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A novel controller for harmonics reduction of grid-tied converters in unbalanced networks

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ABSTRACT

This paper proposes a novel controller for a grid-tied converter interfaced to a network with unbalanced voltage conditions. Due to the influence of negative sequence voltage and current components created by unbalanced voltages, conventional PI controller alone cannot adequately deal with the fluctuations in active and reactive powers generated from converters. In order to overcome this inadequacy, a systematic and comprehensive controller, namely Linear Parameter Varying (LPV) controller is designed and presented in this work. The proposed LPV controller is implemented using the well-known voltage oriented control (VOC) approach. The unbalanced network voltages are first decomposed using a signal delay technique with the support of Clarke's transformation in order to filter out the negative sequence components. An enhanced phase-locked loop (ePLL) is then developed to reduce the higher-order harmonics. The feasibility of the proposed controller and the effectiveness of ePLL are verified by experimental studies.

1. Introduction

Renewable energy generation has become a significant developmental trend for contemporary networks due to environmental concerns. The interfaces between the renewable power sources and power networks have played a crucial role in terms of reliability, connection flexibility, power quality and they have gradually attracted intensive attention of academia and industry in recent years. These interfaces can regulate the power flows with either constant power factor or constant currents. Various studies of these power electronic interfaces and control methodologies have been extensively performed, including switching scheme development to improve power quality [1], converter topology optimisation [2] or the application of probabilistic modelling to reduce harmonic distortion [3].

Traditionally, the grid-tied converter is controlled using Virtual Flux Oriented Control (VFOC) [4] or VOC [5], both of which decouple the three phase currents into direct (i_d) and quadrature (i_q) components, and regulate them separately in a reference frame aligned to either the voltage or virtual flux rotating vectors [6]. VFOC or VOC approaches, however, experience the dependence on the system parameters and various simplifying approximations are made; for example inductor magnetic saturation is not considered, i.e. inductance is taken as constant irrespective of the current values [7].

In order to overcome the parameter dependence of controllers, the direct power control approach was introduced that significantly improved system voltage stability and dynamic responses. This technique required a high sampling frequency and resulted in the converter switching frequency varying, and hence led to variable switching losses [8].

In the beginning of 1990s, a formal framework for Linear Parameter Varying (LPV) systems was first introduced. In this, the synthesis problem can be formulated as a convex optimisation problem with Linear Matrix Inequality (LMI) constraints that can overcome the less accurate interpolation progress [9]. The LPV system and control were originally applied for various type of systems, for example jet engines, submarines and aircrafts [10]. Induction machines in general and power converters in particular are systems that can benefit from this contemporary control method. Reference [11] uses a LPV controller for a doubly fed induction generator (DFIG) based wind turbine, but the results were not validated by experiments.

The contribution of the work in this paper is to implement the contemporary LPV controller to regulate the grid-tied converter current or power flows in the context of unbalanced voltage at the point of common coupling (PCC), which is common within

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low voltage networks. The controller is then experimentally implemented and verified using a Digital Signal Processor (DSP). This work also proposes an enhanced phase-lock loop (ePLL) module that could successfully reduce the Total Harmonic Distortion (THD) at the PCC even with an over-simplified inductive filter. While *LCL* filters are the most commonly used for grid-tied converter applications, the interface of the converter in this paper is chosen as simple as possible, namely a single inductor with parasitic resistance. The aim here is to emphasise that the proposed controller and the improved phase-locked loop system can effectively reduce the negative sequence components and other higher order harmonics.

The rest of this paper is organised as follows: Section 2 presents the balanced and the unbalanced network models that the converter is connected to and the method to decompose the negative sequence components in the time domain; Section 3 details LPV controller design and the implementation process under unbalanced voltage conditions with the support of the ePLL; Section 4 summarises the experimental results obtained from the proposed method and conclusions are drawn in Section 5.

2. Network models

The interface of a grid-tied converter to the utility grid can be inductive (L with parasitic resistance R) or *LCL* filters; each of these configurations poses its unique advantages for power systems. In terms of higher order harmonic reduction, the *LCL* filter with third order dynamics outperforms the L filter for a given value of inductance. However, the system incorporating *LCL* filters has an inherent high-resonant peak at the resonant frequency, which may lead to the unstable operation region if the controller is not carefully designed and tuned [12]. To deal with this stability problem, passive or active damping methods are usually used [13,14]. In this paper, an effective controller with an advanced algorithm will be demonstrated which sufficiently tackles the problem even with a simplified inductor L interface (plus parasitic resistance R).

2.1. Converter operation under balanced voltage conditions

With an L filter (containing parasitic R) interfaced to the utility, the relationship between currents and voltages is expressed as,

$$\mathbf{E} = R \times \mathbf{I} + L \times \frac{d(\mathbf{I})}{dt} + \mathbf{V} \tag{1}$$

where **E**, **V** and **I** are voltage vector at PCC, voltage vector generated by converter and current vector respectively.

By utilizing the conventional Park's transformation [15] to the grid-tied converter with (dq) coordinates rotating at an arbitrary angular frequency ω_0, the second order dynamics of the converter has been widely accepted in the literature,

$$\begin{aligned} v_d &= e_d - L\frac{di_d}{dt} - Ri_d + L\omega_0 i_q \\ v_q &= e_q - L\frac{di_q}{dt} - Ri_q - L\omega_0 i_d \end{aligned} \tag{2}$$

The active power (P) and reactive power (Q) from converter are obtained based on apparent power (S) in the (dq) reference frame,

$$\begin{aligned} P &= \frac{3}{2}Re(S) = \frac{3}{2}Re\left\{\vec{v}.\vec{i}^{*}\right\} = \frac{3}{2}Re\left[(v_d + jv_q)(i_d - ji_q)\right] = \frac{3}{2}(v_d i_d + v_q i_q) \\ Q &= \frac{3}{2}Im(S) = \frac{3}{2}Im\left\{\vec{v}.\vec{i}^{*}\right\} = \frac{3}{2}Im\left[(v_d + jv_q)(i_d - ji_q)\right] = \frac{3}{2}(v_q i_d - v_d i_q) \end{aligned} \tag{3}$$

In the state-space form, the current dynamic characteristics can be expressed as,

$$\begin{aligned} \frac{di_d}{dt} &= -\frac{R}{L}i_d + \omega_0 i_q + \frac{1}{L}(v_d - e_d) \\ \frac{di_q}{dt} &= -\frac{R}{L}i_q - \omega_0 i_q + \frac{1}{L}(v_q - e_q) \end{aligned} \tag{4}$$

2.2. Converter operation under unbalanced voltage conditions

The performance of the converter under unbalanced voltage conditions is derived similar to the case of a balanced network. However, the presence of additional negative sequence voltages and currents leads to double frequency oscillations in the instantaneous power [8] as given by,

$$\begin{aligned} p &= P_0 + P_{2sin}\sin(2\omega_0) + P_{2cos}\cos(2\omega_0) \\ q &= Q_0 + Q_{2sin}\sin(2\omega_0) + Q_{2cos}\cos(2\omega_0) \end{aligned} \tag{5}$$

where P_0 and Q_0 denote the constant power elements and P_{2sin}, P_{2cos}, Q_{2sin}, Q_{2cos} denote the power elements that vary at twice the supply frequency. These power oscillations will cause unexpected ripple and, if not treated, the converter will inject harmonics to the network at PCC.

The real power elements in Eq. (5) are calculated as [8],

$$\begin{aligned} P_0 &= \frac{3}{2}\left(v_d^+ i_d^+ + v_q^+ i_q^+ + v_d^- i_d^- + v_q^- i_q^-\right) \\ P_{2sin} &= \frac{3}{2}\left(v_q^- i_d^+ - v_d^- i_q^+ + v_d^+ i_q^- - v_q^+ i_d^-\right) \\ P_{2cos} &= \frac{3}{2}\left(v_d^- i_d^+ + v_d^+ i_d^- + v_q^- i_q^+ + v_q^+ i_q^-\right) \end{aligned} \tag{6}$$

where ${v_d}^+$ is the voltage along the d-axis in the positive rotating frame, ${v_q}^+$ is the voltage along the q-axis in the positive rotating frame, ${v_d}^-$ is the voltage along the d-axis in the negative rotating frame and ${v_q}^-$ is the voltage along the q-axis in the negative rotating frame, which rotates at the same angular frequency of positive rotating frame but in the opposite direction.

According to Eq. (6), the control targets of positive sequence controller are: (i+) to ensure that constant currents are injected to or drawn from utility network; and (ii+) to regulate constant powers generated to or consumed from the utility network. Similarly, the control targets of negative sequence controller are: (i−) to eliminate the negative sequence currents within the phase currents; and (ii−) to obtain ripple free power by injecting suitable negative sequence currents.

The target (i−) can be achieved by setting the negative sequence reference current as zero,

$$i_q^{*-} = 0; \quad i_d^{*-} = 0 \tag{7}$$

while the (ii−) can be achieved by forcing double grid frequency oscillation terms in Eq. (6), i.e. P_{sin2} and P_{cos2} to be zero. Solving these conditions gives,

$$i_q^{*-} = \left(\frac{v_q^+ v_d^- + v_d^+ v_q^-}{v_d^+ v_d^+ + v_q^+ v_q^+}\right) i_d^+ + \left(\frac{v_q^+ v_q^- - v_d^+ v_d^-}{v_d^+ v_d^+ + v_q^+ v_q^+}\right) i_q^+ \tag{8}$$

$$i_d^{*-} = \left(\frac{v_d^+ v_d^- - v_q^+ v_q^-}{v_d^+ v_d^+ + v_q^+ v_q^+}\right) i_d^+ + \left(\frac{v_d^+ v_q^- + v_q^+ v_d^-}{v_d^+ v_d^+ + v_q^+ v_q^+}\right) i_q^+ \tag{9}$$

It can be seen from Eqs. (7)–(9) that the targets for negative sequence current free and power ripple free cannot be met at the same time; the negative sequence currents can be eliminated but the ripple in power still persists and vice versa.