A New Control Strategy for a Multi-Bus MV Microgrid Under Unbalanced Conditions

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***Abstract*—This paper proposes a new control strategy for the islanded operation of a multi-bus medium voltage (MV) microgrid. The microgrid consists of several dispatchable electronically-coupled distributed generation (DG) units. Each DG unit supplies a local load which can be unbalanced due to the inclusion of single-phase loads. The proposed control strategy of each DG comprises a proportional resonance (PR) controller with an adjustable resonance frequency, a droop control strategy, and a negative-sequence impedance controller (NSIC). The PR and droop controllers are, respectively, used to regulate the load voltage and share the average power components among the DG units. The NSIC is used to effectively compensate the negative-sequence currents of the unbalanced loads and to improve the performance of the overall microgrid system. Moreover, the NSIC minimizes the negative-sequence currents in the MV lines and thus, improving the power quality of the microgrid. The performance of the proposed control strategy is verified by using digital time-domain simulation studies in the PSCAD/EMTDC software environment.**

***Index Terms*—Distributed generation, medium voltage (MV) microgrid, negative-sequence current, power sharing, unbalance load, voltage control.**

I. Introduction

MEDIUM voltage (MV) microgrids will play a key role for active management and control of distribution network in the future smart grids. Moreover, the environmental issues and economical, social, and political interests make the role of MV microgrids even more important [1]. The recently presented concept of multi-microgrids is a motivation for proposing the concept of the higher voltage level structure of microgrids, e.g., MV level. A multi-microgrid consists of low voltage (LV) microgrids and distributed generation (DG) units connected to several adjacent MV feeders [2].

An MV microgrid may inherently be subjected to significant degrees of imbalance due to the presence of single-phase loads and/or DG units. Nevertheless, a microgrid should be able to operate under unbalanced conditions without any performance degradations. Based on the IEEE standards [3], [4], it is required that the voltage imbalance be maintained within 2% for sensitive equipments. In the presence of unbalanced loads, each DG unit must inject some part of the negative-sequence current to balance the load voltages.

Several methods have been proposed in the literature for the control and power management of microgrids [5]–[9]. An abc-frame control strategy is proposed in [10] which is robust to the unmodeled load dynamics. The proposed method employs the droop strategy for the power sharing.

The $G-H$ and $Q^{-}-G$ droop controls are employed to share harmonics and unbalanced currents among the DG units in an islanded microgrid [11], [12]. The proposed methods show good performance when the exact value of the line impedance is available. A combination of the deadbeat and repetitive control has been used to enhance the performance of a single-bus microgrid system in the presence of unbalanced and nonlinear loads [13]. However, the effectiveness of the proposed method is not investigated in the multi-bus microgrids. To overcome the impact of nonlinear and unbalanced loads, a proportional multi-resonant controller is proposed in [14]. The method employs the concept of generalization of virtual output impedance to deal with the nonlinear and harmonic loads. A droop-based control strategy for a microgrid has been proposed in [15]. The method improves the power quality and proper load sharing in both islanded and grid-connected modes in the presence of unbalanced and nonlinear loads. However, the paper assumes that the nonlocal loads are balanced.

This paper presents a new control strategy for an islanded microgrid consisting of several dispatchable electronically-interfaced three-wire DG units. The microgrid consists of several buses and operates in an MV level. Each DG unit supplies the local and nonlocal loads which can be unbalanced. The overall microgrid is controlled based on the decentralized control strategy, i.e., each DG unit is considered as a subsystem equipped with the proposed control strategy. However, it is assumed that each nonlocal bus (feeder) is equipped with a phase measurement unit (PMU) which transmits the phasor information of the feeder to the adjacent DG units.

The proposed control strategy of each DG comprises a voltage control loop, a droop controller and a negative-sequence output impedance controller. The voltage controller adaptively regulates the load voltage using a PR controller. The average power sharing between the DG units is carried out by the droop controller. However, the droop controller is not able to share the negative-sequence current resulting from the unbalanced loads. Thus, a new control strategy is proposed in this paper to efficiently share the negative-sequence current among the DG units. The proposed negative-sequence current controller adjusts the negative-sequence output impedance of its own DG such that the negative-sequence currents of the

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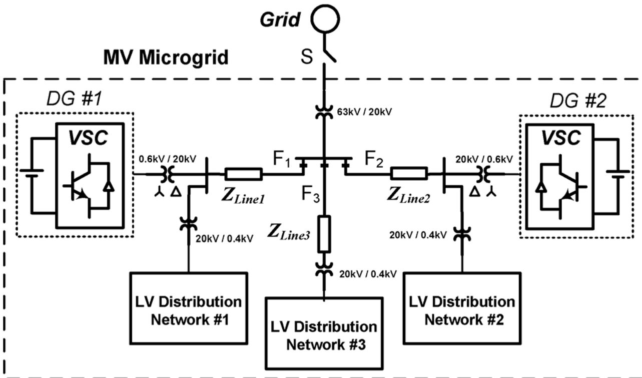

Fig. 1. MV multi-bus microgrid consisting of two DG units.

MV lines will be minimized. Thus, the power quality of the overall MV microgrid will be improved. The effectiveness of the proposed control strategy has been demonstrated through simulation studies conducted in the PSCAD/EMTDC environment. The simulation results show that the method is robust to load perturbations and effectively copes with the unbalanced conditions.

II. Multi-Bus MV Microgrid Structure

Fig. 1 shows a single-line diagram of a multi-bus MV microgrid which is composed of a 20-kV three-feeder distribution system and two electronically-coupled three-wire DG units. A combination of balanced and unbalanced loads are supplied through three radial feeders, F_1, F_2, and F_3. The DG units are connected to feeders F_1 and F_2 through step-up transformers and are assumed to be dispatchable. Thus, each DG unit can supply any amount of the real/reactive power within the pre-specified limits. Moreover, each DG must control its own power in a decentralized control manner. The loads are connected to the MV feeders via Y/Δ transformers, and therefore, the loads do not absorb any zero-sequence current from the MV feeders. Nevertheless, the load current can assume the negative-sequence component. In this paper, it is assumed that the microgrid system operates in the islanded mode. Therefore, the DG units are responsible for compensating the negative-sequence current of the unbalanced loads. The microgrid parameters are given in Table I.

III. Dynamic Model of a Three-wire DG Unit

Each DG unit including its series and capacitive (LC) filters can be considered as a subsystem of the microgird. To control the microgrid using the a decentralized control strategy, it is required that the dynamic model of each subsystem be derived first. Thus, in this section, the dynamic model of a three-wire DG unit, as a subsystem of the overall microgrid, is presented. Fig. 2 shows the circuit diagram of a three-wire DG subsystem.

The objective is to design a feedback control system to robustly regulate the load voltages in the presence of disturbances. It should be noted that since the microgrid system is a three-phase three-wire system, the zero-sequence of the currents become zero. Thus, using the Clarke transformation, the state space equation of the system in the stationary reference ($\alpha\beta$) frame is obtained as follows [16]:

TABLE I
Microgrid System Parameters

Parameter	Value	Comments
S_{base}	2.5 MVA	DG ratings
Z_{line1}	0.7 + j 1.57 Ω	5.7 km overhead line
Z_{line2}	0.5 + j 1.25 Ω	4 km overhead line
Z_{line3}	0.1 + j 0 Ω	2 km underground cable
L_{f1}, L_{f2}	0.3 mH	series filter inductance
R_{f1}, R_{f2}	0.0015 Ω	series filter resistance
C_{f1}, C_{f2}	2200 μF	filter capacitance
V_{dc}	1500 V	dc bus voltage
f_s	2 kHz	switching frequency
$P_{max_{DG_1}}, P_{max_{DG_2}}$	2.5 MW	
$Q_{max_{DG_1}}, Q_{max_{DG_2}}$	1.5 MVAr	
m_{DG_1}, m_{DG_2}	0.333 Hz/MW	P-f droop coefficients
n_{DG_1}, n_{DG_2}	0.0245 kV/MVAr	Q-V droop coefficients
$I^-_{max_{DG_1}}$	0.3 kA	
$I^-_{max_{DG_2}}$	0.5 kA	

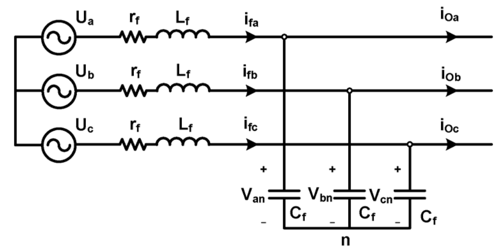

Fig. 2. Circuit diagram of a three-phase, three-wire DG unit.

$$\dot{\mathbf{X}} = \mathbf{AX} + \mathbf{BU} + \mathbf{EW}, \qquad \mathbf{Y} = \mathbf{CX} \tag{1}$$

where $\mathbf{X} = [v_\alpha, v_\beta, i_{f_\alpha}, i_{f_\beta}]^T$, $\mathbf{U} = [U_\alpha, U_\beta]^T$, $\mathbf{W} = [i_{o\alpha}, i_{o\beta}]^T$, $\mathbf{Y} = [v_\alpha, v_\beta]^T$ and

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & \frac{1}{C_f} & 0 \\ 0 & 0 & 0 & \frac{1}{C_f} \\ -\frac{1}{L_f} & 0 & -\frac{r_f}{L_f} & 0 \\ 0 & -\frac{1}{L_f} & 0 & -\frac{r_f}{L_f} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{L_f} & 0 \\ 0 & \frac{1}{L_f} \end{bmatrix}$$

$$\mathbf{E} = \begin{bmatrix} -\frac{1}{C_f} & 0 \\ 0 & -\frac{1}{C_f} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}. \tag{2}$$

The (1) in the Laplace domain is

$$V_{\alpha\beta}(s) = G_{(2\times 2)}(s)U_{\alpha\beta}(s) - Z_{(2\times 2)}(s)I_{o\alpha\beta}(s) \tag{3}$$

where $G_{(2\times 2)}$ and $Z_{(2\times 2)}(s)$ are

$$\begin{aligned} g_{12}(s) &= g_{21}(s) = z_{12}(s) = z_{21}(s) = 0 \\ g_{11}(s) &= g_{22}(s) = \frac{1}{L_f C_f s^2 + r_f C_f s + 1} \\ z_{11}(s) &= z_{22}(s) = \frac{L_f s + r_f}{L_f C_f s^2 + r_f C_f s + 1}. \end{aligned} \tag{4}$$

Equation (4) shows that the matrix transfer function of the DG subsystem is diagonal (completely decoupled) and can be viewed as two SISO control systems.