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A novel direct-current vector control technique for single-phase inverter with *L*, *LC* and *LCL* filters

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ABSTRACT

Single-phase grid-connected converters (GCCs) are widely used to connect small-scale distributed renewable resources to the grid. However, unlike a three-phase system, design of the vector control for a single-phase GCC is more challenging. This paper presents a novel vector control design for a single-phase GCC based on a direct current vector control method. The design of the proposed vector controllers considered different filtering schemes, including *L*, *LC* and *LCL* filters. The behavior of the proposed direct current vector control is investigated through both simulation and hardware experimentation. Both demonstrate that the proposed control approach has strong ability to trace rapidly changing reference commands, tolerate system disturbances, and satisfy various control needs of single-phase GCCs under different filtering configurations.

1. Introduction

Single-phase inverters are broadly used to connect small-scale renewable sources to a microgrid or a low-voltage distribution system [1,2]. Typical applications involving single-phase inverters include roof-top solar photovoltaics [3], fuel cells [4] and home battery charging/discharging facilities.

In these applications, control technology for single-phase inverters is critical. In existing technologies, vector control is the primary technology used to control a three-phase grid-connected inverter [5,6], due to its great advantages. However, to apply vector control to a single-phase inverter, an imaginary circuit has to be created [7], which has caused great challenges to ensure high performance of vector control in single-phase inverter applications.

On the other hands, with the growing use of single-phase GCCs in distributed generation systems, the problem of injected harmonics becomes critical. The current harmonics, if injected into a low-voltage distribution system, can cause sensitive apparatuses connected to the system to malfunction. As a result, single-phase GCCs for grid interfacing of renewable sources will need to incorporate interface filters to attenuate the injection of current harmonics.

The three main harmonic filter topologies are *L*, *LC* and *LCL* filters [8]. The *L* filter is the first-order filter and requires a high switching frequency in order to sufficiently attenuate the inverter harmonics. The *LC* filter is the second-order filter and exhibits better damping behaviors than the *L* filter. The *LCL* filter is the third-order filter. It has good current ripple attenuation even with small inductance values. Thus, a lower inverter switching frequency can be used [9].

In three-phase applications, the well-known conventional standard vector control strategy was generally used to control a *L*-filter GCC [10,11]. For *LC*- and *LCL*-filter GCCs, the conventional vector control approach is to neglect the capacitor dynamics [12]. Thus, the vector controller is designed by considering the equivalent series connection of *LC*- and *LCL*-filter inductors, simplifying the control problem to that of a first-order system. This would result in imprecise description of a *LC*- or *LCL*-GCC system and potential oscillatory and/or unstable dynamic behavior [13,14].

Therefore, a damping strategy was usually accompanied a vector controller for a three-phase *LC*- or *LCL*-filter GCC in two main categories: (1) Passive Damping [15,16], (2) Active Damping [17,18]. Passive damping (PD) is based on adding a resistive element to a *LC* or *LCL* filter. Active damping (AD) does not require additional passive elements and damps the system by modifying the structure of the vector control strategy. PD methods cause a decrease of the overall system efficiency because of the associated power losses while AD methods are more selective to parameter uncertainties [19]. For single-phase inverters, developing vector control technology would be even more challenging because a virtual imaginary circuit must be created [20]. Consequently, proportional resonant control technique using sinusoidal instead of d-q current references

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have been developed as a key method for control of single-phase inverters [21,22].

Recently, an adaptive vector control approach was proposed for control of a three-phase L-filter GCC that employs a direct-current control (DCC) strategy. As shown by [23,24], the conventional standard vector control method has a competing control deficiency and the DCC-based vector control strategy is promising. However, DCC-based control strategy has not been developed for single-phase GCCs and for GCCs with LC and LCL filters.

The novelty of this paper is to develop DCC vector control methods for single-phase L-, LC- and LCL-filter GCCs without using any passive or active damping mechanisms. The contributions of the paper include: (1) analysis of active and reactive power control characteristics of single-phase L-, LC- and LCL-filter GCCs in decoupled d-q reference frame, (2) development of DCCs for L-, LC- and LCL-filter GCCs in single-phase applications, (3) implementation of the single-phase DCC in a nested-loop control structure, (4) development of a DCC control strategy by considering GCC physical system constraints, (5) evaluation of the single-phase DCC vector control technology for dc-link voltage control, active and reactive power control and grid voltage support control and (6) hardware experiment validation.

The rest of the paper is structured as follows. The basic configurations, models and power control characteristics of single-phase GCC systems with L, LC and LCL filters are presented in Section 2. A novel direct-current vector control mechanism is proposed in Section 3. Section 4 evaluates the performance of the DCC for dc-link voltage control, power control, and grid voltage support control for all the three filtering schemes. Section 5 presents the hardware experiment system setup and results. Finally, the paper concludes with summary remarks.

2. Single-phase GCC model in *d-q* reference frame with *L*, *LC* and *LCL* filters

2.1. L-filter based single-phase GCC

The upper half of Fig. 1 shows the schematic of a single-phase L-filter GCC system, in which a dc-link capacitor is on the left and a single-phase voltage source, representing the voltage at the Point of Common Coupling (PCC) with the ac system, is on the right. In Fig. 1, L_f and R_f are the inductance and resistance of the grid filter, v_{a_inv} stands for the GCC output voltage in the single-phase ac system.

To implement the d–q vector control, an imaginary orthogonal circuit (the lower half of Fig. 1) needs to be created based on the real circuit of the GCC. The ac voltage or current of the imaginary circuit should have exactly the same amplitude as that of the real circuit but $-90°$ phase shift. The real and imaginary circuits constitute the α–β frame of the single-phase GCC system, which can be transferred into the d–q frame through

$$T_{\alpha\beta\_dq} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \tag{1}$$

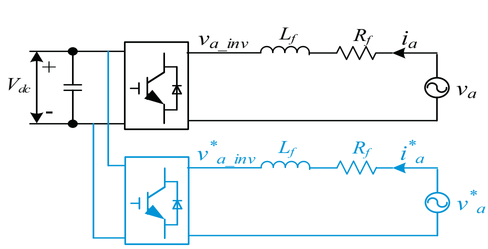

Fig. 1. L-filter GCC schematic: real and imaginary circuits.

Using the motor sign convention, the voltage balance across the L filter in the d–q reference frame is [23]

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_f \begin{bmatrix} i_d \\ i_q \end{bmatrix} + L_f \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_s L_f \begin{bmatrix} -i_q \\ i_d \end{bmatrix} + \begin{bmatrix} v_{d\_inv} \\ v_{q\_inv} \end{bmatrix} \tag{2}$$

where, $\omega_s = 2\pi f_s$ in which f_s is the frequency of the grid voltage. In terms of space vectors, Eq. (2) is expressed by a complex Eq. (3) in which $\mathbf{v}_{dq}$, $\mathbf{i}_{dq}$ and $\mathbf{v}_{dq\_inv}$ are instantaneous space vectors of the single-phase PCC voltage, grid current and inverter output voltage in d-q reference frame.

$$\mathbf{v}_{dq} = R_f \times \mathbf{i}_{dq} + L_f \frac{d}{dt}\mathbf{i}_{dq} + j\omega_s L_f \times \mathbf{i}_{dq} + \mathbf{v}_{dq\_inv} \tag{3}$$

In the steady-state condition, Eq. (3) becomes Eq. (4), where $\mathbf{V}_{dq}$, $\mathbf{I}_{dq}$ and $\mathbf{V}_{dq\_inv}$ stand for the steady-state space vectors of PCC voltage, grid current and converter output voltage in d-q frame.

$$\mathbf{V}_{dq} = R_f \times \mathbf{I}_{dq} + j\omega_s L_f \times \mathbf{I}_{dq} + \mathbf{V}_{dq\_inv} \tag{4}$$

Using the PCC voltage orientation, the PCC d-axis voltage is constant and q-axis voltage is zero. Thus, the instantaneous active and reactive powers transferred from the ac system to the GCC are proportional to d- and q-axis currents, respectively, as shown by Eqs. (5) and (6).

$$p(t) = \left(v_d i_d + v_q i_q\right)/2 = v_d i_d/2 \tag{5}$$

$$q(t) = \left(v_q i_d - v_d i_q\right)/2 = -v_d i_q/2 \tag{6}$$

In terms of the steady state condition, $\mathbf{V}_{dq} = V_d + j0$ since the d-axis of the reference frame is aligned along the PCC voltage position. Assuming $\mathbf{V}_{dq\_inv} = V_{d\_inv} + jV_{q\_inv}$ and neglecting resistor R_f, then, the current flowing between the ac system and the GCC according to Eq. (4) is

$$\mathbf{I}_{dq} = \frac{\mathbf{V}_{dq} - \mathbf{V}_{dq\_inv}}{jX_f} = \frac{V_d - V_{d\_inv}}{jX_f} - \frac{V_{q\_inv}}{X_f} \tag{7}$$

where, $X_f = j\omega_s L_f$ stands for the grid filter reactance.

Since the passive sign convention is applied, the power absorbed by the inverter from the grid can be achieved from the complex power equation, $P_{ac} + jQ_{ac} = \mathbf{V}_{dq}\mathbf{I}^*_{dq}/2 = V_d\mathbf{I}^*_{dq}/2$. By solving this equation with Eq. (7), Eq. (8) is obtained. According to Eq. (8), the ac system active and reactive powers, P_{ac} and Q_{ac}, are controlled through q- and d-axis components, V_{q_inv} and V_{d_inv}, of the voltage injected into the ac system by the GCC, respectively.

$$P_{ac} = -\frac{V_d V_{q\_inv}}{2X_f}, \; Q_{ac} = \frac{V_d\left(V_d - V_{d\_inv}\right)}{2X_f} \tag{8}$$

2.2. LC-filter based single-phase GCC

Fig. 2 shows the real and imaginary circuits of a single-phase LC-filter GCC system, in which C represents the LC-filter capacitor, i_{a1} represents the current flowing through the LC-filter inductor and the corresponding current in the d-q reference frame are i_{d1} and i_{q1}, and other terms are the same as those defined in Section 2.1.

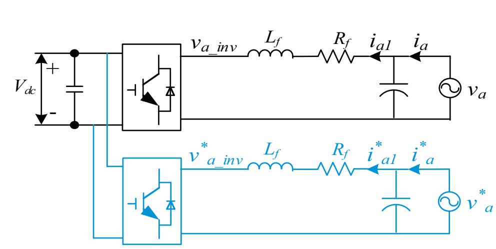

Fig. 2. LC-filter GCC schematic: real and imaginary circuits.