Electric Power Systems Research 160 (2018) 226–233

Contents lists available at ScienceDirect

Electric Power Systems Research

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

An improved virtual current method for single-phase converters under frequency variations

Xiongmin Tang, Yichao Fang, Miao Zhang*

School of Automation, Guangdong University of Technology, Guangzhou 510006, China

ARTICLE INFO

Article history:
Received 9 September 2017
Received in revised form 31 January 2018
Accepted 17 February 2018

Keywords:
Orthogonal signal generation
Instantaneous current control scheme
Single-phase converters
Frequency variations

ABSTRACT

Few papers concern about the instantaneous current control (ICC) scheme for single-phase converters under frequency variations. The inherent relations between inaccurate virtual current and the relevant dynamic and static performances of converters are rarely reported. To address the issue, the inherent relations among the DC error, double-line frequency error and inaccurate virtual current are discussed in the paper. An improved virtual current method is proposed to eliminate the DC error and double-line frequency error, which are caused by frequency variations. Based on this method, a new ICC scheme, which is immune to frequency variations, is presented in steady-state scenarios. The improved virtual current method and the proposed ICC scheme are validated in a single-phase converter. Simulation and experimental results show that a unity power factor under frequency variations and a fast dynamic response under load change and voltage sag can be achieved with the proposed ICC scheme.

1. Introduction

The small-size micro-grid systems with battery energy storage equipment are widely implemented in recent years. Single-phase converters are preferable in these applications [1–4]. The produced energy is injected into the power grid by the single-phase converters, and single-phase converters absorb the energy from the power grid [5–9]. Since more and more converters are connected to the AC bus of the micro-grid systems, the inertia of the micro-grid systems is reduced sharply and the frequency of micro-grid systems is easy to be disturbed [10]. If the additional reactive power caused by frequency variations is not compensated reasonably, this will cause that the stability of the voltage in micro-grid systems is reduced in the scenario and the grid-tied converters will be shut down for self-protection [11]. It is vital to propose a high robustness control scheme against frequency variations for single-phase converters.

To achieve a sinusoidal line current with unity power factor and obtain a stable dc-link voltage, different control schemes are applied. These control schemes can be categorized into three major classes, namely, proportional-resonant (PR) control scheme [12], direct power control (DPC) scheme [6,8–9] and instantaneous current control (ICC) scheme [13,14]. Although PR control schemes can effectively reduce the effects of frequency variations, the independent control of active and reactive current cannot be realized. It is difficult to satisfy the reactive power requirement of micro-grid systems for voltage support when the fault occurs in the power system. Since the performance of single-phase converters with DPC schemes is deeply related to the accuracy of the model of converters, the application of DPC schemes is limited in micro-grid systems. Because the active and reactive power can be controlled independently in ICC schemes, the ICC schemes are sensible choices for micro-grid systems. Hence, an ICC scheme is used in the paper.

As shown in Fig. 1, the conventional ICC scheme [13] consists of a current controller, a PQ controller, a synchronization unit, and two orthogonal signal generations (OSGs). The current controller is used for tracking a reference current [13]. The PQ controller is used for obtaining a constant dc-line voltage [6]. The synchronization unit is used for a fast and accurate estimation of the frequency and phase angle of AC bus of the micro-grid systems [15]. The synchronization unit is usually performed by a phase-locked loop (PLL) [16]. Although there are many different types of PLLS, which are capable of tracking the frequency and the angle of the grid voltage, the virtual voltage component and the virtual current component cannot be generated directly with the PLLs [17]. The virtual components are usually generated by OSG methods.

There are four major types of OSG methods in single-phase converters. For example, a second order generalized integrator (SOGI) is developed in Ref. [6]; an all-pass filter is suggested in Ref. [18]; a Hilbert transformation is presented in Ref. [18] and T/4 delay unit is used in Ref. [19]. Since the all-pass filter method and the Hilbert

---

* Corresponding author.
E-mail address: bezhangm@126.com (M. Zhang).

https://doi.org/10.1016/j.epsr.2018.02.011
0378-7796/

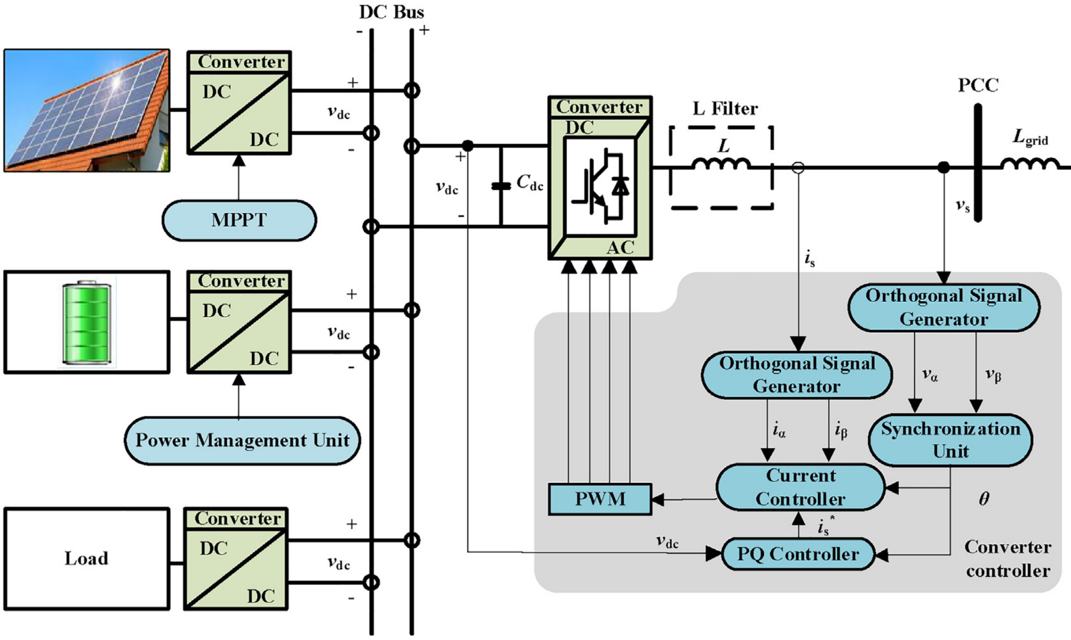

Fig. 1. Structure of the small-size micro-grid systems with battery energy storage equipment and the conventional ICC scheme block diagram of single-phase grid-tied converters.

transformation method cannot remove the DC component of the input signal, the two methods are also not used directly in single-phase converters under frequency variations. The SOGI method is a commonly used method to generate the orthogonal currents and orthogonal voltages in single-phase converters. Since the two output signals of SOGI are generated using a second-order band-pass filter and a second-order low-pass filter respectively, the output signals of SOGI cannot follow the actual signals fast and precisely. This affects the dynamic characteristic of single-phase converter, and may cause the controller system to be unreliable. To reduce the effects of frequency variations, an adaptive OSG method by changing the angular frequency of grid is presented in Ref. [20] and Ref. [21]. Because the parameters in the adaptive methods must be modified in each regulating period to lower the impact of frequency variations, this affects the calculating speed in engineering application [22,23]. Unfortunately, since the adaptive OSG method has nearly the same filtering characteristics, the method is difficult to be used directly in single-phase converters [24]. The T/4 delay unit method is a simple OSG method, and the current information can be retained. Hence, the method is widely used in single-phase converters [25,26]. To reduce the effects of frequency variations, variable sampling frequency or variable delay value is used in converters. However, an additional error, especially for low switching frequency converters, will occur if the two above-mentioned compensation methods are used.

To reduce the effects of frequency variations and reduce the computing effort, an improved virtual current method based on T/4 delay unit OSG method is proposed in the paper. Through analysis of the relations among the DC error, double-line frequency error and inaccurate orthogonal current, the DC error and double-line frequency error caused by frequency variations are reduced with the proposed virtual current method. A new ICC scheme based on the proposed method is presented in the paper. The proposed method and the ICC scheme are validated by the simulation and experimental results.

This paper is organized in the following manner. In Section 2.1, the effects of inaccurate virtual current are discussed, and an improved virtual current method is developed. In Section 2.2, a new ICC scheme is presented with the proposed virtual current method and the performance is analyzed. In Section 3, simulation and experimental results of the new ICC scheme are demonstrated, and it is followed by a conclusion in Section 4.

2. Principle of the improved ICC scheme

Since the line current is controlled to be sinusoidal with unity power factor in single-phase converters, the expression of line current $i_s(t)$ and the grid voltage $v_s(t)$ can be defined in Eqs. (1) and (2).

$$v_s(t) = V_m \cos(\omega t) \tag{1}$$

$$i_s(t) = I_m \cos(\omega t) \tag{2}$$

where, V_m and I_m are peak values of the grid voltage and line current, while ω is angular frequency of grid.

2.1. Generalized orthogonal signal generator (GOSG) method

The steady-state virtual current generated by the T/4 delay unit OSG method in stationary reference frame (named as αb reference frame in the paper) are expressed in Eq. (3).

$$\begin{cases} i_\alpha(t) = i_s(t) = I_m \cos(\omega t) \\ i_\beta(t) = I_m \cos(\omega t - \pi/2) = I_m \sin(\omega t) \end{cases} \tag{3}$$

where, $i_\alpha(t)$ and $i_\beta(t)$ are α axis and β axis current component of $i_s(t)$, respectively.

The discrete expressions of $i_\alpha(t)$ and $i_\beta(t)$ are given in Eq. (4).

$$\begin{cases} i_\alpha(k) = i_s(k) \\ i_\beta(k) = i_s(k-n) \end{cases} \tag{4}$$

where, $n = T/(4T_S)$. T is the period of grid voltage, T_S is the discrete period, and k is the sampling instant. The ratio between T_S and T usually is set to an integer under nominal frequency.

The phase difference between $i_\alpha(k)$ and $i_\beta(k)$ is given in Eq. (5).

$$\varphi(\omega) = -\omega n T_s \tag{5}$$