Interactive Distributed Generation Interface for Flexible Micro-Grid Operation in Smart Distribution Systems

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***Abstract*—This paper presents an interactive distributed generation (DG) interface for flexible micro-grid operation in the smart distribution system environment. Under the smart grid environment, DG units should be included in the system operational control framework, where they can be used to enhance system reliability by providing backup generation in isolated mode, and to provide ancillary services (e.g. voltage support and reactive power control) in the grid-connected mode. To meet these requirements, the proposed flexible interface utilizes a fixed power–voltage–current cascaded control structure to minimize control function switching and is equipped with robust internal model control structure to maximize the disturbance rejection performance within the DG interface. The proposed control system facilitates flexible and robust DG operational characteristics such as 1) active/reactive power (PQ) or active power/voltage (PV) bus operation in the grid-connected mode, 2) regulated power control in autonomous micro-grid mode, 3) smooth transition between autonomous mode and PV or PQ grid connected modes and vice versa, 4) reduced voltage distortion under heavily nonlinear loading conditions, and 5) robust control performance under islanding detection delays. Evaluation results are presented to demonstrate the flexibility and effectiveness of the proposed controller.**

***Index Terms*—Distributed generation (DG), flexible control, micro-grids, smart distribution systems.**

I. Introduction

FLEXIBLE operation of distributed generation (DG) units is a major objective in future smart power grids [1]–[4]. The majority of DG units are interfaced to grid/load via power electronics converters. Current-controlled voltage-sourced inverters (VSIs) are commonly used for grid connection [5]. Under the smart grid environment, DG units should be included in the system operational control framework, where they can be used to enhance system reliability by providing backup generation in isolated mode, and to provide ancillary services (e.g. voltage support and reactive power control) in the grid-connected mode. These operational control actions are dynamic in nature as they depend on the load/generation profile, demand-side management control, and overall network optimization controllers (e.g., grid reconfiguration and supervisory control actions) [4]. To achieve this vision, the DG interface should offer high flexibility and robustness in meeting a wide range of control functions, such as seamless transfer between grid-connected operation and islanded mode; seamless transfer between active/reactive power (PQ) and active power/voltage (PV) modes of operation in the grid connected mode; robustness against islanding detection delays; offering minimal control-function switching during mode transition; and maintaining a hierarchical control structure.

Several control system improvements have been made to the hierarchical control structure to enhance the control performance of DG units either in grid-connected or isolated micro-grid systems [5]–[11]. However, subsequent to an islanding event, changing the controlling strategy from current to voltage control, in a hierarchical control framework, may result in serious voltage deviations especially when the islanding detection is delayed [12]. Further, mode transition transients will be imposed on the output voltage vector, where both the magnitude of the output voltage and the power angle will be subjected to disturbances. Few studies addressed the extended nature of micro-grid operation during mode transition and flexible operation. Seamless voltage transfer control between grid-connected and isolated local-voltage-controlled modes is reported in [13]. An indirect current control technique is proposed in [12] to mitigate voltage transients in mode transition. In [14], a direct control structure that mimics synchronous generator operation is proposed to provide seamless transfer characteristics. These control schemes, however, do not cope with the hierarchical control structure in modern power converters. A nonlinear sliding-mode voltage controller and adaptive power sharing controller are proposed in [15] to achieve seamless mode transfer in micro-grids. These controllers adopt complicated control structure. Further, the robustness against islanding detection delays is not tested in previously developed controllers. Therefore, there is a strong need to develop a robust and flexible hierarchical control structure with simple linear control design that provides powerful control platform for high-level controllers in the smart grid environment. It is highly desirable to maintain the hierarchical control structure as it is widely accepted in DG applications due to the benefits of using current-controlled VSIs (e.g., controlled short-circuit current and reduced power coupling), and its inherent ability to cope with hierarchical control and communication standards in power electronic converters [6]. These features do not inherently exist in direct controllers that mimic synchronous machine performance [14].

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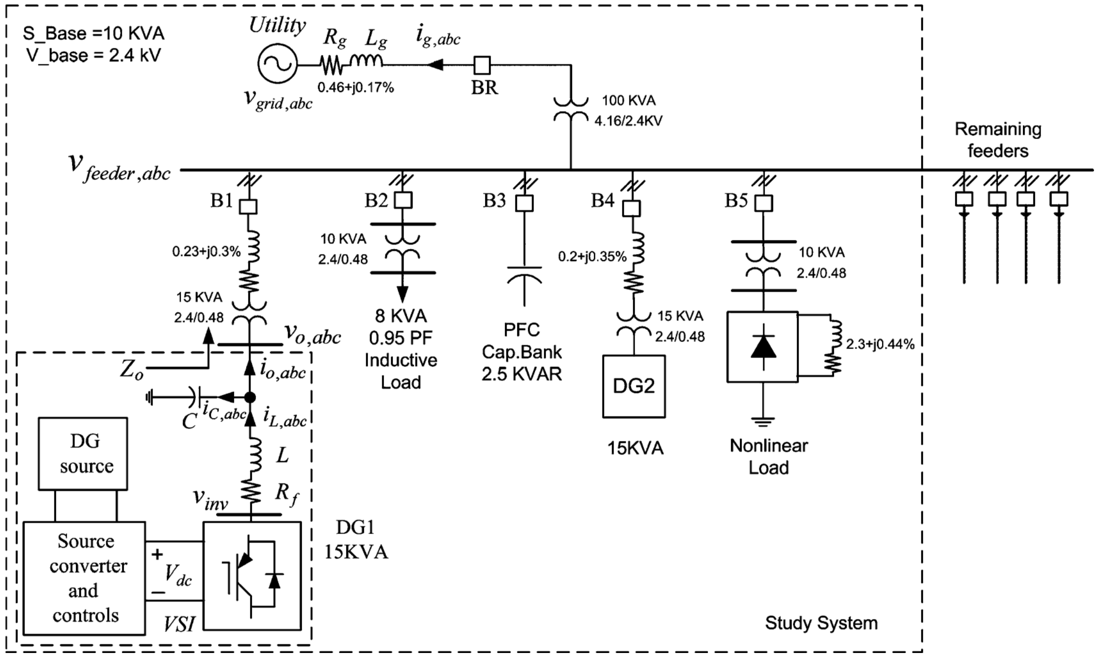

Fig. 1. Single line diagram of the micro-grid study system.

Motivated by the aforementioned difficulties, this paper presents an interactive DG interface for flexible micro-grid operation in smart distribution systems. The proposed control scheme utilizes a fixed hierarchical power–voltage–current control structure, which is used under different modes of operation. Therefore, only the magnitude of the reference voltage vector is subjected to variation, which minimizes the internal disturbances generated by switching a current-controlled interface to a voltage-controlled interface in conventional control techniques. The voltage controller is robustly designed to offer internal model control characteristics against random disturbances associated with mode transfer and harmonic and unbalanced voltage disturbances associated with DG operation under unbalanced voltages and nonlinear loads. Further, the proposed controller offers robustness against islanding detection delays due to the fixed control structure. Theoretical analysis and evaluation results verify the effectiveness of the proposed control scheme.

II. System Configuration

Fig. 1 shows the micro-grid system under study, which is adapted from the IEEE 1559 standard for low voltage applications. The adopted study system represents a general low voltage distribution system, where different types of loads and different numbers of DG units can be considered to be connected to the main feeder. The DG units can be employed to work either parallel to the utility grid, or in isolated mode to serve sensitive loads connected to the main feeder when the main breaker (BR) is open. Without loss of generality, the performance of the micro-grid system is studied under the presence of two DG units, supplying general types of loads.

The load on the second feeder is an inductive load where a 2.5-KVAr power factor correction capacitor bank is also considered to be connected to the main feeder. The adopted load model is in line with the IEEE 1547 test load used in DG applications [17]. The nonlinear load is a three-phase diode rectifier with an $R-L$ load at the dc-side. The addition of the diode rectifier helps in assessing the effectiveness of the proposed controller in rejecting voltage harmonics associated with nonlinear loading, and rejecting load-DG-unit-grid interactions at harmonic frequencies. Power circuit and control parameters of DG units are given in the Appendix.

The schematic diagram of a single DG unit as the building block of the sample micro-grid system is also shown in Fig. 1. When the DG unit is connected to the grid, the voltage and frequency at the point of common coupling are dominantly dictated by the grid. However, in case of weak grids, the voltage is prone to voltage sags and disturbances. In this case, the DG unit can be controlled to support the grid voltage. Therefore, both PQ and PV operational modes can be adopted in the grid-connected mode. Subsequent to an islanding event, DG units can form an autonomous micro-grid system to enhance the reliability of sensitive loads. This flexible operation requires robust control infrastructure, which is essential for system operators and supervisory controllers in the smart grid environment.

In both grid-connected and isolated modes, the state space presentation of the DG interface dynamics can be given in the natural frame by

$$v_{\mathrm{inv},abc} = L\frac{di_{L,abc}}{dt} + v_{o,abc}$$
$$i_{L,abc} = i_{o,abc} + i_{c,abc} = i_{o,abc} + C\frac{dv_{o,abc}}{dt} \qquad (1)$$

where L and C are the filter inductance and capacitance, $v_{\mathrm{inv},abc}$ is the inverter output voltage, $i_{L,abc}$ is the inverter output current, $v_{o,abc}$ is the voltage at the point of common coupling, and $i_{o,abc}$ is the network-side current. Note that $v_{\mathrm{inv},abc}$, $i_{L,abc}$, $v_{o,abc}$ and $i_{o,abc}$ are 3×1 vectors representing phase quantities corresponding to each phase, and the filter-inductor resistance