of these DG systems forms a microgrid [2]–[7]. Compared to a single DG, the microgrid has more capacity and control flexibilities to fulfill system reliability and power quality requirements. The microgrid also offers opportunities for optimizing DG through the combined heat and power (CHP) generation, which is currently the most important means of improving energy efficiency. By presenting itself to the utility as a dispatchable load, the microgrid could "behave" well and avoid problems caused by single DG units [2]. Furthermore, the microgrid can operate in grid-connected mode or autonomous islanding mode and benefits both the utility and customers. Depending on the locations and capacities of DG units, a microgrid could operate at a medium-voltage or low-voltage distribution level. Since most microsources are of relatively low-power capacities at around several hundred kilowatts, a low-voltage microgrid is considered in this paper.

With a nonradial system configuration due to the presence of DG units, the power control complexity for a microgrid is substantially increased, and the "plug and play" feature is the key to ensure that the installation of additional DG units will not change the control strategies of DG units already in the microgrid. A popular approach to realize this "plug and play" characteristic is to employ the frequency and voltage droop control for real and reactive power regulation by mimicking the parallel operation characteristics of synchronous generators, which is initially proposed in [8] for parallel uninterruptible power supply (UPS) operations. While the stability analysis of this droop control is an important aspect as discussed recently in [9], [10], when implemented in a low-voltage microgrid system, this method is subject to a few particular problems, which are as follows.

1) The method is developed based on the predominantly inductive line impedance. In a low-voltage microgrid, as the distribution feeder is mainly resistive, this droop method is subject to poor transient (or even poor stability) due to the real and reactive power coupling among DG units when no additional inductance is present.
2) The unequal line impedances and DG output impedances significantly affect the accuracy of reactive power control during grid-connected operation mode and the reactive power sharing during islanding mode due to the unequal voltage drops.
3) The reactive power sharing accuracy is further deteriorated if there are local loads at DG output.

To avoid the power control coupling, the virtual real and reactive power frame transformation was recently proposed [11]. However, this method cannot directly share the actual real and reactive powers. Another way to avoid the power coupling is to properly control the interfacing inverter with virtual output impedance [12]–[14]. While effective in preventing the power coupling, this approach may increase the reactive power control

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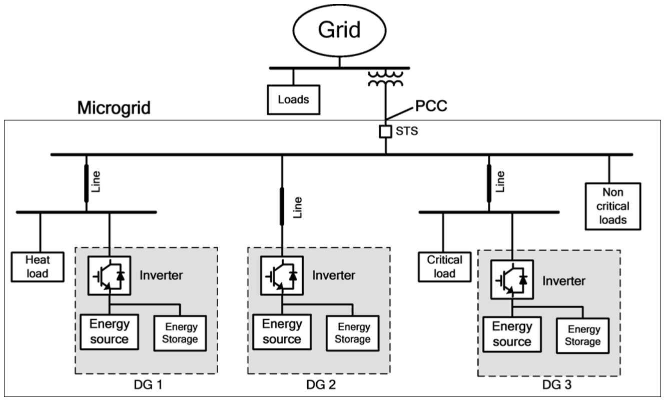

Fig. 1. Example microgrid with power electronics interfaced DG systems.

and sharing error due to the increased impedance voltage drops. To improve the reactive power sharing accuracy, a method has been proposed based on additional control signal injection [15]. However, this method has a few disadvantages such as increased control complexity and possible line current distortions.

In this paper, a power control strategy is developed for the low-voltage microgrid. The strategy comprises a virtual inductor at the interfacing inverter output and an accurate reactive power control and sharing algorithm with consideration of impedance voltage drop and DG local load effects. Specifically, the virtual inductance can effectively prevent the coupling between real and reactive powers by presenting a mainly inductive impedance even in a low-voltage network with resistive line impedances. This is done without physically connecting any passive components at the DG output. On the other hand, based on the predominantly inductive impedance, the proposed accurate reactive power sharing algorithm functions by estimating the impedance voltage drop to reactive power ratio and significantly improves the reactive power control and sharing accuracy. Finally, considering the complex locations of loads in a multibus microgrid, the reactive power control accuracy is further improved by employing an online estimated reactive power offset to compensate the effects of DG local load power demands. The proposed power control strategy has been tested in MATLAB/Simulink simulation and experimentally on a low-voltage experimental microgrid system.

II. Microgrid Structure

An example structure of a microgrid is shown in Fig. 1. The microgrid is connected to the utility system through a static transfer switch (STS) at the point of common coupling (PCC). The STS ensures that the microgrid can be disconnected from the main grid promptly (typically half a line frequency cycle) in the event of a utility interruption. As shown in Fig. 1, three DG systems are employed in the microgrid. Each DG system comprises an energy source, an energy storage system, and a grid-interfacing inverter. In Fig. 1, DG1 is connected near a heat load for CHP application, DG3 is connected with a local critical load, and DG2 is connected to the feeder directly for voltage and power support. This microgrid structure allows the line loss reduction, local voltage and power support, and waste heat usage.

The microgrid can operate in grid-connected mode or islanding mode. In grid-connected operation, the microgrid is connected to the utility, and the DG systems in the microgrid provide heat and power support for the nearby loads. When there is a fault in the utility system, the STS at PCC opens and the microgrid is disconnected from the utility as fast as possible and picks up the loads and operate in islanding mode. The STS is preferably controlled independently with a central control or power management unit, which constantly monitors the utility voltage condition and opens the switch in the case of a utility fault.

Once transferred to islanding operation, the DG systems must immediately share the changed power demand and continue supplying power to all critical loads within the microgrid. Also, the least important loads can be shed if the power capacity of the microgrid is insufficient to support all the loads in it. Note that if a single-direction communication from the STS (or central control unit) to a DG unit is not available, an islanding detection algorithm has to be implemented in this DG unit to ensure a successful transition of microgrid operation from grid-connected mode to islanding mode [7], [16]. When the utility voltage is back to normal condition, for smooth connection of the microgrid and utility, synchronization of the two systems can be done by monitoring the voltages at both ends of the STS and closing the switch when the two voltages are in phase. More advanced "seamless" synchronization that guarantees a perfect match of both voltage magnitude and phase angle could also be realized if the single-direction communication from the central control unit to the DG units is available, where the synchronization reference signal can be sent from the central control to the DG units [4] (note that communication among the DG units is unnecessary).

This multibus microgrid structure increases the complexity of power and voltage control along the feeder. Therefore, the "plug and play" concept or "wireless communication" is the key to this arrangement. To realize this "plug and play" characteristic, conventional power and frequency droop power control methods have been implemented in [4]. However, as mentioned previously, the conventional droop method is subject to a number of issues such as a coupling between real and reactive powers at a low-voltage microgrid with resistive line impedances and degradation of reactive power control accuracy in both grid-connected and islanding operations.

III. Traditional Frequency and Voltage Droop Method

A. Frequency and Voltage Droop Control

A well-known method to realize the "plug and play" feature for each DG unit is to control the DG terminal voltage by employing the "real power versus frequency (P–ω)" and "reactive power versus voltage (Q–E)" droop control [8]. Put simply, this method is based on the flow of real power and reactive power (per phase) between two nodes separated by a line impedance