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THE USE OF INSTANTANEOUS POWER SPECTRUM IN THE DETECTION OF ROTOR CAGE FAULTS ON 3-PHASE INDUCTION MOTORS

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Abstract: Electric motors play a very important role for safe and efficient running of any industrial or power plant. Early detection of abnormalities in the motors will help avoid expensive failures. It has been shown that rotor faults such as broken rotor bar can be detected by several methods. Intensive research effort has been for some times focused on the spectral analysis of the motor current. Reliable interpretation of the spectra is difficult, since distortions of the current waveform caused by the abnormalities in the drive system are usually minor. This paper introduces a new approach, based on the spectral analysis of the instantaneous power. Both simulation and experimental results demonstrate that the spectrum of the instantaneous power carries more information than that of the current itself.

1. - INTRODUCTION

Induction motors are known to have simple and robust construction, as well as very high reliability. Thus, these motors have been universally in industrial applications. However, induction motors, as with all types of rotating machines, have the disadvantage of frequent occurrence of faults [1]. The occurrence of such a fault will eventually destroy the machine.

Moreover, a variety of faults can occur within three phase induction motors during the course of normal operation [2], such as rotor-stator eccentricity and broken rotor bars. If undetected, they may lead to potentially catastrophic failure. For example, rotor cage faults, such as, broken rotor bars or end-ring, can occur due to a combination of various stresses that act on the rotor. The consequences of faulty rotor are poor starting performance, excessive vibration and higher thermal stresses. All these contribute to a further deterioration of the rotor as well as to secondary failures of the stator. Stator insulation can fail under thermal stresses imposed by the excessive and often unbalanced stator current. Thus timely detection of the onset of rotor imperfections is vital for effective condition monitoring on induction machines, and the ability to calculate the effect of simulated faults is vital to an understanding of the fault mechanisms [3].

Monitoring the operation of drive system allows detection of abnormal electrical and mechanical conditions. The appropriate maintenance of electrical drives is essential for their efficient and reliable operation in any industry. The lack of an effectively designed and implemented maintenance policy will result in the increased downtime and capital losses due to catastrophic failures. In order to avoid these unwanted events, preventive-maintenance testing is necessary. Off line testing procedures are of limited applicability under field and plant conditions. On line and continuous monitoring methods offer significant advantages in this regard, since incipient failures can be detected and appropriate maintenance actions can be scheduled, thus avoiding problems associated with unexpected failures [4].

Traditional methods of incipient fault detection applied in large electric machines are generally not applied in small size machines. Because, they have limitations related to sensing-device size and economic reasons.

So far, research in this area has focused on sensing magnetic flux, stator current, shaft flux, vibrations and speed fluctuations. The common approach is to monitor from time to time mechanical vibrations, radio noise, stray magnetic field or motor line current in order to detect some irregularities in the signal spectrum. Usually, the parameters under considerations are recorded at regular time intervals and analysed off-line on a computer. It is very convenient to perform these measurements while motor is running, despite the fact that off line testing of machine provides more accurate data [4].

The analysis of the current spectrum is very popular due to an easy way of recording the stator input current while motor is running under load [5]. The widely accepted approach is based on the fact that in the case of broken rotor bars it is possible to detect side bands in the line current spectrum around the fundamental frequency. Unfortunately, the same phenomenon is correlated to other rotor defects, e.g.

magnetic anisotropy, air gap eccentricity, damaged gear box, damaged load machine (pump or fan) [4].

As reported in [1][5], a sophisticated examination of the machine stator current spectrum provides a method for detecting rotor bar faults. Several problems are associated with the above-mentioned approach, such as the interpretation of the current spectra. This is not an easy task and the practical results are often unreliable because of the typically small extent of distortions of the current waveform and noisiness of the spectrum [6]. This is necessary for preventive recording of stator current under load conditions, differential diagnostics between gear box damage, air gap eccentricity and broken rotor bars, maintaining the signature library for a lot of machines. Moreover, another question arises, and that is how distinguish between the broken rotor bar fault and the damaged gear box or loading machine on an easy and accurate way. This is not, so straightforward the analysis of the current spectrum only is carried out [4].

In this study, instead of the stator current spectrum, the spectral analysis of instantaneous power is used, as an approach for detection of rotor cage faults in operating three-phase induction motors. It is worth mentioning that the application of the instantaneous input power for detecting electrical faults in the stator has already been proposed [7].

Recently, other authors have used this variable as a mean for the signature analysis of induction motor, in the case of mechanical fault [6]. It has also been proposed for the detection of broken rotor bars, where the rotor asymmetry due to rotor cage fault was simulated by introduction of additional resistance in one phase of wound rotor [4].

This paper introduces the application of the instantaneous electrical power spectrum for detection of broken rotor bars. It is shown by simulated and experimental results on squirrel cages induction motors, that the amount of information carried by the instantaneous power, which is a product of the supply voltage and current, is higher than that extracted from the current alone.

2. - INSTANTANEOUS POWER SPECTRUM TECHNIQUE

In the following, an ideal three-phase supply voltage is assumed with no abnormalities in stator windings. The instantaneous power, p(t), is defined as:

$$p(t) = v_{LL}(t) i_L(t) \qquad (1)$$

Where $v_{LL}(t)$ is the voltage between any two of the three-stator terminals and $i_L(t)$ is the terminal current input. Taking as a reference perfectly healthy drive system running with a constant speed, the expressions of the voltage, $v_{LL}(t)$, current, $i_{L,0}(t)$, and instantaneous power, $p_0(t)$, are given by [6]:

$$v_{LL}(t) = U_m \cos(2\pi f t) \qquad (2)$$

$$i_{LL}(t) = I_m \cos(2\pi f t - \varphi) \qquad (3)$$

$$p_0(t) = v_{LL}(t) i_{L,0}(t)$$
$$= \frac{U_m I_m}{2}\cos(2(2\pi f)t - \varphi) + \frac{U_m I_m}{2}\cos(\varphi) \qquad (4)$$

Where U_m and I_m denote the amplitudes of the supply line to line voltage and line current, respectively, f is the supply frequency, and φ is the motor load angle. The spectrum of the current has only the fundamental component at the frequency f, while the spectrum of the instantaneous power has a dc component (average power or input active power) and the fundamental component at $2f$.

If a rotor cage fault occurs in the induction motor, harmonic torques is generated in the motor, accompanied by slip and speed oscillations. Therefore, this speed oscillation around the medium value ω_r gives rise to another frequency in the stator windings, by inducing e.m.fs which modulate the current main-frequency component at twice slip frequency $f_s = 2sf$. Frequency components characteristic for the type of abnormality appear in the stator current spectrum. Location of these components allows identifying the abnormality.

If it is assumed that, rotor cage fault causes sinusoidal modulation of the stator current amplitude. On the other hand the load angle does not change significantly.

The modulated current can be expressed as [6]:

$$i_L(t) = i_{L,0}(t)\left[1 + M\cos(2\pi f_s t)\right] \qquad (5)$$

$$= i_{L,0}(t) + \frac{MI_m}{2}\cos\left[2\pi(f - f_s)t - \varphi\right] + \frac{MI_m}{2}\cos\left[2\pi(f + f_s)t - \varphi\right] \qquad (6)$$

Where M is the modulation index and $f_s = 2sf$ is the modulating frequency and s is the slip. Clearly, in the current spectrum, two sideband components will appear around the fundamental component at frequencies: $f_1 = f - f_s$ and $f_2 = f + f_s$.

The expression for the modulated instantaneous power is obtained as:

$$p(t) = p_0(t) + \frac{MU_m I_m}{4}\cos[2\pi(2f - f_s)t - \varphi] + \frac{MU_m I_m}{4}\cos[2\pi(2f + f_s)t - \varphi] + \frac{MU_m I_m}{2}\cos(\varphi)\cos(f_s t) \quad (7)$$

It can be seen that besides the fundamental and the two sideband components at $(2f - f_s)$ and $(2f + f_s)$, the instantaneous power spectrum contains an additional component at the modulation frequency, f_s. The latter component, subsequently called characteristic component, provides an extra piece of diagnostic information about the state of the motor.

3. - SIMULATION RESULTS

To study the performance of squirrel cage induction motors with rotor faults, a mesh model of the rotor is selected [3]. The rotor is described in the terms of loops. Rotor loop currents are defined as the currents flowing in loops comprising two adjacent rotor bars and the portions of end ring joining them. Each rotor bar and end ring segment are characterised by a resistance and inductance. For a N_b bars-rotor, three-phase squirrel cage induction motor, N_b+3 windings couple with each other through the airgap flux

In a healthy machine the resistance value of every bar and every end-ring segment is R_b and R_e respectively. When breaks are considered, the resistance value of the broken bar or end ring segment will be considered by $R = 10^6 R_b$ [8].

A fourth order Runge-Kutta numerical integration method is used to solve the first-order differential equations .

The advantages of the presented technique are confirmed by simulation, on wye-connected squirrel cage induction motor, 380V, 50Hz, 2 poles, 16 bars, (whose parameters are given in [3]). Initially, the healthy motor drives a load with a constant torque. The spectra of the stator current and instantaneous power are shown in Fig. 2a and Fig. 2b, respectively. Obviously, only a fundamental 50 Hz component appears in the spectrum of current, while the spectrum of the instantaneous power contains only the 100Hz fundamental component and a dc component.

When the rotor cage fault occurs (in this case, four adjacent broken bars are considered), the constant speed and slip of motor begin oscillating due to the pulsating of the torque at $f_s = 2sf = 2x0.055x50$ Hz. As a result of this situation, the spectra of current and power significantly differ from those of healthy motor.

In the stator current spectrum shown in Fig.2c, prominent side band component appears at 44.5 Hz and 55.5 Hz, at 50 Hz (fundamental frequency) plus and minus f_s. The 44.5 Hz component at -81.4dB has the highest magnitude after that of the fundamental.

On the contrary, in the spectrum of instantaneous power, shown in Fig. 2d, the highest magnitude nonfundamental frequency component (not containing the dc component) appears directly at the 5.5 Hz frequency of speed oscillation. Moreover, its magnitude, at -77.4 dB is higher by 5 dB than that of the highest nonfundamental spectral component of current.

4.- EXPERIMENTAL RESULTS

The test motor used in the experimental investigation was a three-phase, 50 Hz, 4-pole, 3kW, ABB induction machine type MBT 100 LB, with several rotors of identical type, witch can be interchanged. Each of them is a single-squirrel cage type rotor with 28 skewed and uninstalled bars. Separately excited dc generator feeding a variable resistor provided a mechanical load. The diagnostic instrumentation system used basically comprises a microcomputer, supporting data acquisition to two clip-on current and differential voltage probes, through a preconditioning module.

The motor was initially with its cage intact. The results by the conventional current and instantaneous power spectral analysis are shown in Fig 3a and Fig. 3b. It is also shown that in the absence of fault, the behaviour of the motor is mostly characterised by the presence of only the fundamental component, 50 Hz in current spectrum and 100 Hz in the power one.

The occurrence of four broken rotor bars appears in the current spectrum at 43.3 Hz and at 56.7 Hz, as shown in Fig. 3c. It is worthy mentioning, that sometimes it may be difficult to distinguish the second side band component, which depends on the inertia of the motor [9]. The appearance of a spectral component, at 6.7 Hz, i.e.,

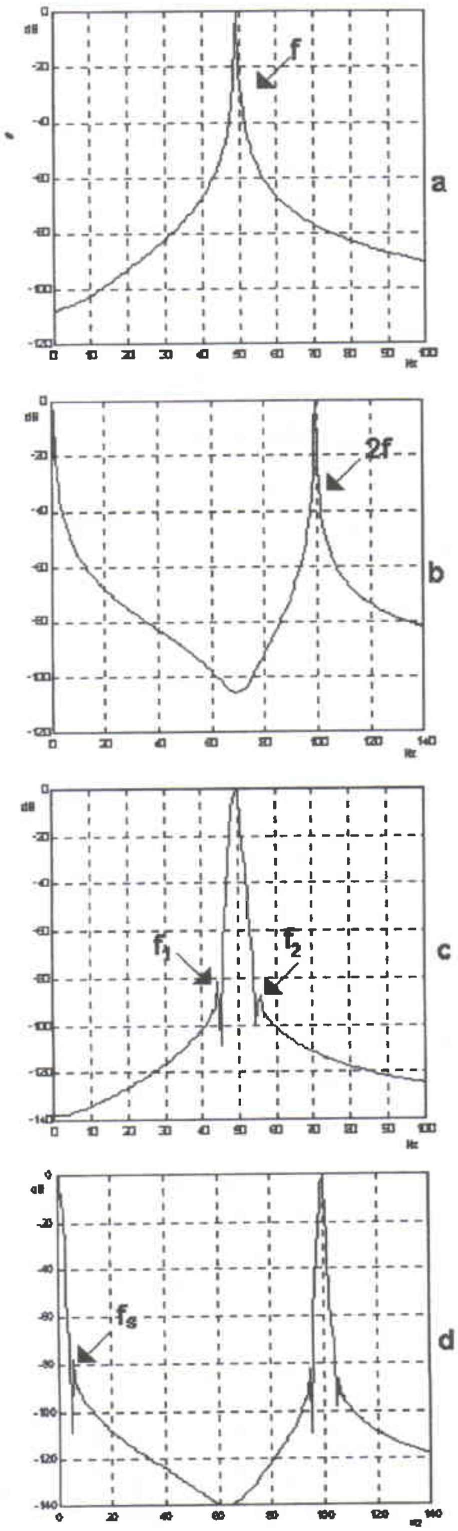

Figure 1 - FFT of simulated motor variables:
(a) and (b)- current and power of healthy motor
(c) and (d)- current and power of faulty motor.

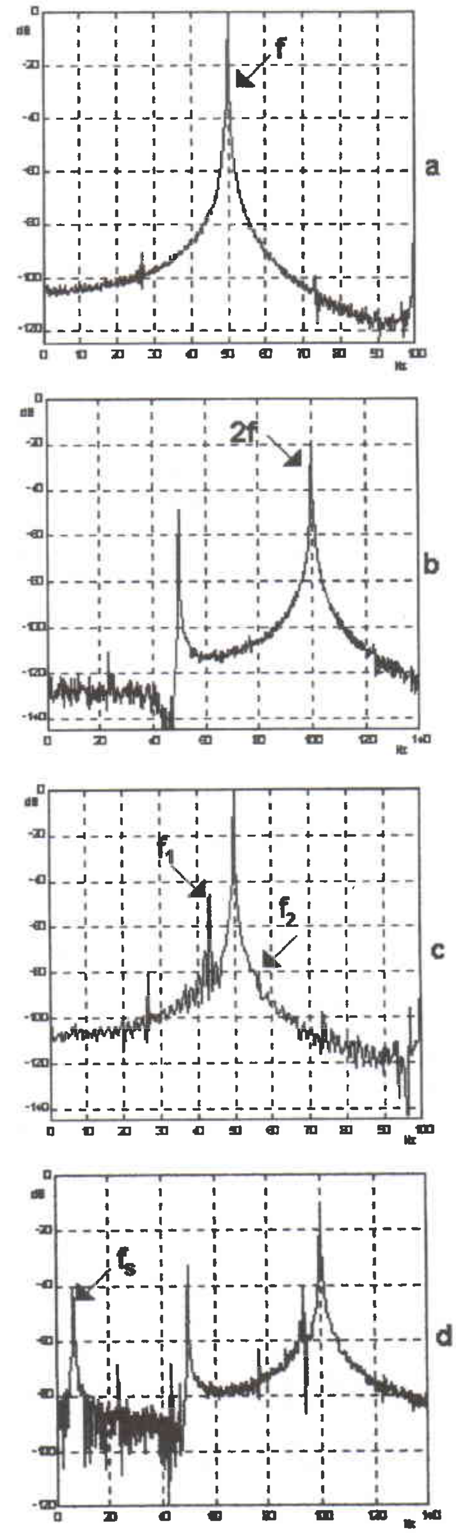

Figure 2 - FFT of motor variables (experimental results): (a) and (b)- current and power of healthy motor
(c) and (d)- current and power of faulty motor.

2x0.067x50 in the spectrum of the instantaneous power is clearly visible it is showing in Fig 3d. This characteristic component can be easily distinguished, since the fundamental is far apart and its amplitude is 5 dB higher than that of f_1 in the current spectrum. The characteristic component f_s is far than the fundamental in the power spectrum as was theoretically predicted

It is to be mentioned that all experimental results have been obtained without any filter. Despite this, it can be seen that simulated results are in good agreement with the experimental ones.

5. - CONCLUSION

This paper introduces a new approach, based on a spectral analysis of the instantaneous power for detecting the occurrence of rotor cage faults in operating three-phase induction motors. The experimental and simulated results show that rotor cage faults can be effectively detected by this new technique, whose operating approach relies on the behaviour of the spectral component at frequency of $2sf$. This characteristic spectral component of power appears directly at the frequency of disturbance, independently of the synchronous speed of the motor. This is important in automated diagnostic system, in which the irrelevant frequency component i.e., those multiples of the supply frequency, are screened out.

It is known that broken bar faults generate side-band components at frequencies differing from the fundamental by only the double slip frequency. Clearly it would be difficult to filter out the fundamental without affecting the side-band component. In contrast, the characteristic component in the spectrum of the power can easily be separated from the dc component by compensation of the latter one. The spectrum of the power provides easier filtering conditions, than that of the stator current.

Furthermore, the use of this variable for the detection of bar faults allows us to have simultaneous information on the current and voltage. For example, in the case of unbalance of the supply voltage, which is not taken into account in the conventional method of the current spectrum. So this technique allows us to monitor the motor by two different electrical variables: voltage and current.

The present work and others [4][6][7], demonstrate, that the use of this variable as a tool for diagnostic of induction motor deserves serious consideration.

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REFERENCES

[1] P.J. Tavner, and J. Penman, "Condition monitoring of electrical machines.", Researchs Studies Press, John Willey & Sons, 1987.

[2] S.M.A. Cruz, and A.J. Marques Cardoso,"Rotor cage fault diagnostis in three-phase induction motors, by extended Park's vector approach.", ICEM'98 proceeding, pp. 1844-1848.

[3] Ewen Ritchie, Xiaolan Deng, and Tapani Jokinen "Dynamic model of three-phase squirrel cage induction motors with rotor faults." ICEM'94 proceeding, pp. 694-698.

[4] Zarko Janda, Dragan Petrovic, and Zoran Lazarevic "New approach for broken rotor bars detection in induction motors." ICEM'94 proceeding, pp. 6-10.

[5] M. Drif, N. Benouzza, A. Bendiabdellah and J. A. Dente "Application of spectral analysis of stator current for detection of faults in three-phase asynchronous motors", (in French), ICEL'98 proceeding ALGERIA, pp. 529-534.

[6] Stanislaw F. Legowski , A.H. M.Sadrul Ula, and Andrzej M. Trzynadlowski "Instantaneous power as a medium for the signature analysis of induction motors.", IEEE Trans. Ind. Applicat., vol . 32, n°4, July/August 1996, pp. 904-909.

[7] Reinhard Maeir, "Protection of squirrel-cage induction motor utilising instantaneous power and phase information.", IEEE Trans. Ind. Applicat., vol . 28, n°2, March/April 1992, pp. 376-380.

[8] Vas P, Filippetti F., Franceschini G., and Tassoni C. "Transient modelling otiented to diagnostics of induction machines with rotor asymetries.", ICEM'94 proceeding, pp. 62-67.

[9] F. Filippetti, G.Franceschini, C. Tassoni, and P. Vas "Impact of speed ripple on rotor fault diagnosis of induction machines." ICEM'96 proceeding, pp 452-457.