Electrical Power and Energy Systems 53 (2013) 956–966

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

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

Direct power control of DFIGs based wind energy generation systems under distorted grid voltage conditions

E.G. Shehata *, Gerges M. Salama

Electric Engineering Department, Faculty of Engineering, Minia University, Egypt

ARTICLE INFO

Article history:
Received 8 February 2013
Received in revised form 1 June 2013
Accepted 6 June 2013

Keywords:
Doubly fed induction generators
Coordinate control of RSC and GSC
Direct power control
Harmonically grid

ABSTRACT

This paper presents an improved direct power control (DPC) strategy of a wind turbine driven doubly fed induction generators (DFIGs) connected to distorted grid voltage conditions. A coordinate control strategy of the grid side converter (GSC) and rotor side converter (RSC) of the DFIG is designed to improve the overall scheme performance. The RSC is controlled based on a DPC principle to eliminate the electromagnetic torque and stator reactive power oscillations. The total active and reactive power oscillations are compensated by the GSC control to achieve constant active and reactive powers from the overall DFIG system. A current control scheme consisting of a proportional integral controller and a resonant compensator tuned at six the grid frequency is proposed to provide accurate control of the GSC current. The proposed control scheme removes rotor current regulators and the decomposition process of the rotor and GSC currents. In addition, the proposed scheme preserves the advantages of the classical DPC. The feasibility of the proposed DPC scheme is validated by simulation studies on a 1.5 MW wind power generation system under harmonically distorted grid voltage conditions. The performance of the proposed and conventional DPC schemes is compared under the same operating conditions. The proposed scheme results show significant improvements in the scheme performance.

1. Introduction

Doubly fed induction generators have been widely used for large scale wind generation systems. Wind farms based on doubly fed induction generators with converters rated at 25–30% of the generator rating for a given rotor speed variation range of ±25% are becoming increasingly popular. Compared with the wind turbines using fixed speed induction generators or fully-fed synchronous generators with full size converters, the DFIG based wind turbines offer not only the advantages of variable speed operation and four quadrant active and reactive power capabilities, but also lower converter cost and power losses [1,2]. Since the stator of the DFIG is connected directly to the grid via step-up transformers and the rating of the grid side and rotor side converters is limited, the DFIGs is pretty to any grid unbalances and harmonics. Different algorithms have been proposed to improve the conventional vector control of the DFIG system during network voltage unbalance [2–6].

Alternative approaches to the vector control such as a direct power control of DFIG based wind turbine systems have been studied recently [7–12]. In the classical DPC, two hysteresis controllers are used to determine the instantaneous switching state of the inverter [7,8]. The instantaneous switching state of the rotor side converter is determined based on the stator active and reactive power errors. Switching vectors were selected from an optimal switching table using an estimated rotor flux position and errors of the stator active and reactive powers. In spite of its merits, DPC scheme has some problems such as unfixed switching frequency, where; the switching frequency depends on the active and reactive power variations, generator speed, and power controllers' hysteresis bandwidth. In [9], a modified DPC strategy has been proposed based on a stator flux oriented (SFO) control for DFIG-based wind power generation systems with a constant switching frequency. Different algorithms are designed to improve the DPC performance under unbalanced grid voltage conditions [10–13].

Recently, the DFIGs based on wind generation are connected to distribution networks; however, these networks can have voltage harmonic distortion. It is known that the presence of harmonics in the supply voltage increase the torque pulsations, copper and iron losses in the electric machines. In the induction generators, if the voltage harmonics are not taken into account by the control system, highly stator/rotor current distortions, electromagnetic torque and power oscillations could result. In [14], harmonic current loops are added to the RSC current control so that the harmonic current components can be injected into the grid. These currents compensate the harmonics of the non-linear load or the current drawn from the grid becomes qusi-sinusoidal. In [15], a

* Corresponding author. Tel.: +20 1271216894.
E-mail address: emadgameil@mu.edu.eg (E.G. Shehata).

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http://dx.doi.org/10.1016/j.ijepes.2013.06.006

generalized platform for harmonic analysis in DFIG systems under such conditions is present. The objective of the analysis is to estimate the magnitudes of the frequency components in the stator and rotor currents, and therefore, in the torque. In [16], a finite element analysis was proposed to study the effects of voltage unbalanced and system harmonics on the DFIG performance. In [17], a proportional-integral (PI) controller and a harmonic resonant (R) compensator tuned at six times the grid frequency are used to regulate the fundamental, fifth and seventh order components of the rotor currents. In [18], fifth and seventh order harmonics in the stator output voltage at the point of common coupling for a stand-alone DFIG feeding a three phase diode rectifier are eliminated. The proposed algorithm is investigated based on the rotor current controller employing a PI–R controller. The impacts of the resonant controller on system stability, steady state error, and dynamic performance are discussed in [19]. In [20], two coordinated control algorithms for the RSC and GSC are designed based on a sliding mode controller to eliminate the effects of unbalanced and distorted grid voltage conditions. However, the proposed scheme suffers from variable switching frequency problem. In [21], the RSC and GSC are controlled based on vector control to eliminate the effect of grid harmonics, where, two different control targets are proposed to improve the DFIGs performance. In [22], four alternative control targets and their corresponding rotor current references are calculated and assigned. A current controller, consisting of a conventional PI regulator and a dual frequency resonant compensator, tuned at twice and six times the grid frequency is designed to regulate the fundamental and the fifth- and seventh-order harmonic components simultaneously. However, the analysis and performance of the DPC of the DFIGs driven by wind turbines connected to harmonically grid voltage conditions has not been studied till now in the publishing.

In this paper, the DPC of a wind turbine driven doubly fed induction generator connected to harmonically distorted network voltage conditions is analyzed. The RSC and GSC are controlled simultaneously to improve the overall scheme performance and eliminate the bad effects of the distorted grid (stator) voltage on the DFIG. In the proposed scheme, the RSC is controlled based on the DPC to eliminate the stator reactive power and electromagnetic torque oscillations, while; the GSC is controlled based vector control to provide constant active and reactive powers output from the overall system. The calculations of rotor voltage references require only simple operations of multiplication and division. For GSC control, a PI–R controller tuned at six multiples of synchronous frequency to eliminate the fifth and seventh harmonic voltage. The rotor current regulators and decomposition processing of the rotor and GSC currents are not required. Finally, the proposed scheme performance is verified by simulation study on 1.5 MW DFIG system under harmonically grid voltage conditions. The simulation results of the proposed and conventional DPC schemes are compared to illustrate the effectiveness of the proposed scheme.

2. DFIG model under distorted network conditions

Neglecting zero sequence components, the balanced three phase quantities such as voltage, current and flux may be decomposed into fundamental and harmonics components at the frequencies of $-5\omega_s$ and $7\omega_s$ when the network voltage is distorted. Fig. 1 shows the relationships between the fundamental and harmonic components. For stator voltage oriented control (SVO), the d-axis of the positive sequence synchronous reference frame (dq_+^+) is fixed to the positive sequence stator voltage ($V_{sq+}^+ = 0$) and rotates at the synchronous angular speed of ω_s. For 5th harmonic components, the direct axis (d_{5-}^-) rotates at angular speed of $-5\omega_s$ with a phase angle to the α_s-axis being $5\theta_s$. For 7th harmonic components, the direct axis (d_{7+}^+) rotates at angular speed of $7\omega_s$ with a phase angle to the α_s-axis being $7\theta_s$. For a vector F, the transformation between different reference frames are given as [17]

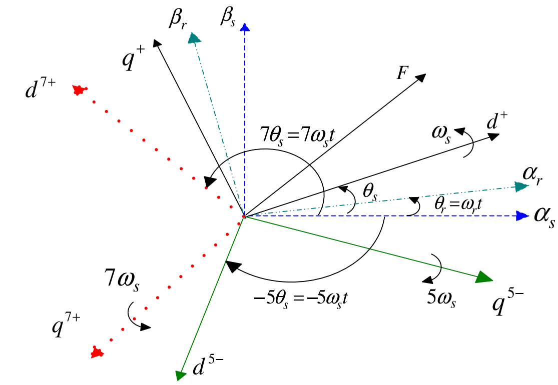

Fig. 1. Phasor diagram of SVO during harmonically network voltage.

$$F_{dq}^{+} = F_{\alpha\beta}e^{-j\omega_s t}, \quad F_{dq}^{5-} = F_{dq}^{7+}e^{j12\omega_s t}, \quad F_{dq}^{+} = F_{\alpha\beta}^{r}e^{-j\omega_{slip}t} \tag{1}$$

$$F_{dq}^{5-} = F_{\alpha\beta}e^{j5\omega_s t}, \quad F_{dq}^{+} = F_{dq}^{5-}e^{-j6\omega_s t}, \quad F_{dq}^{5-} = F_{\alpha\beta}^{r}e^{j\omega_{slip5}t} \tag{2}$$

$$F_{dq}^{7+} = F_{\alpha\beta}e^{-j7\omega_s t}, \quad F_{dq}^{+} = F_{dq}^{7+}e^{j6\omega_s t}, \quad F_{dq}^{7+} = F_{\alpha\beta}^{r}e^{-j\omega_{slip7}t} \tag{3}$$

where F represents voltage, current and flux, ω_r is the rotor angular speed, $\omega_{slip} = \omega_s - \omega_r$, $\omega_{slip5} = 5\omega_s + \omega_r$ and $\omega_{slip7} = 7\omega_s - \omega_r$.

According to Fig. 1, F can be expressed in the dq^+ synchronous reference frame as

$$F_{dq}^{+} = F_{dq+}^{+} + F_{dq5-}^{+} + F_{dq7+}^{+} = F_{dq+}^{+} + F_{dq5-}^{5-}e^{-j6\omega_s t} + F_{dq7+}^{7+}e^{j6\omega_s t} \tag{4}$$

Fig. 2 shows the generalized equivalent circuit of a DFIG represented in the dq^+ synchronous reference frame rotating at angular speed of ω_s. The stator and rotor voltages are given, respectively, as follows:

$$\begin{aligned} V_{sdq}^{+} &= R_s I_{sdq}^{+} + \tfrac{d}{dt}\lambda_{sdq}^{+} + j\omega_s\lambda_{sdq}^{+} \\ V_{rdq}^{+} &= R_r I_{rdq}^{+} + \tfrac{d}{dt}\lambda_{rdq}^{+} + j\omega_{slip}\lambda_{rdq}^{+} \end{aligned} \tag{5}$$

where R_s and R_r are the stator and rotor resistances, respectively, I_s and I_r are the stator and rotor currents, respectively.

The stator and rotor flux in the dq^+ reference frame can be expressed as follows:

$$\begin{aligned} \lambda_{sdq}^{+} &= L_s I_{sdq}^{+} + L_m I_{rdq}^{+} \\ \lambda_{rdq}^{+} &= L_m I_{sdq}^{+} + L_r I_{rdq}^{+} \end{aligned} \tag{6}$$

where $L_s = L_{\sigma s} + L_m$ and $L_r = L_{\sigma r} + L_m$. L_m, $L_{\sigma s}$ and $L_{\sigma r}$ are the mutual, stator and rotor leakage inductances, respectively.

Neglecting the voltage drop across the stator resistance, the stator voltage Eq. (5) in the synchronous reference frame can be expressed as:

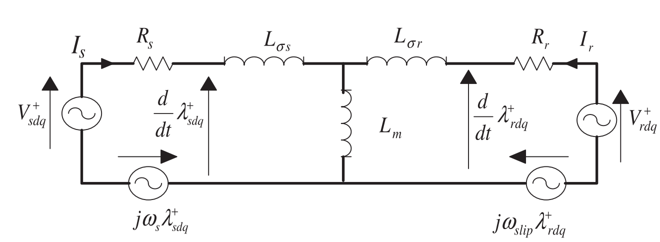

Fig. 2. Equivalent circuit of the DFIG in dq^+ synchronous reference frame.