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Instantaneous power spectrum analysis for broken bar fault detection in inverter-fed six-phase squirrel cage induction motor

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ABSTRACT

Many researches deal with the detection of broken bar fault in three-phase induction motor, however in high-power applications the multiplication of phases number allows the segmentation of the power on more than three phases which reduces the price of power electronic device and gives greater fault tolerance in open phases. For this reason, it becomes very interesting and demanding to detect faults in case of $n > 3$ phases induction motor. In this study, a novel investigation of broken bar faults in instantaneous power spectrum is presented. The method is based on calculations and frequency analysis of instantaneous six-phase power spectrums when the motor is fed by PWM six-phase IGBT voltage source inverter (VSI). The used model takes into account the geometry and winding layout. The analytical study is confirmed by simulation and experimental results.

Introduction

In the last years the interest in multi-phase induction motor has been growing in industry and have been getting much attention in the literature, as summarized in [1]. Their main advantages have been identified in many works. Multi-phase machine offer higher efficiency in [2], in [3] reduced torque pulsation and in [4] gives greater fault tolerance in open phases.

Due to low price, simple manufacture, best quality, the induction motor have been reconfigured to increase phases number. The specific number of phases extensively discussed is the six-phase induction motor [5–8]. The six-phase induction motor is most frequently configured with two sub-windings shifted by 0°, 30° and 60° electrical degrees and two isolated neutral points.

However, the six-phase is similar to three-phase case; it can be submitted to external and internal stresses of various nature, degradation can occur in their performances. The broken bar fault presents a significant percentage among other faults; it can cause torque and speed ripple, decrease average torque, noise and imbalanced stator current. For these reasons, an amount of papers have been published.

In literature, many papers deal with broken bar faults in case of three-phase induction motor, the basic method of diagnostic is the motor current signature analysis (MCSA) [9–12]. The harmonic components related to broken bar fault are closed to the fundamental supply frequency and defined as: $f_{bbr} = (1 - 2ks)f_s$ where $k = 1, 2, 3, \ldots, s$ is the motor slip and f_s is the frequency of the main voltage supply. To overcome the dependence of the fundamental supply frequency, several papers [13–18] have evaluated the failure signature close to the dc component of the instantaneous power, instantaneous power factor and torque.

Under closed-loop control in induction motor drives, many papers propose the use of the available control data of the voltage source inverter drive for diagnostic purposes [19–22]. For instance in [23,24] the broken bar fault detection is based on the computation supply voltage modulation. However in the presence of broken bar fault the closed-loop control has to adapt the reference stator voltage vector in order to correct speed oscillation and the stator voltage will contain some information about failure signatures.

The detection of broken bar fault signatures are strongly related to the advanced data and signal processing algorithms, many methods have been proposed in literatures, the predominant method is the Fast Fourier Transformation (FFT) and Hilbert method for steady state analysis [25–30]. For nonstationary signals the Wavelet Transform (WT) has been widely used [31–33].

The aim of this paper is to deal with the detection of broken bar fault in six-phase induction motor fed by PWM voltage source inverter using instantaneous power. The paper contains of six main sections. Section 'Introduction' deals with the analytical model of six-phase induction motor using a model based on the winding function approach which takes into account the real winding

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distribution. Section 'Harmonic components of instantaneous power under healthy condition' discusses the RSH harmonic components of instantaneous power spectrum in healthy condition. Section 'Harmonic components of instantaneous power under broken bar condition without consideration of pulsating torque' explains the mechanism of generation of additional harmonics without consideration of pulsation torque. Section 'Harmonic components of instantaneous power under broken bar condition with consideration of pulsating torque' gives the additional broken bar fault signatures with consideration of pulsation torque. Section 'Experimental validation' encompasses the presentation of obtained experimental results for both healthy and faulty conditions, as well as the validation of analytically predicted harmonics. Section 'Conclusion' is devoted to a general conclusion for this work.

Harmonic components of instantaneous power under healthy condition

In order to show the mechanism of harmonic components generation in instantaneous power, a model that permits numerical modeling and analytical analysis is used. This model is based on winding function approach takes into account the geometry and winding layout. Compared with a three-phase, the six-phase has the same rotor and the same magnetic core, but the stator windings are split into two three-phase sets shifted by α electrical degrees. Suppose that the two stator sets of dual three windings sets are Y connected and have two isolated neutrals. The rotor cage having n_b bars is viewed as n_b identical spaced loops, and the current distribution can be specified in terms of n_b+1 independent rotor currents.

The primary equations of the dual three-phase induction motor can be written in vector–matrix form as follows:

$$[v_s] = [R_s]\cdot[i_s] + \frac{d}{dt}[\psi_s] + [v_n] \tag{1}$$

$$\begin{bmatrix}[v_r]\\ v_e\end{bmatrix} = [0] = \begin{bmatrix}[R_r] & & \frac{R_e}{n_b}\\ & & \vdots\\ \frac{R_e}{n_b} & \cdots & R_e\end{bmatrix}\begin{bmatrix}[i_r]\\ i_e\end{bmatrix} + \frac{d}{dt}\begin{bmatrix}[\psi_r]\\ \psi_e\end{bmatrix} \tag{2}$$

$$[\psi_s] = [L_s][i_s] + [M_{sr}][i_r] \tag{3}$$

$$\begin{bmatrix}[\psi_r]\\ \psi_e\end{bmatrix} = \begin{bmatrix}[M_{sr}]\cdot[i_s]\\ 0\end{bmatrix} + \begin{bmatrix}[L_r] & & \frac{L_e}{n_b}\\ & & \vdots\\ \frac{L_e}{n_b} & \cdots & L_e\end{bmatrix}\cdot\begin{bmatrix}[i_r]\\ i_e\end{bmatrix} \tag{4}$$

where

$[v_s] = [\,v_{sa}\;\; v_{sb}\;\; v_{sc}\;\; v_{sd}\;\; v_{se}\;\; v_{sf}\,]^t$,
$[i_s] = [\,i_{sa}\;\; i_{sb}\;\; i_{sc}\;\; i_{sd}\;\; i_{se}\;\; i_{sf}\,]^t$,
$[\psi_s] = [\,\psi_{sa}\;\; \psi_{sb}\;\; \psi_{sc}\;\; \psi_{sd}\;\; \psi_{se}\;\; \psi_{sf}\,]^t$ are the stator voltage, current and flux vectors respectively.
$[v_r] = [\,v_{r1}\;\cdots\; v_{rn_b}\,]^t, [i_r] = [\,i_{r1}\;\cdots\; i_{rn_b}\,]^t$ and $[\psi_r] = [\,\psi_{r1}\;\cdots\;\psi_{rn_b}\,]^t$ are the rotor voltages, current and flux linkage vectors, respectively with dimensions $1\times n_b$.
v_e, i_e and ψ_e respectively refer to voltage, current and flux of the end ring.
$[L_r]$ and $[R_r]$ are the rotor inductance matrices and rotor resistance matrices respectively and are described by the same manner as in [12].
$[R_s]$ and $[L_s]$ are the stator resistance matrices and stator inductance matrices are given in [35].

$v_n = [\,v_{o1n1}\;\; v_{o1n1}\;\; v_{o1n1}\;\; v_{o2n2}\;\; v_{o2n2}\;\; v_{o2n2}\,]^t$ is the line neutral voltage taking place between the supply sets and the stator sets neutral and is given by:

$$v_{o1n1} = \frac{1}{3}(v_{sa}+v_{sb}+v_{sc}) \tag{5}$$

$$v_{o2n2} = \frac{1}{3}(v_{sd}+v_{se}+v_{sf}) \tag{6}$$

As there is no method to infer it, we have to set the stator equations of the model in line-to-line voltage form

$$\begin{bmatrix}v_{sab}\\ v_{sbc}\\ v_{sde}\\ v_{sef}\end{bmatrix} = \begin{bmatrix}R_s & -R_s & 0 & 0\\ R_s & 2R_s & 0 & 0\\ 0 & 0 & R_s & -R_s\\ 0 & 0 & R_s & 2R_s\end{bmatrix}\cdot\begin{bmatrix}i_{sa}\\ i_{sb}\\ i_{sd}\\ i_{se}\end{bmatrix} + \frac{d}{dt}\begin{bmatrix}\psi_{sab}\\ \psi_{sbc}\\ \psi_{sde}\\ \psi_{sef}\end{bmatrix} \tag{7}$$

The mutual inductance between the q^{th} stator phase of the i^{th} sub-winding and the k^{th} rotor loop can be developed into Fourier series as [34]:

$$M_{s_{qi}r_k}(\theta) = \sum_{h=1}^{\infty} M_{sr}^h \cos\left(h\left(\theta + ka - (q-1)\frac{2\pi}{3} - (i-1)\alpha - \phi_o\right)\right) \tag{8}$$

where

$$M_{sr}^h = \frac{\mu_0 rL}{g_0}\frac{N_t}{\pi p^2}\frac{k_{wh}}{h^2}\sin\left(h\frac{a}{2}\right)$$

L is the length of stack, r is the average radius of the air gap, g_0 is the air gap function and N_t is the number of turns.
k_{wh} is the winding factor and p is number of pole pairs.
$a = p(2\pi/n_b)$ is the electrical angle of a rotor loop.
ϕ_o is the initial phase angle.
$q = 1,2,3$ and $i = 1,2$ are the q^{th} stator phase at the i^{th} sub-winding.
$k = 1\cdots n_b - 1$ is a counter of a rotor loop.

The mutual inductance matrix $[M_{sr}]$ between the stator and rotor is defined following the same way as in [17].

The induction motor is supplied from a balanced six-phase source of sinusoidal voltages. In this case a forward rotating field is induced in its air gap, and the rotor currents which flow in the rotor loops as a result of the forward field can be expressed as:

$$[i_r]^t = [\,\cdots\;\; I_{rpk}\cos(s\omega_s t - ka - \gamma_p)\;\;\cdots\,] \tag{9}$$

where

s is the slip, γ_p is the initial phase angle, I_{rpk} is the maximum value of the k rotor loop current, and ω_s is the main voltage supply pulsation.

The total instantaneous power P_6 of six-phase induction motor with two isolated neutrals is defined as:

$$P^6 = [\,[i_s]^t\;\; [i_r]^t\;\; i_e\,]\begin{bmatrix}[v_s]\\ [v_r]\\ v_e\end{bmatrix} \tag{10}$$

The stator current of the q^{th} stator phase at the i^{th} sub-winding in both healthy and faulty conditions can be written as following:

$$i_{s_{qi}}^{h_s} = \sum_{h_s=1}^{\infty}\sum_{f_{sh_s}} I_m^{h_s}\cos\left(h_s\left(f_{sh_s}2\pi t - (q-1)\frac{2\pi}{3} - (i-1)\alpha\right)\right) \tag{11}$$

where