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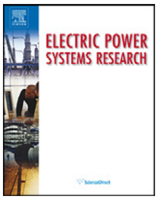

Using equidistant vector-based hysteresis current regulators in DFIG wind generation systems

Mansour Mohseni*, Syed Islam, Mohammad A.S. Masoum

Department of Electrical and Computer Engineering, Curtin University of Technology, Perth, WA, Australia

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ABSTRACT

This paper proposes a novel equidistant vector-based hysteresis current regulator (VBHCR) in the rotor-side converter (RSC) of DFIG-based wind generation systems. The Γ-form equivalent circuit is used for the machine modelling, with the discrete formulation of the RSC output voltage. The overall vector control scheme is then explored and the control structure of the proposed equidistant VBHCR is presented. When compared to the commonly used PI current regulators, the proposed VBHCR exhibits several advantages such as very fast transient response, simple hardware implementation, satisfactory steady-state performance, and intrinsic robustness to machine parameters variations. Moreover, fixed hysteresis bands are replaced with equidistant bands in order to limit the instantaneous variations of the switching frequency and reduce the maximum switching frequency of the RSC. Detailed simulation studies are carried out for a 1.5 MW DFIG-based wind generator to examine the operation of the proposed current regulator under various operating conditions and demonstrate its superiority over the standard PI current regulator.

1. Introduction

The past decade has seen the emergence of wind as the world's most dynamically growing energy source. Wind energy conversion systems (WECS) are divided into fixed- and variable-speed technologies. Variable-speed WECS have recently become more popular due to many technical advantages compared to the fixed-speed concepts, including maximized power capture, reduced mechanical stresses imposed on the turbine, and reduced acoustical noise [1]. The variable-speed technologies can be further subdivided into two major concepts: synchronous generators with full-scale converters and doubly fed induction generators (DFIGs). For high-power applications, the DFIG concept is more economically viable as it implements back-to-back voltage source converters (VSCs) rated at 30–35% of the generator size for a given rotor speed variation of ±25% [2,3].

Field-oriented vector control, using rotational transformations and linear PI controllers, has so far proven to be the most popular control technique implemented in DFIGs [4–7]. This double-closed-loop control strategy can provide a decoupled control over the electrical torque (active power) and the machine excitation (reactive power) through regulating the quadrature components of the rotor current [4,5]. The standard PI current regulators are then employed to control the rotor current vector in a synchronous reference frame fixed to either the stator-flux or stator-voltage space-vector. However, there are two main drawbacks associated with this type of current regulator: the discrete operation of the RSC is not taken into account and the DFIG system is assumed as a linear time-invariant (LTI) model. Based on these simplifying assumptions, the gains of PI controllers are tuned using the small signal analysis of the nonlinear equations describing the DFIG behaviour [6–8]. Therefore, the system formulation is only valid around a specific operating point and the response will deviate if the operating condition changes. This will obviously lead to degraded performance of the overall control scheme over a wide operation range. The problem is especially crucial for wind generator applications where the machine must properly function at operating points which have greatly deviated from the nominal condition, e.g. voltage sag/swell ride-through specifications outlined in modern grid codes [9]. Therefore, the PI controller gains must be tuned with a trade-off between maintaining the system stability over the whole operating range and achieving adequate dynamic response under transient conditions [6], [8]. This will noticeably degrade the transient performance of the overall vector control scheme and jeopardize the controller stability.

Nonlinear control techniques, such as direct torque/power control (DTC/DPC) methods, have been proposed to overcome these deficiencies [10–12]. In these techniques, the current control loop is eliminated and the average control signal (the output voltage vector) is directly selected from a look-up table that is aimed to

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* Corresponding author at: GPO Box U1987 Perth, Western Australia 6845, Australia. Tel.: +61 8 92664511; fax: +61 8 92662584.
E-mail addresses: mansour.mohseni@postgrad.curtin.edu.au (M. Mohseni), s.islam@curtin.edu.au (S. Islam), m.masoum@curtin.edu.au (M.A.S. Masoum).

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control both active and reactive power during a sample period. The main advantages of DTC/DPC methods are the enhanced transient response, minimum use of machine parameters, and non-complex control structure. However, there is always a significant torque/power ripple due to the high bandwidth of the controller, the converter switching frequency varies depending on the operation conditions, and the controller performance may deteriorate during machine start-up and while operating close to the synchronous speed. Modified methods have been proposed to overcome these problems [13–17], but extra drawbacks were introduced, such as the inclusion of additional PI controllers [14,15], reduced robustness to the machine parameter variations [13–15], and complex online calculations [16,17]. Based on the same principle used in DTC/DPC, Xu et al. have suggested replacing the conventional PI current regulator with a non-linear predictive current regulator [18]. However, its performance depends on the accurate estimation of the machine parameters and it suffers from a complex control structure.

This paper addresses the aforementioned problems by implementing an equidistant VBHCR in the field-oriented vector control of DFIG wind generation systems. The proposed current regulator was originally introduced by the authors for conventional VSCs, showing superior performance under steady-state and transient operating conditions [19]. It was already demonstrated that the proposed VBHCR can retain the inherent advantages of the conventional hysteresis method (such as the excellent transient performance, simple hardware implementation, outstanding stability, and robustness to the machine parameters variations) and remove its severe disadvantages in three-phase applications (such as very high average switching frequency and large oscillations in the output current) [20]. Moreover, the proposed VBHCR is superior to other vector-based methods proposed in the literature since it avoids the redundant control actions observed in [21,22], has a simpler structure as compared to [23], and suppresses the current vector oscillations more effectively than the methods reported in [24]. In this paper, fixed hysteresis bands used in the proposed current regulator are replaced by equidistant hysteresis bands in order to limit instantaneous variations of the converter switching frequency during the fundamental period and reduce the maximum switching frequency required near the zero crossing point of the reference current [25].

2. DFIG system modelling

The DFIG-based WECS are constituted of a wound rotor induction machine (WRIM) mechanically coupled to the wind turbine. The stator winding is directly connected to the coupling transformer whereas the rotor winding is connected through back-to-back partial-scale VSCs. A common dc-link capacitor is placed between the RSC and the grid-side converter (GSC). In this wind generation technology, the machine operation is fully controlled from the RSC while the GSC is only designed to keep the dc-link voltage constant.

2.1. The Γ-form machine model

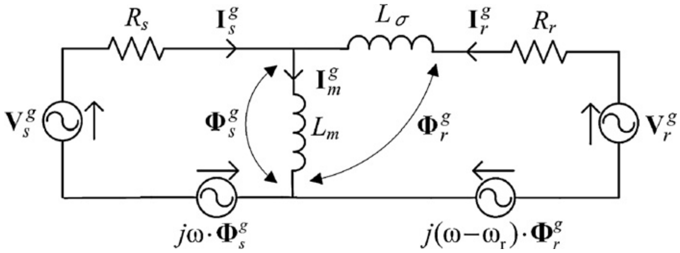

Fig. 1. "Γ-form" equivalent circuit of the DFIG.

In most reported studies, WRIM is modelled in the well-known "T-form" equivalent circuit using self and mutual inductances [4,5,7,8]. However, the T-form equivalent circuit is more complex than necessary. Therefore, this paper uses the more convenient "Γ-form" equivalent circuit without losing information or accuracy of the model [26]. The general expression of Γ-form equivalent circuit is graphically represented in Fig. 1, where ω is the angular speed of the arbitrary reference frame. According to this model, the stator and rotor voltage are given by

$$\mathbf{V}_s^g = R_s\mathbf{I}_s^g + \frac{d\mathbf{\Phi}_s^g}{dt} + j\omega\cdot\mathbf{\Phi}_s^g \tag{1}$$

$$\mathbf{V}_r^g = R_r\mathbf{I}_r^g + \frac{d\mathbf{\Phi}_r^g}{dt} + j(\omega-\omega_r)\cdot\mathbf{\Phi}_r^g \tag{2}$$

where

$$\mathbf{\Phi}_s^g = L_m(\mathbf{I}_s^g + \mathbf{I}_r^g) = L_m\mathbf{I}_m^g \tag{3}$$

$$\mathbf{\Phi}_r^g = L_\sigma\mathbf{I}_r^g + L_m(\mathbf{I}_s^g + \mathbf{I}_r^g) \tag{4}$$

Using (3) and (4), the stator current and rotor flux vectors can be omitted in (1) and (2). Accordingly, the rotor voltage equation is obtained as

$$\mathbf{V}_r^g = R_r\mathbf{I}_r^g + L_\sigma\frac{d\mathbf{I}_r^g}{dt} + \frac{d\mathbf{\Phi}_s^g}{dt} + j(\omega-\omega_r)\cdot(L_\sigma\mathbf{I}_r^g + \mathbf{\Phi}_s^g) \tag{5}$$

Also, the stator power is defined by

$$\mathbf{S}_s^g = P_s + jQ_s = -\frac{3}{2}\mathbf{V}_s^g.\hat{\mathbf{I}}_s^g \tag{6}$$

2.2. Discrete formulation of the RSC output voltage

The power circuit of the RSC is shown in Fig. 2(a). At each instant, the output voltage vector generated by the converter is determined based on the gating signals S_a^*, S_b^*, and S_c^*. If $S_a^* = 1$, the current in phase a is flowing through the phase upper switch (S_1); otherwise, S_4 is conducting the phase current ($S_a^* = 0$). Using the same definitions for phase b and phase c, the output voltage vector generated by the RSC can be defined by

$$\mathbf{V}_r = \frac{1}{3}V_{dc}\left[(2S_a^*-1) + e^{(j2\pi/3)}\cdot(2S_b^*-1) + e^{(-j2\pi/3)}\cdot(2S_c^*-1)\right] \tag{7}$$

Considering all the possible combinations of gating signals in (7), eight switching states, and consequently, eight output voltage vectors are obtained, given by

$$\begin{cases} \mathbf{V}_r = \dfrac{2}{3}V_{dc}\exp\left(j(k-1)\cdot\dfrac{\pi}{3}\right); \quad k = 1,2,\ldots,6 \\ \mathbf{V}_r = \mathbf{V}_0 = \mathbf{V}_7 = 0 \end{cases} \tag{8}$$

Based on (8), the available discrete output voltage vectors consists of six non-zero ($\mathbf{V}_1$–$\mathbf{V}_6$) and two zero ($\mathbf{V}_0$, $\mathbf{V}_7$) voltage vectors, as graphically presented in Fig. 2(b) [20].

3. DFIG overall control scheme

This section presents the overall field-oriented vector control scheme developed in the paper. In this control technique, the synchronous reference frame is usually aligned with the stator-flux vector to provide a decoupled control of the active and reactive powers [4–7]. Accordingly, the d-axis of the complex frame is fixed to the stator-flux space-vector and rotates anti-clockwise at the synchronous speed of ω_s ($\omega = \omega_s$). If the slip angle is defined