Electrical Power and Energy Systems 95 (2018) 188–201

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Review

Hierarchical control for flexible microgrid based on three-phase voltage source inverters operated in parallel

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ARTICLE INFO

Article history:
Received 3 March 2017
Received in revised form 6 June 2017
Accepted 21 August 2017

Keywords:
Hierarchical Control
Flexible microgrid
Universal droop controller
Voltage source inverters
Grid-connected mode
Islanded mode

ABSTRACT

In this paper, a hierarchical control for flexible operation of a microgrid is proposed. The structure of the hierarchical control consists of inner, primary and secondary levels. The inner control is used to regulate the output voltage of the inverter which is commonly referred as zero-level. The primary control based on the universal droop control which we improve it to handle both operation modes. It is used to share the active and reactive power accurately with regardless of the output impedance of the inverters. The secondary control compensates the deviation of the microgrid voltage caused by the primary control as well as synchronizes the microgrid voltage with the grid for a smooth transition. Thus, the microgrid can operate either in grid-connected or in islanded mode by using the same control scheme. The small-signal stability of the ameliorated universal droop control is analyzed for both modes, and other levels of control are modeled. Moreover, a technique based on meta-heuristic optimization to design the hierarchical control parameters optimally is introduced. Finally, the simulation was performed on a microgrid that has three voltage source inverters (VSIs) connected in parallel and a local nonlinear load. The results demonstrate the disturbance rejection performance and the flexibility of the proposed control scheme.

Contents

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http://dx.doi.org/10.1016/j.ijepes.2017.08.027
0142-0615/

1. Introduction

Motivated by the climate change and the global warming, the most countries have adopted the Paris Agreement in December 2015 [1]. This agreement draws lines to limit the global warming below 2 °C above pre-industrial levels and making efforts to reduce the greenhouse gas emissions. According to the International Energy Agency, the largest source of the greenhouse gas emissions comes from the electricity generation based on fossil fuels (i.e., coal, oil, natural gas, etc.) [2]. Hence, the world starts looking at alternative ways to generate the electricity mainly in using clean and renewable sources such as wind energy, photovoltaic, thermal energy and tidal energy [3–6]. These prime sources are distributed by nature and come with deferent form, some are DC sources, and others are AC sources. Therefore, the distributed generations (DGs) were introduced in the literature, in order to supply the demand locally [7,8].

The DGs are connected to the utility grid through a power electronic interface which is responsible for controlling the injected power. However, the increasing integration of DGs into the utility grid can cause as many problems [9]. Thus, the microgrid is used as a bridge between them and the grid. In other words, a microgrid is a local electrical distribution network which gathering a combination of DG units, distributed energy storage systems, and loads. The microgrid operates in grid-connected mode when is connected to the main grid through the point of common coupling (PCC), where it can export or import energy. And can operates in islanded mode when is disconnected from the grid [10–17].

The DGs are interfaced with the synchronous AC microgrid bus through inverters, as they can generate either DC power or asynchronous frequency AC power which can be transferred into DC power via an uncontrolled rectifier [18,12].

The inverters behave as current source inverter (CSI) when the microgrid is operated in grid-connected mode, and as voltage source inverter (VSI) when it operates in islanded mode. Nowadays, the VSIs are most used as electronics interface where they can be implemented with a current controller (CC-VSI) to transfer the maximum power into the local grid, or they can be implemented with a voltage controller (VC-VSI) to regulate the voltage amplitude and frequency of the microgrid. According to Gao and Iravani [19], VC-VSI can be operated either in islanded mode or in grid-connected mode.

The control strategy of the paralleled VSIs is based on the droop method which uses the local measurements to operate independently without external communications between the VSIs. This method was inspired from the conventional droop control of power system, where it is used by the synchronous generators to re-establish the active power balance [20]. Furthermore, the objectives of the droop control in the microgrid are:

- Accurate active and reactive power sharing among the paralleled VSIs in proportion to their power ratings.
- Stabilize the microgrid voltage amplitude and frequency at the PCC.
- Inject the demanded power when the microgrid is operated in grid-connected mode.

In order to achieve these objectives, several droop methods were proposed in the literature, and some of them are reviewed by Bidram et al. [14].

Recently, a new method is developed by Zhong et al. [21–23] which called the universal droop control. This method can operate in islanded mode which is robust to disturbances, noise and component mismatches. Moreover, it works regardless of the output impedance of the inverters.

However, the universal droop control can't handle the grid-connected mode, and it would cause a deviation in amplitude and frequency of the islanded microgrid voltage which leads to phase difference with the utility grid. In this sense, we have ameliorated the universal droop control, and we have enhanced it via a hierarchical structure which becomes its primary control. The secondary control of the hierarchical structure is used to compensate the voltage and frequency deviation caused by the primary control and synchronizes the microgrid voltage with the grid voltage in order to ensure a smooth transition. The secondary control can be classified in two structures [24,17,25,26,9]:

1. Centralized structure is implemented in the microgrid central controller (MGCC) which is suitable for islanded operation.
2. Decentralized structure allows DG units to interact with each others which is suitable for grid-connected operation.

The centralized structure is used throughout this paper.

The paper is organized as follows. In Section 2, the microgrid structure is presented, and the hierarchical control is described. In Section 3, the voltage source inverter is modeled, and an improved universal droop control is described with small-signal analysis, as well as the secondary control for voltage restoration and the synchronization process is presented. In Section 4, an optimal controller design technique is given. Section 5 shows the simulation results. In Section 6, gives the conclusion of the paper.

2. Microgrid structure

The microgrid structure adopted in this paper is shown in Fig. 1. It consists of three VSIs operating in parallel and a local nonlinear load which is composed of three-phase uncontrolled rectifier loaded with LC filter and a variable resistor (see Table 1). Each VSI is connected to the common bus through LCL filter and line impedance that represents a physical distance (see Table 2). In another hand, the microgrid is interfaced to the main grid via an intelligent static switch (SS) that allows monitoring the voltages of both sides [10,15]. The SS disconnects automatically the microgrid when detects any disturbance or fault in the main grid [27], and when the grid is restored, SS informs the MGCC to start the synchronization process in order to reconnect.

We control the microgrid by using a hierarchical scheme that has multiple control loops which are separated into different time scales and it can be classified in the following control levels:

1. *Inner Control (Level 0)*: This level controls and regulates the output voltage and current of the VSI.
2. *Primary Control (Level 1)*: It is a local controller that provides a proportional power sharing among the DGs and mitigates the circulating current that appears when VSIs operate in parallel. The idea comes from the traditional primary control of the synchronous generator that realized by turbine-governors and voltage regulator.
3. *Secondary Control (Level 2)*: When power sharing is achieved by the primary control, the frequency and the voltage amplitude may deviate from their nominal values. Thus, the secondary control is needed to restore the microgrid voltage; this controller is centralized and located in MGCC where it sends the corrected values by using low bandwidth communications to all paralleled VSIs. MGCC can also contain a synchronization loop to facilitate the transition from islanded to grid-connected mode.
4. *Tertiary Control (Level 3)*: This is the last and the slowest control level that is responsible to schedule the power of each DGs. It depends on global economic and current energy prices. One of