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A backstepping high-order sliding mode voltage control strategy for an islanded microgrid with harmonic/interharmonic loads

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ABSTRACT

This paper presents a new nonlinear voltage control strategy based on backstepping control and a high-order sliding mode differentiator for an islanded microgrid. The microgrid consists of multiple distributed generation (DG) units with an arbitrary configuration that can be parametrically uncertain or topologically unknown. The proposed controller robustly regulates the microgrid voltages in the presence of parametric uncertainties, unmodeled dynamics, load imbalances, and nonlinear loads with harmonic/interharmonic currents. In contrast to existing methods, the controller does not need to know the frequency of harmonic and interharmonic current of microgrid loads that lead to the reduction of the steady-state error of the voltage controller in the frequency of unknown harmonics and interharmonics. The MATLAB/SimPowerSystems toolbox has verified the proposed control strategy's performance.

1. Introduction

Distributed generation (DG) includes renewable or nonconventional energy resources such as wind turbines and photovoltaic arrays. These resources are connected to the grid using power electronic interfacing converters. A microgrid, consisting of DGs and loads in a local area, is an appropriate solution to problems caused by the high penetration of DGs. A microgrid can be operated in both grid-connected and islanded modes. In grid-connected mode, the frequency and voltages of microgrid are imposed by the main grid. In this case, each DG unit controls its own real/reactive power. In the islanded operation of a microgrid, the control techniques used in the grid-connected mode no longer ensure the desired operation of the microgrid (Nikkhajoei & Lasseter, 2009). Hence, after an islanding event, a proper control strategy must be adopted to regulate the frequency and voltages of the microgrid at the point of common coupling (PCC) and manages/shares power between DG units.

In stand-alone applications, the main objective of the control system is to regulate the microgrid loads' voltages (e.g., RLC loads, unbalanced loads, and nonlinear loads with harmonic/interharmonic currents) without any performance degradation. According to IEEE standards (IEEE, 2009), the voltage's total harmonic distortion (THD) for sensitive loads should be maintained within 5%. Based on IEEE standards (Gunther, 2002), components with frequencies that are between harmonics are called interharmonics. Interharmonic currents, which are usually presented in the industrial microgrids, have become more significant because of the widespread use of nonlinear loads in such systems. The main sources of interharmonic currents include arcing loads and rapid current changes in equipment and installations; in many cases their amplitude and frequency of harmonics and interharmonics are unknown. Therefore, the improvement of the microgrid power quality through the proper control strategy of converter-based DG units is an issue with high potential for engineering solutions (Cespedes & Sun, 2014).

Many control strategies for islanded operation of DGs have been developed in recent years. The best known strategies are the frequency/real-power and voltage/reactive-power based on the droop control technique for voltage and frequency control of a multi-DG microgrid (Guerrero, Vasquez, Matas, de Vicua, & Castilla, 2011; Majumder, Ledwich, Ghosh, Chakrabarti, & Zare, 2010). Several islanded mode control strategies have been proposed for voltage control of microgrid (Karimi, Davison, & Iravani, 2010; Karimi, Yazdani, & Iravani, 2011). However, existing methods have the following drawbacks:

1. Many control methods are usually synthesized in small-signal equations. Despite its simplicity, small-signal-based controllers lack global stability, which is a necessary requirement in complex networks (Ahmed, Massoud, Finney, & Williams, 2011; Babazadeh & Karimi, 2013; Bahrani, Saeedifard, Karimi, & Rufer, 2013; Hamzeh, Emamian, Karimi, & Mahseredjian, 2016).

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2. Several presented models assume that the load current is a measurable disturbance signal. Because the disturbance signal is a combination of fundamental and high-order harmonics, the controller must be a set of parallel proportional resonant (PR) controllers (Paridari, Hamzeh, Emamian, Karimi, & Bakhshai, 2013). These control strategies should know the frequency content of the nonlinear load current, be high-order, and be ineffective with respect to uncertainties in the microgrid system. Moreover, to attenuate the impact of the disturbance signal on the performance of the system effectively, a robust control strategy attenuates the impact of the disturbance signal on the load voltage (Babazadeh & Karimi, 2013; Bahrani et al., 2013; Dai, Marwali, Jung, & Keyhani, 2008; Do, Leu, Choi, Choi, & Jung, 2013; Hamzeh et al., 2016; Karimi et al., 2011; Su, Han, Guerrero, & Sun, 2015). Moreover, these strategies cannot guarantee the minimization of large variations in the load current.
3. Key drawbacks of previous methods are that they cannot guarantee robust stability when faced with parametric uncertainties, unmodeled dynamics, and disturbances from unknown frequency and amplitude (Ahmed et al., 2011; Karimi et al., 2010; Liu, Liu, & Zhao, 2014; Sadabadi, Karimi, & Karimi, 2015; Wai, Lin, Huang, & Chang, 2013). In practice, nonlinear loads with harmonic and interharmonic currents are connected to the industrial microgrid which in many cases their amplitude and frequency of harmonics and interharmonics are unknown. The connection of the load with an interharmonic current, such as an induction furnace, to the microgrid has not been investigated before.

To overcome these difficulties, this paper proposes a new nonlinear control strategy for the voltage control of an islanded microgrid that includes arbitrary number of DGs. It is noted that the proposed voltage control strategy can be merged with any types of power sharing methods, such as the droop or master–slave methods. In this paper, for power sharing purpose, the master–slave approach is used for power management among DG units. For the master DG unit, the proposed voltage controller regulates the voltage of the microgrid loads robustly. The loads are assumed to be unknown. Under the proposed control strategy, it does not matter whether the loads are measurable; the inverter output current that is imposed by microgrid loads is considered as a disturbance signal, which can be either known or unknown. To reject the impact of the disturbance signal on the system performance, a new backstepping control with an arbitrary order exact differentiator strategy is proposed. According to the separation principle, a controller and a differentiator can be designed separately. A differentiator rejects the impact of the disturbance signal and backstepping control regulates the output voltages and frequency of the islanded microgrid. For the slave DGs, the state feedback controller regulates the inverter output current. The salient features of the proposed method are the following:

1. The use of a new backstepping control with an arbitrary order exact differentiator technique for the control of islanded microgrid systems is first proposed irrespective of the parametric uncertainties and disturbances associated with interharmonics and harmonics of unknown frequencies and amplitudes.
2. In contrast to existing methods, this strategy of control does not require knowledge of the frequency content of the nonlinear loads current (including harmonics and interharmonics) leading to zero steady-state errors in the frequency of harmonics and interharmonics and reducing the computational burden for its digital implementation.
3. To the best of our knowledge, the connection of the load with interharmonic currents, such as induction furnace, to the microgrid has not been investigated before.
4. Unlike existing methods, if the harmonic/interharmonic frequency of the local loads is changed, altering the control structure is not necessary, which reduces the controller's steady-state error.

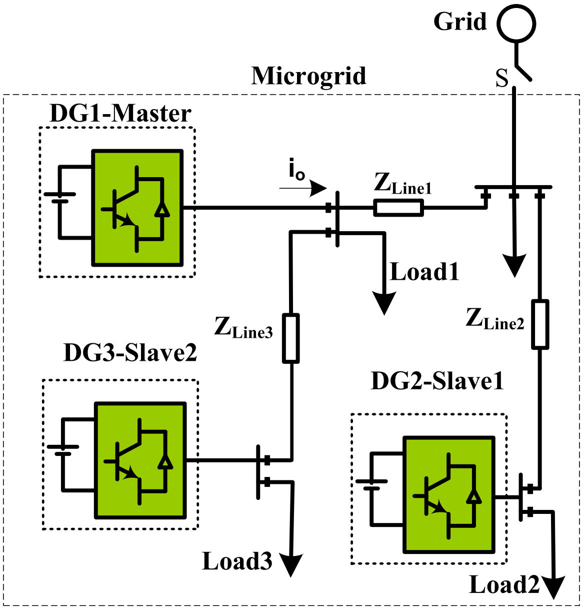

Fig. 1. Microgrid consisting of three DG units.

5. In comparison with the popular parallel PR controller, the proposed controller offers smoother transient responses with lower levels of voltage distortion. Moreover, the new controller demonstrates the robust performance and stability of the microgrid system with respect to the filter parameters uncertainties and the unknown load dynamics.

Finally, a comparison of the proposed controller's simulation results with those of the conventional parallel PR control method in the MATLAB/SimPowerSystems toolbox confirms the proposed nonlinear voltage controller's superiority.

2. System description and mathematical model

A typical single line diagram of a three-phase inverter in islanded mode is shown in Fig. 1. The islanded microgrid studied in this paper includes three three-phase four-wire DG units. In this microgrid, each DG unit supplies a load through a voltage-source converter (VSC). However, the control strategy can be extended to a multi-DG microgrid in any configuration of a microgrid. Fig. 2 shows the circuit diagram of a three-phase four-wire DG unit. A standard three-phase VSC is connected to the microgrid through an LC filter. L_f is the inverter-side inductor along with parasitic resistance; C_f is the filter capacitor.

In the state-space form, the microgrid system in the stationary *abc*-frame with the isolation of grid-neutral N can be represented through the following equations:

$$C_f \dot{v}_{abc}(t) = i_{abc}(t) - i_{oabc}(t) L_f \dot{i}_{abc}(t) = -R_f i_{abc}(t) - v_{abc}(t) + u_{abc}(t), \quad (1)$$

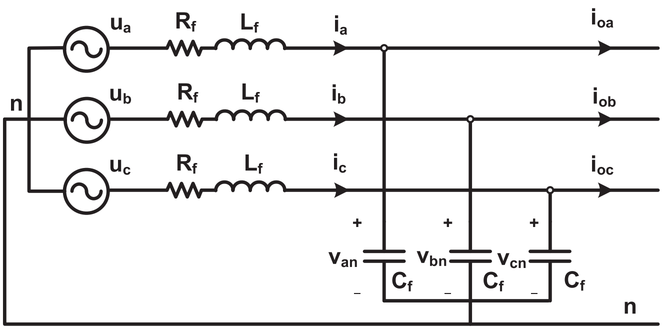

Fig. 2. Circuit diagram of a three-phase four-wire DG unit.