Electrical Power and Energy Systems 94 (2018) 354–362

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Modeling and design of a multivariable control system for multi-paralleled grid-connected inverters with *LCL* filter

Ali Akhavan [a], Hamid Reza Mohammadi [a,*], Josep M. Guerrero [b]

[a] University of Kashan, Kashan, Iran
[b] Aalborg University, Aalborg, Denmark

ARTICLE INFO

Article history:
Received 8 March 2017
Received in revised form 14 June 2017
Accepted 21 July 2017
Available online 4 August 2017

Keywords:
Multi-paralleled inverters
Active damping
Coupling effect
LCL filter

ABSTRACT

The quality of injected current in multi-paralleled grid-connected inverters is a matter of concern. The current controlled grid-connected inverters with *LCL* filter are widely used in the distributed generation (DG) systems due to their fast dynamic response and better power features. However, designing a reliable control system for grid-connected inverters with *LCL* filter is complicated. Firstly, overcoming to system resonances due to *LCL* filters is a challenging task, intrinsically. This could become worse as number of paralleled grid-connected inverters increased. In order to deal with resonances in the system, damping methods such as passive or active damping is necessary. Secondly and perhaps more importantly, paralleled grid-connected inverters in a microgrid are coupled due to grid impedance. Generally, the coupling effect is not taken into account when designing the control systems. In consequence, depending on the grid impedance and the number of paralleled inverters, the inverters installed in a microgrid do not behave as expected. In other words, with a proper control system, a single inverter is stable in grid-connected system, but goes toward instability with parallel connection of other inverters. Therefore, consideration of coupling effect in the multi-paralleled grid-connected inverters is vital. Designing control systems for multi-paralleled grid-connected inverters becomes much more difficult when the inverters have different characteristics such as *LCL* filters and rated powers. In this paper, the inverters with different characteristics in a microgrid are modeled as a multivariable system. The comprehensive analysis is carried out and the coupling effect is described. Also, the control system design for multi-paralleled grid-connected inverters with *LCL* filter is clarified and a dual-loop active damping control with capacitor current feedback is designed. Finally, the proposed multivariable control system for a microgrid with three-paralleled grid-connected inverters with *LCL* filter is validated by simulation.

1. Introduction

Renewable energy is harvested from nature, it is clean and free. However, it is widely accepted that renewable energy is not a panacea that comes without challenges. As an interface between the distributed generation (DG) plants and the grid, the grid-connected inverters are essential to convert all kinds of generated power into a high quality AC power and inject it into the grid reliably [1]. The inverters installed in microgrids are generally voltage source inverters with an output filter. Nowadays, the *LCL* filter is considered to be a preferred choice for attenuation of switching frequency harmonics in the injected grid current compared with the *L* filter [2,3]. Because of using smaller reactive elements, the cost and weight of the inverter system are reduced when using *LCL* filter. However, due to the resonance of the *LCL* filter, damping methods are needed for the grid-connected inverters to stabilize the system [4]. Passive and active methods for damping the resonance of the *LCL* filter have been extensively discussed in literature [5–8]. Active damping is preferred to passive damping due to its high efficiency and flexibility of the conversion.

The quality of the grid injected current is very important in the grid-connected systems. International standards regulate the connection of inverters to the grid and limit the harmonic content of the injected current. IEEE std. 1547-2003 [9] gives the limitation of the injected grid current harmonics. If the harmonic content of the injected current exceeds the standard limits, it is required to disconnect the inverter from the grid. Thus, the *LCL* filters are implemented to prevent the grid from being polluted with switching harmonics. Therefore, designing adequate control system for grid-connected inverters with *LCL* filter is a matter of concern.

* Corresponding author at: Department of Electrical and Computer Engineering, University of Kashan, Ravand Blvd., P.O. Box, 8731753153 Kashan, Iran.
E-mail address: mohammadi@kashanu.ac.ir (H.R. Mohammadi).

http://dx.doi.org/10.1016/j.ijepes.2017.07.016
0142-0615/

A more difficulty is appeared when multi-paralleled grid-connected inverters are coupled due to the grid impedance Z_g. In this condition, the inverters influence each other as a result. All inverters in Fig. 1, share the voltage in the point of common coupling (PCC) V_{pcc} and are able to modify this voltage by injecting their currents [10]. It should be noted that, if the grid impedance was ideally considered to be zero, the coupling effect would not exist because the voltage in the PCC would always be V_g. Depending on the number of paralleled inverters and the grid impedance Z_g, the inverters installed in a microgrid might not behave as expected. In other words, with proper control system, a single inverter is stable in grid-connected system, but goes toward instability with parallel connection of other inverters. Therefore, consideration of coupling effect in the multi-paralleled grid-connected inverters is very important and microgrid should be modeled as a multivariable system.

Many literatures with regard to active damping strategies are published [11–18]. However, their analyses are done for single grid-connected inverter. In consequence, coupling effect among inverters due to grid impedance is not considered and the stability and performance of the inverter in a microgrid might be questioned. In [10], authors have been modeled the *N*-paralleled inverters in a PV power plant as a multivariable system. However, all inverters are assumed to be the same including their hardware, software, rated powers, *LCL* filters and reference injected currents. It is widely accepted that this assumption is not valid in the real microgrid since different sources such as photovoltaic panels, wind turbines and fuel cells with different inverters, *LCL* filters and reference injected currents may be collected in a microgrid. Also, in case of PV power plants as considered in [10], even though the same panels and inverters are used, the reference current of each inverter may be different due to partial shadow. In [19], a robust control strategy for a grid-connected multi-bus microgrid containing several inverter-based DG units is proposed. However, only compensation of positive and negative sequence current components using Lyapunov function and sliding mode method is discussed. In [20], a back to back (B2B) converter connection is proposed to provide a reliable interface, while it can provide isolation between utility and microgrids.

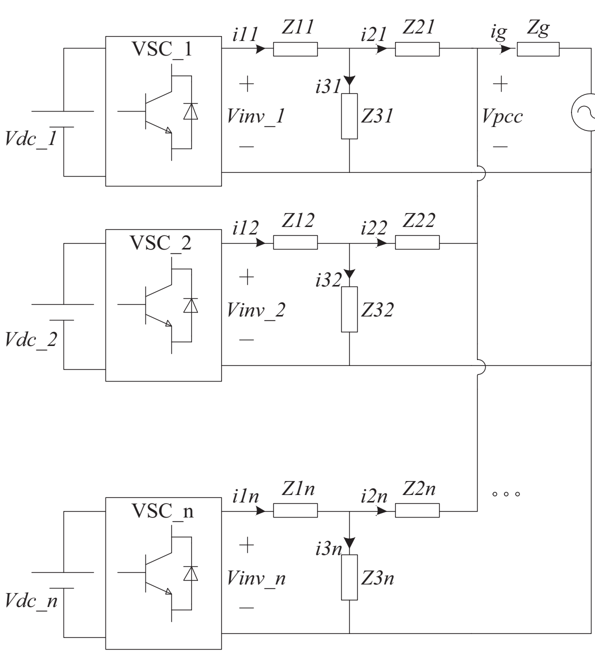

Fig. 1. Typical multi-paralleled grid-connected inverters.

In this paper, modeling and control of three-paralleled grid-connected inverters with different characteristics are described. In fact, the *LCL* filter parameters, rated powers and also, reference injected currents of the inverters are considered to be different. For this task, all inverters are modeled as a multivariable system in order to modeling the coupling effect among inverters due to grid impedance. Also, dual-loop active damping control using the capacitor current feedback as inner loop [5] is chosen for its simple and effective implementation. Due to single phase application, the proportional and resonant (PR) controllers are considered for control system.

This paper is organized as follows. In Section 2, modeling and control of a single grid-connected inverter is described. In Section 3, modeling and control of the three-paralleled grid-connected inverters with different characteristics in a microgrid are analyzed. In Section 4, controller design regarding to PR controllers for the multivariable system that is modeled in previous section is described. In Section 5, the theoretical study is validated through simulation in MATLAB software. Finally, Section 6, concludes this paper.

2. Modeling and control of a single grid-connected inverter

In this section, the modeling and control of a single grid-connected inverter with *LCL* filter is described. Although, this issue has already been addressed in available literatures [11–17], the goal is to get the reader familiarized with the methodology used along this paper.

A generic structure of the *LCL*-filtered grid-connected inverter is shown in Fig. 2. The *LCL* filter consists of an inverter-side inductor L_1, a filter capacitor C, and a grid-side inductor L_2. Parasitic resistances are neglected in order to simplicity.

$$Z_1 = L_1 \cdot s, Z_2 = L_2 \cdot s, Z_3 = \frac{1}{C_3 \cdot s}, Z_g = L_g \cdot s \tag{1}$$

In this figure, V_{dc} is the input DC voltage, V_{inv} is the output voltage of the inverter bridge, i_1, i_g, i_C are inverter-side current, grid-side current and capacitor current, respectively. Also, $G_i(s)$ is the current regulator and i_C is fed back to damp the *LCL* filter resonance. At the PCC, the grid is modeled by its Thevenin equivalent circuit for simplicity, consisting of a voltage source V_g in series with grid impedance Z_g. $G_d(s)$ is the transfer function which combines the computational delay, the PWM delay, and the sampler [10].

$$G_d(s) = \frac{1 - 0.5 \cdot s \cdot T_s}{(1 + 0.5 \cdot s \cdot T_s)^2} \tag{2}$$

where T_s refers to the sampling period.

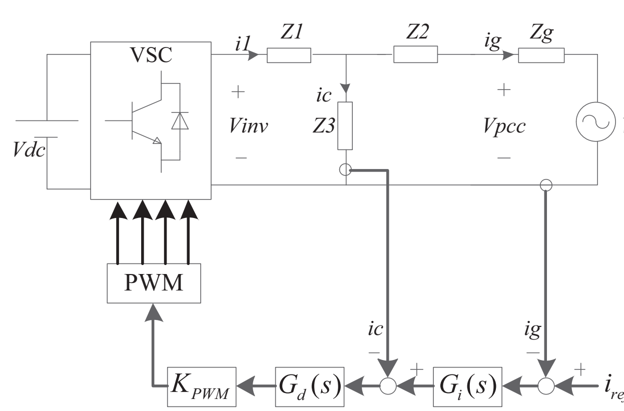

Fig. 2. Configuration of a single grid-connected inverter with *LCL* filter.