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Harmonic elimination of quasi-sine rotor injected DFIG-based wind power generation systems connected to electric power networks

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ABSTRACT

In this study, a novel control scheme including a proportional–integral–harmonic resonant (PI–R) controller is presented to eliminate the produced harmonics resulting from the quasi-sine rotor voltage injection in a doubly fed induction generator (DFIG) connected to power electric networks. The control scheme is implemented in the rotor reference frame $(\alpha_r\beta_r)$ under quasi-sine rotor injection by performing the well-known six-step switching technique. The contribution of this study is to propose a control scheme that not only keeps a grid-connected DFIG in an acceptable operating margin but also effectively eliminates the harmonic and pulsation components both in the stator and the rotor circuits caused by quasi-sine rotor injection. To validate theoretical results, a DFIG practically used to implement the available wind power plants is simulated using MATLAB/Simulink. The simulated results not only validate the theoretical results but also explicitly verify the excellent performance of the proposed control scheme.

Introduction

There are three types of induction generators which are used in wind turbines to convert wind energy into electric power. Squirrel cage induction generator (SCIG), opti-slip induction generator (OSIG) and doubly fed induction generator (DFIG) are these three types [1]. The DFIG type has the properties such as generating an AC output voltage with constant frequency compared to the other two types [2,3]. DFIGs are generally used in wind power generation systems along with other types of generators such as the synchronous type to provide a practical power generation plant in the some countries such as Netherlands and Iran. Wind-turbine-driven DFIG power generation systems are also utilized to generate power for local consumptions, so they are classified as one important type of distributed generation (DG) systems. A wind-turbine-driven DFIG is connected to a power network through the power electronic converters as shown in Fig. 1. As shown in Fig. 1, the stator and rotor circuits are connected to the power network in different manners. Although the stator is connected directly, the rotor connection is through a double back-to-back converter which can be decomposed into the two parts that are grid side converter (GSC) and rotor side converter (RSC).

Asymmetrical and/or unbalanced grid voltage is the first abnormal condition which affects on the operation of a DFIG [4]. The asymmetrical voltage impacts on a DFIG were studied in [4]. The transition response of a DFIG used in a wind energy system was reported in [5]. Control of a DFIG-based wind power plant by considering unbalanced grid voltage has attracted many researchers [6,7]. Two appropriate control schemes for control of a DFIG connected to an unbalanced power network were proposed in [8,9]. As another work, the unbalanced stator voltage was firstly decomposed into a positive-sequence, a negative-sequence, and a zero-sequence component. Then, based on this decomposition, two proportional–integral (PI) current controllers together with two resonant part implemented in RSC and GSC were designed [10,11]. Distorted grid voltage is the second abnormal condition which results an effective decrease in the DFIG performances. The analysis of a DFIG-based wind power system connected to a distorted power network was reported in some researches [2], [12,13]. The PI and PI–R controllers implemented in the positive synchronous reference frame by considering distorted grid voltage conditions were reported in [14]. A proposed control scheme consisting of a resonant (R) controller was also designed and presented for a DFIG operating under distorted grid voltage conditions in [15]. Some other researches related to the first and second abnormal problems such as the analysis of voltage faults have been reported in [16–20]. The third abnormal problem is nonsinusoidal rotor voltage injection that effectively reduces the performances of a DFIG [3]. There are two methods for rotor injection of a DFIG. The six-step switching and pulse width modulation (PWM) techniques are these two methods but both produce considerable harmonics [2].

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Nomenclature

P	number of pole pairs
V_{dc}	voltage of DC link
θ_s, θ_r	stator and rotor voltage angles
$\omega_s, \omega_r, \omega_m$	stator, rotor, and rotor rotating angular frequencies
ψ_s, ψ_r	stator and rotor flux linkage vectors
R_s, R_r	stator and rotor resistances
L_m	mutual inductance
$L_{\sigma s}, L_{\sigma r}$	stator and rotor leakage inductances
I_s, I_r	stator and rotor current vectors
U_s, U_r	stator and rotor voltage vectors
P_s, Q_s	stator output active and reactive powers
T_e	electromagnetic torque
P_e	electromagnetic power

Subscripts

α_s, β_s	stationary $\alpha_s\beta_s$ axis
α_r, β_r	rotor $\alpha_r\beta_r$ axis
d, q	synchronous dq axis
s, r	stator, rotor
$+, -, 5-, 7+$	fundamental, negative sequence, fifth-order and seventh-order components

Superscripts

$+, -, 5-, 7+, s, r$	positive$(dq)^+$, negative $(dq)^-$, $(dq)^{5-}$, $(dq)^{7+}$, $(\alpha_s\beta_s)$ and $(\alpha_r\beta_r)$ reference frames
$*$	reference value for controller
$\wedge$	conjugate complex

The objective of this study is the third abnormal problem, so that, a novel PI–R controller is designed and implemented in the rotor$(\alpha_r\beta_r)$ reference frame for control of a wind turbine-driven DFIG system under nonsinusoidal rotor voltage injection condition. This paper is organized as follows. The harmonic produced by quasi-sine rotor injection of a DFIG is analyzed in Section 'Harmonic analysis of a quasi-sine rotor injected DFIG'. The PI–R controller and implemented control scheme are presented in Section 'PI–R controller and control scheme proposed for a quasi-sine rotor injected DFIG'. The simulations carried out in MATLAB/Simulink along with the results are also given in Section 'Simulated results', and finally, Section 'Conclusion' concludes the paper.

Harmonic analysis of a quasi-sine rotor injected DFIG

In a wind turbine-driven DFIG, a DC/AC bridge converter implemented in RSC side provides the AC voltage which should be injected to the rotor circuit. As mentioned, the six-step switching and PWM techniques are two available techniques to provide the AC voltage [3], [21]. In many practical wind turbine-driven DFIG plants, the six-step switching technique is used because it has very simpler control circuit compared to the PWM technique. The other benefit is that it does not need the triangular and/or sine voltage waveforms because the rotor frequency is adjusted by only varying the level of a provided voltage. The six-step switching technique produces an AC voltage waveform which is called quasi-sine waveform. Producing $6n \pm 1$ voltage harmonics is the main defect of the six-step switching technique. The DC/AC bridge converter in RSC side is shown in Fig. 2. The produced line/phase quasi-sine waveforms are also shown in Fig. 3 [2]. A quasi-sine waveform does not have triple-n harmonics (3, 6, 9, ...), so the a-phase quasi-sine voltage shown in Fig. 3 is expressed as [21]:

$$v_{ra}(t) = \frac{2}{\pi} V_{dc} \sum_{k}^{\infty} \frac{1}{k} \sin(k\omega t) \tag{1}$$

where $k = 1, 5, 7, \ldots$. Eq. (1) shows that harmonics with the orders of $6n \pm 1$ $(n = 1, 2, 3, \ldots)$ are only available, so the phase voltages are expressed using phasor representation as:

$$\begin{cases} v_{ra}(t) = \frac{2}{\pi} V_{dc} \mathrm{Im}\left(\frac{1}{6n\pm1} e^{j(6n\pm1)\omega t}\right) \\ v_{rb}(t) = \frac{2}{\pi} V_{dc} \mathrm{Im}\left(\frac{1}{6n\pm1} e^{j(6n\pm1)\omega t}\right) e^{-j\frac{2\pi}{3}} \\ v_{rc}(t) = \frac{2}{\pi} V_{dc} \mathrm{Im}\left(\frac{1}{6n\pm1} e^{j(6n\pm1)\omega t}\right) e^{-j\frac{4\pi}{3}} \end{cases} \tag{2}$$

The $6n + 1$ and $6n - 1$ harmonics are considered as positive- and negative-sequence harmonics, respectively. Thus, they produce the rotor current harmonics at the frequencies of $-(6n - 1)\omega_r$ and $(6n + 1)\omega_r$, respectively. Therefore, the harmonics with the orders of $\omega_r + \omega_m$, $-5\omega_r + \omega_m$, $7\omega_r + \omega_m$, $-11\omega_r + \omega_m$, $13\omega_r + \omega_m$, etc., are observed in the stator current. The harmonics with the order

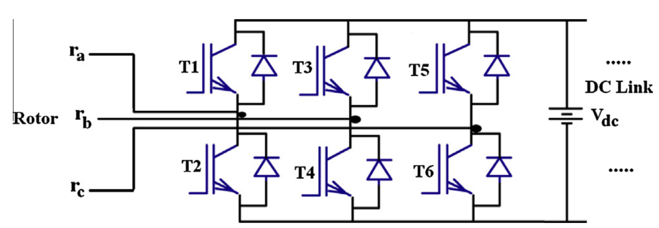

Fig. 2. DC/AC bridge converter in RSC.

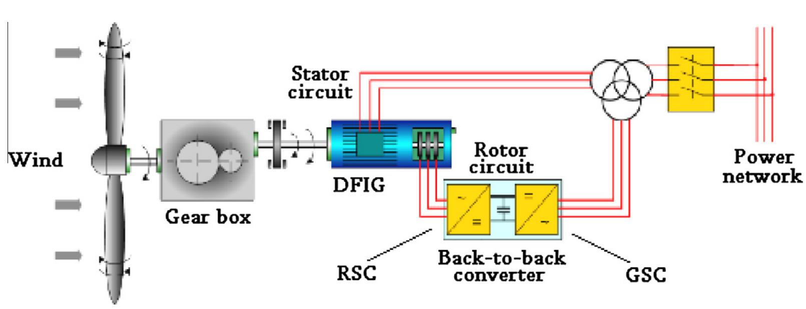

Fig. 1. DFIG connections to the power network.