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A robust control strategy for a grid-connected multi-bus microgrid under unbalanced load conditions

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ABSTRACT

The increasing presence of inverter-based distributed generation (DG) units in microgrid application requires control methods that achieve high performance not only during normal operating conditions, but also under unbalanced conditions. These conditions can occur permanently due to distribution of unbalanced loads on the three phases of the microgrid. This paper proposes a robust control strategy for a grid-connected multi-bus microgrid containing several inverter-based DG units. Each of the DG units can supply a combination of balanced and unbalanced local loads. The proposed control strategy employs an adaptive Lyapunov function based control scheme to directly compensate the negative-sequence current components caused by unbalanced loads in some part of microgrid; and a sliding mode based control scheme to directly regulate the positive-sequence active and reactive power injected by DG units to the microgrid. The control method proposed in this paper is shown to be robust and stable under load disturbances and microgrid parameter uncertainties even in the presence of nonlinear and time-variant unbalanced loads. The effectiveness of the presented controller is validated through time-domain simulation studies, under the MATLAB/Simulink software environment.

Introduction

Recently, due to a general increasing demand for electrical energy and a rising interest in clean technologies, the energy sector is moving to the era of distributed energy resources (DERs), such as wind turbines, photovoltaic systems, fuel-cells, micro-turbines and hydropower turbines [1,2]. Typical modern distributed generation (DG) units, which are collectively referred to DERs, do not generate 50/60 Hz ac voltages and therefore require electronic power converters as the interfacing medium between a prime energy source and the network [3–5].

The application of individual DG system has some major issues such as limited capacity and high cost per watts [4]. To solve the common problems of individual DG units in power systems, researchers have introduced a new concept called microgrid [6]. Microgrid is usually a part of distribution subsystem, which consists of cluster of loads and multiple DG units. A microgrid can be operated either in grid-connected mode or in islanding mode. Normally, microgrids operate in grid-connected mode because main-grid can support the system frequency and bus voltages by covering the power mismatch immediately. In the grid-connected operation, the microgrid is connected to main-grid at the point of common coupling (PCC), and each DG unit generates proper real and reactive power [7,8]. The PCC voltage is dominantly determined by main-grid, and the main role of the microgrid is to accommodate the load demand and the real or reactive power generated by the DG-units [9,10]. Proper operation of the microgrid requires high performance control techniques, not only during normal operating conditions, but also under unbalanced conditions [11].

Besides the primary purpose of the DG units, compensation of power quality problems can also be achieved through proper control strategies [12]. Among various power quality phenomena, voltage unbalances are very common. A major cause of voltage unbalance in a microgrid is the connection of unbalanced loads. In the conventional distribution systems, most of the unbalanced loads can compensate each other because many loads are installed [13]. Nevertheless, in the microgrid systems, unbalanced loads are very common and result from the uneven distribution of numerable loads among the three phases [14]. Therefore, a microgrid should be controlled in such a way that can operate under unbalanced load conditions without any performance degradations [15].

Unbalanced loads can cause the lines current and hence the microgrid voltage suffering from significant values of negative-sequence which can lead to increased losses, abnormal second

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Nomenclature

Variables

$\mathbf{v}_i, \mathbf{v}_f, \mathbf{v}_c$	inverter, filter, PCC voltage vectors
$\mathbf{i}_f, \mathbf{i}_L, \mathbf{i}_l$	filter, local load, line current vectors
$v_{\alpha\beta}, i_{\alpha\beta}$	$\alpha\beta$ components of voltage and current
V, I	voltage and current amplitude
R, L, C	resistance, inductance, capacitance
P, Q	active and reactive powers
S	sliding surface
e	tracking error
W	Lyapunov function

Superscripts

p, n	positive-, negative-sequence components
2ω	double-frequency oscillating component
ref	reference value

harmonic at the dc-link, and negative effects on equipment such as induction motors, power electronic converters, and adjustable speed drives [16,17]. Note that unbalanced loads are often connected on the wye side of a delta to grounded-wye transformer. Therefore the zero-sequence current is isolated from the delta side [9].

Several methods have been proposed in the literature for compensation of microgrid unbalances [16–22]. A vector control approach for controlling the voltage source converter (VSC) which is capable of mitigating the harmonics under unbalanced operating conditions is proposed in [18]. The method in [18] is implemented in stator-voltage-orientation synchronous reference frame, based on proportional-integral (PI) controllers. However, the main drawbacks for this control method are the tuning of the controller parameters, the necessity of synchronous coordinate transformations, the tracking of grid voltage phase angle, and the complexity of method. Moreover, the proposed control method is highly sensitive to variations of system parameters, but no parametric uncertainty is considered [23–25].

A direct power control strategy has been presented in [19,20] for a grid-connected VSC under voltage unbalanced conditions. The power control scheme is based on the sliding mode control approach, which controls the instantaneous active and reactive powers in the stationary reference frame. Three power control targets have been proposed during network unbalance to obtaining sinusoidal and symmetrical grid current, removing reactive power ripples, and canceling active power ripples. However in the chosen study system, the VSC is directly connected to main-grid that makes the system control very simple. In addition, the effectiveness and validity of proposed methods in the presence of loads has not been demonstrated. Furthermore, the NS power control method has been designed based on knowledge of actual values of the resistances and inductances of the system. Hence, the system stability is not guaranteed with subject to system parametric uncertainties.

A combination of the deadbeat and repetitive control has been used in [21] to compensate the impact of load imbalance on the performance of a single-bus microgrid. The control method of [21] is based on the vector control approach described in [18], and implemented in the discrete-time domain. However, the presented control method is complex and its effectiveness is not investigated in the multi-bus microgrids.

The control method described in [22] uses a linear proportional-resonant-based controller in combination with a PI-based virtual impedance controller in order to regulate the load voltage and compensate the negative-sequence (NS) current of unbalanced loads. In [22], two separated and independent equivalent circuits have been used for load positive-sequence (PS) and NS current components. One may note that in a three-phase circuit with unbalanced loads, the PS and NS components of load voltage are linear functions of both the PS and NS components of load current. It means that the equivalent circuits, used in [22], are not independent and should be electrically coupled. In addition, the stability and robustness of proposed control system, with respect to microgrid parametric uncertainties, is not verified.

The main contribution of this paper is to design a control structure, based on well-known LF and SM control techniques, in order to (1) compensate the negative-sequence current components caused by unbalanced loads in some part of a grid-connected multi-bus microgrid containing several inverter-based DG units and a combination of balanced and unbalanced loads; and (2) regulate the positive-sequence active and reactive power injected by DG units to the microgrid under both balanced and unbalanced conditions. In the designed controller, the load dynamics are masked and the DG unit dynamic performances are made independent of load characteristics and circuit configuration. Moreover, to overcome the computational burden associated with the tracking of grid voltage phase angle and frame transformations, the proposed controller is performed in stationary reference frame. The control method proposed in this paper is shown to be robust and stable under load disturbances and microgrid parameters uncertainties even in the presence of nonlinear loads. Some simulation results are presented to support the validity and effectiveness of the proposed control method.

Microgrid structure description

Fig. 1(a) shows a single-line diagram of the microgrid study system. The microgrid includes two inverter-based DG units and a cluster of loads. Each DG unit is connected to the corresponding point of connection (PC) through a LC filter to reduce the voltage ripple (and hence, the current ripple) caused by the switching. The local load of each DG unit is connected to the corresponding PC and is a combination of balanced and unbalanced loads. The common load is connected to the PCC and is a balanced load. The interlink-line 1 and 2 (hereafter, line 1 and 2), which connect PCs to the PCC, are represented by series RL branches. In this paper, it is assumed that the microgrid is connected to main-grid. The microgrid parameters are given in Table 1.

Modeling of a three-phase DG unit

Fig. 1(b) shows the control scheme of an inverter-based DG unit with LC-filter microgrid-interface. By using the well-known Clarke transformation, the current and voltage dynamics in the stationary ($\alpha\beta$) reference frame can be derived as:

$$\frac{d\mathbf{i}_f}{dt} = \frac{1}{L_f}(\mathbf{v}_\mathbf{i} - R_f \mathbf{i}_f - \mathbf{v}_f) \tag{1}$$

$$\frac{d\mathbf{v}_f}{dt} = \frac{1}{C_f}(\mathbf{i}_f - \mathbf{i}_L - \mathbf{i}_l) \tag{2}$$

$$\frac{d\mathbf{i}_l}{dt} = \frac{1}{L_l}(\mathbf{v}_f - R_l \mathbf{i}_l - \mathbf{v}_c) \tag{3}$$