Power Management Strategies for a Microgrid With Multiple Distributed Generation Units

F. Katiraei, *Member, IEEE*, and M. R. Iravani, *Fellow, IEEE*

***Abstract*—This paper addresses real and reactive power management strategies of electronically interfaced distributed generation (DG) units in the context of a multiple-DG microgrid system. The emphasis is primarily on electronically interfaced DG (EI-DG) units. DG controls and power management strategies are based on locally measured signals without communications. Based on the reactive power controls adopted, three power management strategies are identified and investigated. These strategies are based on 1) voltage-droop characteristic, 2) voltage regulation, and 3) load reactive power compensation. The real power of each DG unit is controlled based on a frequency-droop characteristic and a complimentary frequency restoration strategy. A systematic approach to develop a small-signal dynamic model of a multiple-DG microgrid, including real and reactive power management strategies, is also presented. The microgrid eigen structure, based on the developed model, is used to 1) investigate the microgrid dynamic behavior, 2) select control parameters of DG units, and 3) incorporate power management strategies in the DG controllers. The model is also used to investigate sensitivity of the design to changes of parameters and operating point and to optimize performance of the microgrid system. The results are used to discuss applications of the proposed power management strategies under various microgrid operating conditions.**

***Index Terms*—Distributed generation (DG), droop characteristics, eigen analysis, microgrid, power management, real and reactive power control, small-signal dynamic analysis.**

I. INTRODUCTION

PROLIFERATION of distributed resource (DR) units in the form of distributed generation (DG), distributed storage (DS), or a hybrid of DG and DS units has brought about the concept of microgrid [1]–[3]. A microgrid is defined as a cluster of DR units and loads, serviced by a distribution system, and can operate in 1) the grid-connected mode, 2) the islanded (autonomous) mode, and 3) ride-through between the two modes. The idea supporting the formation of the microgrid is that a paradigm consisting of multiple generators and aggregated loads is adequately reliable and economically viable as an operational electric system.

A power management strategy (PMS) is required for sound operation of a microgrid with multiple (more than two) DG units, particularly during the autonomous mode of operation. Fast response of PMS is more critical for a microgrid as compared with a large interconnected grid. The reasons are 1) presence of multiple small-DG units with significantly different power capacities and generation characteristics, 2) presence of no dominant source of energy generation during autonomous mode of operation, and 3) fast response of electronically interfaced DG (EI-DG) units, which can adversely affect voltage/angle stability if appropriate provisions are not in place.

The microgrid PMS assigns real and reactive power references for the DG units to 1) efficiently share real-/reactive-power requirements of loads among the DG units, 2) quickly respond to disturbances and transients due to the changes in the system operating mode, 3) determine the final power generation set-points of the DG units to balance power and restore frequency of the system, and 4) provide a means for re-synchronization of the autonomous microgrid with the main grid for reconnection. PMSs for a microgrid system and their impacts on the controls of DG units have neither been fully understood nor comprehensively investigated in the technical literature. The main objective of this paper is to cover this gap.

To investigate various PMSs, a three-DG microgrid study system is introduced. The system includes two EI-DG units and one conventional synchronous machine-based DG unit. The system represents all characteristics of a radial microgrid in terms of PMS requirements and their impacts on the microgrid behavior.

This paper also presents a methodology to systematically develop a small-signal dynamic model of a microgrid for eigen studies. Frequency variations of autonomous microgrid are also considered in the model. The model is general and can accommodate any microgrid configuration and any number of DG units. The model is used to 1) investigate the dynamic behavior, 2) select control parameters of DG units, and 3) imbed various PMSs in the DG controllers and investigate their impacts on the behavior of the study microgrid.

The rest of this paper is arranged as follows. Section II briefly describes the microgrid study system. Sections III and IV discuss the needs for PMSs and outline three PMSs adopted for the study microgrid. Sections V and VI deal with small-signal modeling and analysis of the microgrid system. Sections VII and VIII summarize the proposed PMSs and conclude the results obtained from eigen analysis of the study system.

II. MICROGRID SYSTEM

Fig. 1 shows a single-line diagram of a 13.8-kV distribution system used to investigate possible microgrid PMSs. The microgrid system includes a conventional DG unit, i.e., $DG1$ (1.8-MVA), connected to feeder 1, two EI-DG units, i.e., $DG2$ (2.5-MVA) and $DG3$ (1.5-MVA), connected to feeders 3 and 4

Manuscript received September 27, 2005; revised March 16, 2006. Paper no. TPWRS-00620-2005.

F. Katiraei is with the Natural Resource Canada at the CETC-Varrenes, Varennes, QC J3X 1S6, Canada (e-mail: farid.katiraei@nrcan.gc.ca).

M. R. Iravani is with the Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON M5S 3G4, Canada (e-mail: iravani@ecf.utoronto.ca).

Digital Object Identifier 10.1109/TPWRS.2006.879260

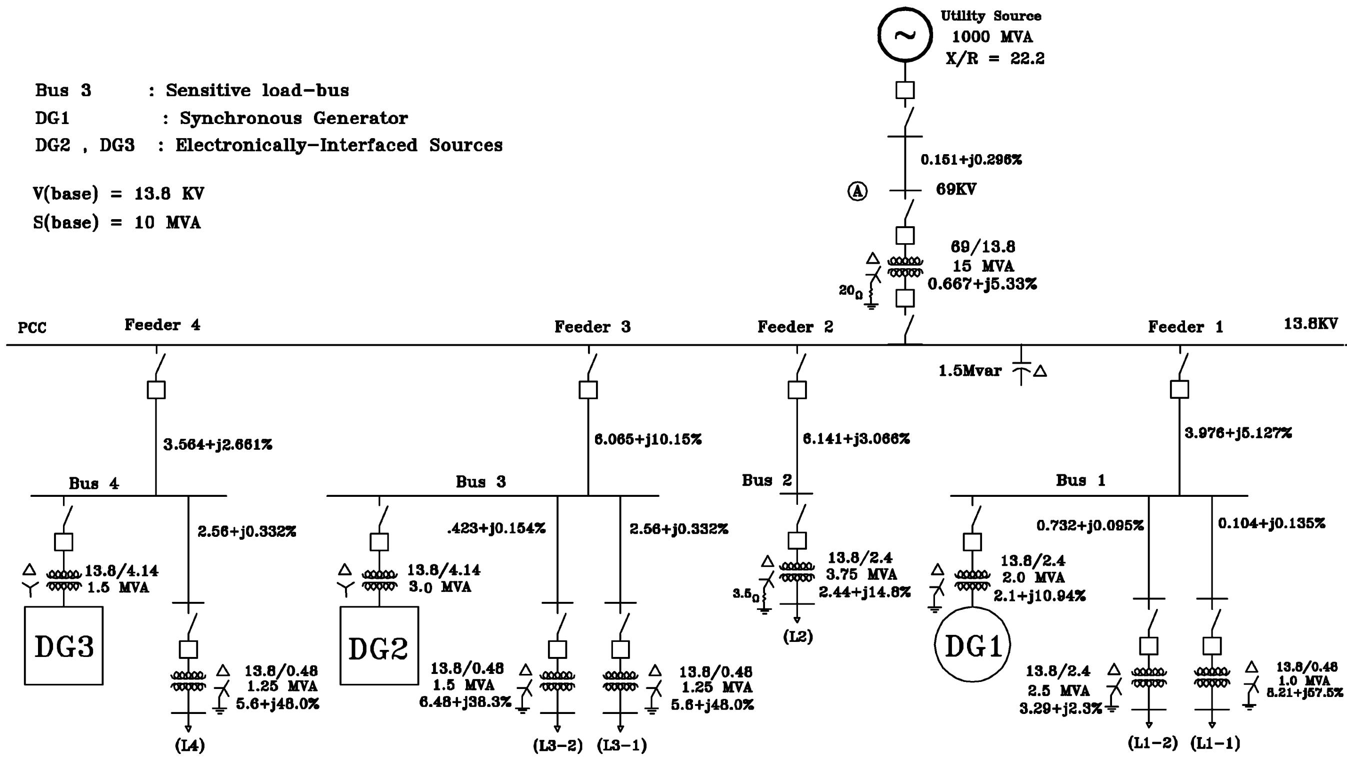

Fig. 1. Single-line diagram of the microgrid study system.

respectively. $DG1$ represents a slow-response DG unit, e.g., a diesel-generator or a gas-fired unit equipped with excitation and governor control systems. $DG2$ and $DG3$ are fast-acting, dispatchable sources. It is assumed that $DG2$ and $DG3$ each has adequate capacity to supply independently controlled real and reactive power to the system, within limits, based on pre-specified control commands. It should be noted that the PMSs discussed in this paper are only applicable to dispatchable DG units. Non-dispatchable sources are controlled based on optimal power generation schemes to deliver maximum available power [4].

The three-DG system can be used to investigate possible interaction phenomena 1) among EI-DG units, 2) between EI-DG units and conventional DG units, and 3) between DG units and the network. The focus of this paper is on the interaction phenomena and small-signal dynamics of DG units that are interfaced to the host utility grid through voltage-sourced converters (VSCs). The dynamic behavior of the conventional DG unit is relatively well known [5] and is not emphasized in this paper.

III. Power Management Strategy of a Microgrid

Regardless of the microgrid mode of operation, i.e., 1) grid-connected, 2) islanded (autonomous), or 3) transition between the two modes, the adopted PMS has a direct impact on the system operational behavior in terms of voltage/angle stability, power quality, and availability of service to consumers. In contrast to the philosophy of operation of interconnected power systems, in a microgrid system, none of the DG units acts as a spinning reserve or as a backup generation.

In the grid-connected mode, DG units are expected to supply pre-specified power, e.g., to minimize power import from the grid (peak shaving). Such requirements are system dependent and vary from system to system. In a grid-connected mode, similar to a conventional utility system, each DG unit can be controlled to generate pre-specified real and reactive power components (PQ-bus) or generate pre-specified real power and regulate its terminal voltage (PV-bus). The utility grid is expected to support the difference in real/reactive power requirements and maintain the frequency [6].

In the autonomous mode of operation, the available power of the DG units must meet the total load demand of the microgrid; otherwise, the system must undergo load shedding to match generation and load demand. In addition, fast and flexible real/reactive power control strategies are required to minimize the microgrid dynamics, e.g., due to islanding, and damp out system oscillations. This paper only considers PMSs based on locally measured signals when no communication exists among DG units. Thus, controllers should operate based on local information.

The main criteria that should be met by the PMS are as follows:

- load sharing among DG units while minimizing the total power loss of the system;
- consideration of specific limits of each DG unit, including type of the DG unit, cost of generation, time-dependency of the prime source, maintenance interval, and environmental impacts;
- maintaining the power quality inclusive of voltage profile, voltage fluctuations, and harmonic distortion;
- improving the dynamic response, maintaining stability margin, and voltage/frequency restoration of the system during and after transients.