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GEARBOX FAULT DETECTION OF INDUCTION MOTOR USING STATOR CURRENT SIGNAL DEMODULATION

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Abstract- All of the induction motor faults are not detect in beginning and late perception of these faults will cause to very lose tolerance. Thus, fault detection and identification in induction motors have high importance for industrial activities. One of the most fault detection methods is motor current signal analysis. In this paper, we use a new method with title induction motor stator current signal demodulation for gearbox faults. Gearbox faults are often results of gear tooth damages and this problem causes to creation some frequencies with harmonics in stator current signal. Gearbox faults detection are under study and demodulation analysis presented. In fact, fault frequency will directly observe by beneficiary without calculating fault bandwidth. The results present high performance and accuracy of proposed method in compare of Fourier transform analysis.

Keywords: Stator Current Signal, Induction Motor, Demodulation Method, Gearbox Fault.

I. INTRODUCTION

The parameters monitoring is the main part of induction machine in industrial applications and factories considering the condition based maintenance actions. The most methods for industrial induction machine monitoring is classified into several items based on the measurements: vibration, torque and temperature monitoring, oil/debris analysis, acoustic emission monitoring, optical fiber monitoring, and current/power monitoring. Current monitoring methods have several advantages since it is an on invasive technique that avoids the use of extra sensors and measurement instruments. Therefore, most of recent researches on induction machine faults detection have been directed toward electrical monitoring with emphasis on stator current analysis [1, 2].

Also, various faults detection methods of rotor in induction machines have been published. The methods used motor current signature analysis (MCSA) [3, 4, 5], direct spectral analysis of motor stator current, Vienna monitoring method (VMM) [6, 7], technique of global modulation index [8], wavelet analysis of startup stator current [9], instantaneous power analysis [10], torque analysis [11], search coils voltage analysis [12], vibration and acoustic analysis [13], etc. The comparison of some methods is also presented in [13].

One of the most important methods for stator current signal analysis is MCSA. The MCSA ultimate a noninvasive online diagnosis action of faults, e.g. broken bars and air-gap eccentricity in three-phase induction motors and includes a Hall-effect sensor for measuring the stator current signals as well as a data acquisition system to acquire the signals. The wave form of the stator current signals is analyzed based on a diagnostic algorithm which is an examination of the frequency spectrum of the current signal. This examination should expose the presence of side band frequencies if there are broken rotor bars [14].

The application of MCSA technique in industry during the recently years has shown that broken rotor bars can be a serious problem with certain induction motors due to ponderous duty cycles [14]. The defined fault signature frequencies of broken rotor bars fault in [2, 3]:

$$f_{brb} = f_e\left(1 \pm 2ks\right) \quad , \quad k = 1, 2, ... \tag{1}$$

where f_e is fundamental frequency of the supply line and s is the per-unit slip of the induction machine. The frequencies of the side band components are near to the frequency (50 Hz) of the fundamental component, and the magnitude of the side band components are in the variety of −20 to −60 dB, which are smaller than the magnitude of the fundamental component[15, 16 , 17]. Alternatively, the amplitude of the fundamental frequency is really high in match to other signature components. Thus, more important signature components will get buried in the fundamental component. If the fundamental component has not been filtered or removed, the amplitude variation of some signature components related to a fault may not be noticed while the fault is getting worse case. Therefore, as concerns the motor initial fault detection is concerned, the main mission is how to filter the fundamental frequency for proper capture of the sideband frequency components.

In this paper a new method for induction machine gearbox fault detection is proposed. In this method fundamental fault frequency will observe directly without observing its sidebands frequencies and titled stator current signal demodulation analysis and there used for gearbox fault detection for first time.

II. PLANETARY GEARBOX FAULT

Gearbox faults are result of gear tooth abrasion, one or several tooth fracture, deviation of gears and etc. The motor supply current, being an image of the load torque, seems to be a relevant tool for the detection of local tooth faults, which will induce sharp variations of the mesh stiffness and consequently of the instantaneous torque.

A. Planetary Gearbox Description

Planetary gearboxes are mostly practical in different industries. These gearboxes are designed based on solar system which consists of planets around the sun as center of system. Components of planetary gearbox inclusive of: sun and planet gears, planet carrier and ring gear. The central sun gear is pivoted by planet gears that are mounted on the planet carrier. Thus, This principals to the load being divided between many contact points nearby each gear, warranting less friction and an increased efficiency. Figure 1, depicts all the components of a simple global gearbox.

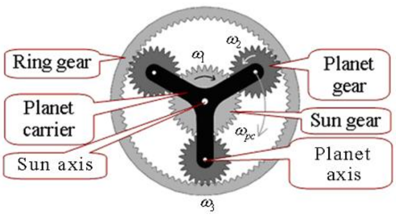


Figure 1. Planetary gearbox configuration

B. Effect of a Small Torque Variation on the Stator Current

Let us consider a small torque variation applied to a mechanical system formed by the elements from the driving AC motor to the mechanical element submitted to the torque variation (e.g. due to a cracked tooth on one gear). By neglecting the frictional forces, it writes:

$$J\frac{d\Omega}{dt} = \tau_e - \tau_{load} \tag{2}$$

where, J is the total inertia moment of the system, Ω is the rotational speed of the motor (we will consider here only one shaft for simplicity), τ_e is the electro-mechanical torque of the motor and τ_{load} is the loading torque applied to the system. In normal operating conditions, i.e. when Ω is close to the synchronous speed Ω_S of the motor, the torque characteristic can be linearized as:

$$\tau_e = k_m S = k_m \frac{\Omega_S - \Omega}{\Omega_S} \tag{3}$$

where, k_m is a constant depending of the motor characteristics and s the motor slip. Now by considering a small variation of the load torque $\delta\tau_{load}$ occurring during the time interval δt, we obtain from (2) and (3):

$$J\frac{\delta\Omega}{\delta t} = \delta\tau_e - \delta\tau_{load} = -k_m\frac{\delta\Omega}{\Omega_S} - \delta\tau_{load} \tag{4}$$

So:

$$\delta\Omega = -\frac{\delta\tau_{load}}{\left[J/\delta t + k_m/\Omega_S \right]} \tag{5}$$

Therefore, the effect on the speed variation $\delta\Omega$ will be reduced when:

- the moment of inertia J of the system is important,

-the time interval δt of the torque variation is small, i.e. the torque variation is high frequency,

- the constant k_m of the motor is high (note that this constant depends on the motor supply voltage and will be higher for a high voltage motor).

The stator current of the motor being directly linked to the motor torque Γ_e, which is itself dependent on the speed from Equation (3), the induced current variation δI will follow that of $\delta\Omega$. Moreover other parameters will also have an effect on the motor torque variations: the type of gears which will influence the mesh stiffness due to the variation of the number of teeth in contact, the type of the mechanical coupling of the motor which will add a filtering effect between the load torque and the motor torque, etc.

From this simple analysis it is clear that the effect of small load torque variations in the driven mechanical system on the stator current of the driving motor is strongly dependent on a few parameters (moment of inertia, frequency of the torque variation, type of the motor and of the gears). Therefore we can expect different behaviors depending on the system under analysis.

III. METHODS OF DEMODULATION

The demodulation methods are related to the approximation of the analytic signal $z[n]$ and the real valued signal $x[n]$ which categorized into mono dimensional and multidimensional approaches [25].

A. Mono-Dimensional Methods

The analytical signal calculations for mono-dimensional methods are as the following [18, 25]:

$$x[n] = a[n]\cos\left[\Phi[n]\right]$$
$$\Phi[n] = 2\pi f_0 n + \varphi[n] \text{ , } f_0 \text{: central frequency} \tag{6}$$

$$z[n] = a[n]e^{j\phi[n]}$$
$$a[n] = \left|z[n]\right| \tag{7}$$

$$f[n] = \frac{1}{2\pi}(\angle(z[n+1]) - \angle(z[n])) \times f_s \tag{8}$$

A.1. Synchronous Demodulator: The synchronous demodulation is used to imprecise Joint instantaneous amplitude (IA) and instantaneous frequency (IF) [18, 25]. The SD scheme of a Butterworth low-pass filter with cut-off frequency of 50 Hz is shown as Figure 2 which the discrete time analytic signal is as the following [25].

$$z^S[n] = x_1^S[n] + jx_2^S[n] = a[n]e^{j\varphi[n]} \tag{9}$$

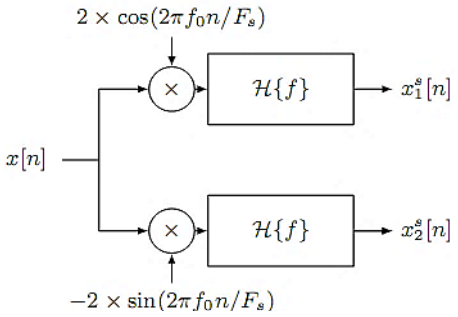


Figure 2. Synchronous demodulator [25]

A.2. Hilbert Transform: The Hilbert Transform (HT) for analytic signal approximation $x[n]$ is as the following [19]:

$$x^h[n] = x[n] \times h[n] \tag{10}$$

where, the $h[n]$ function is the impulse response.

$$h[n] = \begin{cases} 0 & \text{for } n \text{ even} \\ \dfrac{2}{\pi n} & \text{for } n \text{ odd} \end{cases} \tag{11}$$

And the corresponding analytical signal can be calculated as [26, 27]:

$$z^h[n] = x[n] + jx^h[n] = a[n]e^{\Phi[n]} \tag{12}$$

B. Multi Dimensional Techniques

The multi-dimensional methods need a 3-D stator current. Therefore, let to signify $x[n] = \left[x_1[n], x_2[n], x_3[n]\right]^T$ the 3×1 vector covering the machine stator currents.

B.1. Concordia Transform Method: The Concordia transform (CT) technique is a multidimensional linear transform which permits to extract a two orthogonal components from the three-phase stator currents of induction machine. Let's consume $x^c[n] = \left[x_1^c[n], x_2^c[n]\right]^T$ the two Concordia components. The CT can be clarified into a matrix form as [20, 21, 22].

$$x^c[n] = \begin{bmatrix} x_1^c[n] \\ x_2^c[n] \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \dfrac{\sqrt{2}}{\sqrt{3}} & -\dfrac{1}{\sqrt{6}} & -\dfrac{1}{\sqrt{6}} \\ 0 & \dfrac{1}{\sqrt{2}} & -\dfrac{1}{\sqrt{2}} \end{bmatrix} x[n] \tag{13}$$

Under the guess of a balanced system, it can be clarified that the analytic signal $z^c[n]$ is given by [31].

$$z^c[n] = x_1^c[n] + jx_2^c[n] = a[n]e^{j\Phi[n]} \tag{14}$$

The main disadvantage of CT method is the fact that it is based on balanced system assumption. This assumption is verified in three phase systems mainly in the case of abnormal operating conditions.

B.2. Principal Component Analysis Method: Principal Component Analysis (PCA) technique is a statistical tool that transforms a number of correlated signals into a small number of un-correlated signal components that called the principal components. The principal components of $x[n]$, denoted $x^P[n] = \left[x_1^P[n], x_2^P[n]\right]^T$ are given by:

$$x^P[n] = \begin{bmatrix} x_1^P[n] \\ x_2^P[n] \end{bmatrix} = \beta \Lambda^{\frac{-1}{2}} S^T x[n] \tag{15}$$

where, β is a scaling term given by:

$$\beta = \sqrt{\frac{\mathrm{Tr}[R_x]}{3}} \tag{16}$$

where, the operator $\mathrm{Tr}[.]$ is described to be the sum of the elements on the main diagonal. The covariance matrix R_x of $x[n]$ is defined as:

$$R_x = E\left[x[n]x^T[n]\right] = U\Lambda U^T \tag{17}$$

where, Λ and $U = [S\ G]$ are matrices containing the eigenvalues, respectively and vectors of R_x. Under the assumptions that $\Phi[n]$ is regularly distributed in [0; 2π] and that $a[n]$ and $\Phi[n]$ are in dependent, it can be shown that the analytic signal $z^p[n]$ can be predictable up to a phase in determination as [21].

As contrasting to Concordia transform, the PCA-based demodulation method is less restrictive since it holds whatever the balance denotation which is interesting for fault detection in electrical machine. Also, a method for dynamic speed control for linear induction motors introduced in [23] and some accepts for magnetic field distribution described in [24] that can useful for this paper.

IV. EXPERIMENTAL RESULTS

The experimental situation for valuation proposed method, consists of two winches run by a squirrel cage induction three phase motor showed in figure 3. These set up has been created in order to show the effect of the load on the stator current and output torque of induction motor. These factors are detecting with appropriate sensor which installed on induction motor. The winch A is used for load lifting and the purpose of winch B is to simulate the load operating conditions of the winch A. The winch A is running by an induction motor 22 kW, 47 Hz, 230/400 V, 4 poles specification and the squirrel-cage three-phase induction motor which is connected to a planetary gearbox for reducing the speed and increasing output torque with the characteristics listed in Table 1.

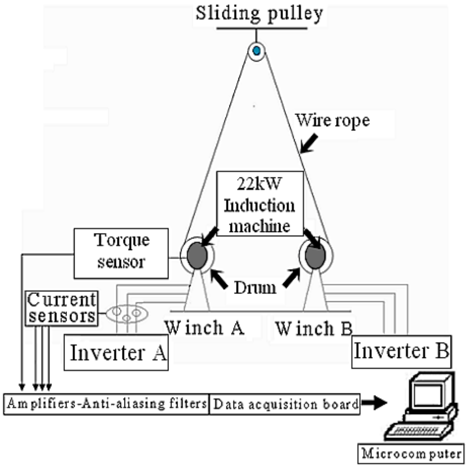


Figure 3. Set-up configuration

In is worth mentioning that the planetary gearbox has been used in this experimental fault detection. Planetary gearbox specifications have been listed in Table 1.

Table 1. Planetary gearbox specifications

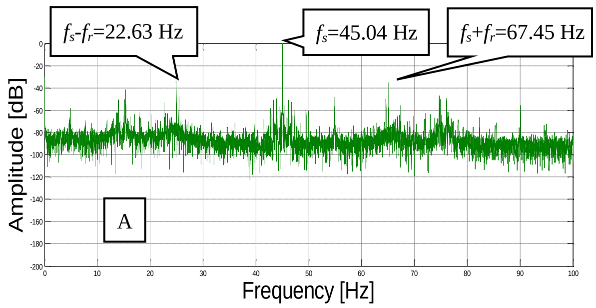
Planetary stages	Number of teeth		
	Parts		
	Sun	Planet	Ring
Stage 1	27	23	75
Stage 2	15	18	72
Stage 3	27	20	69

For creating fault condition in the tested gearbox, three modified planet axes with 50μm deviation heve been replaced with the three planet axes of the stage 1. This created fault changes the rotation mechanism of sun gear and carrier planet.

Based on proposed set-up configuration, the test applied on two induction motor which feeding by two inverters. Components of output torque and rotor rotation speed are listed in Table 2. Information signal has been named C15. This signal contains 6 million samples in 90 seconds. Fourier transform of stator current signal resulted from experiment in faulty and healthy conditions shown in Figure 4. Also, the results of Fourier transform of modulated original signal listed in Table 3 which matched with Figure 5.

Table 2. Frequency components of torque

	Healthy condition			Faulty condition		
	$3f_r$	$2f_r$	f_r	$3f_r$	$2f_r$	f_r
C15	67.23	44.82	22.41	67.26	44.84	22.42



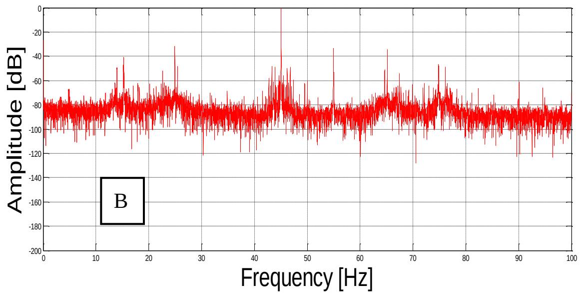


Figure 4. Fourier transform of stator current signal: A. healthy, B. faulty

Table 3. Frequency components of induction machine stator current

	Healthy conditions		Faulty conditions	
	Frequency (Hz)	Amplitude (dB)	Frequency (Hz)	Amplitude (dB)
f_s	45.04	0	45.04	0
$f_s - f_r$	22.63	-53.3	22.64	-52.3
$f_s + f_r$	67.45	-55.67	67.46	-54.07

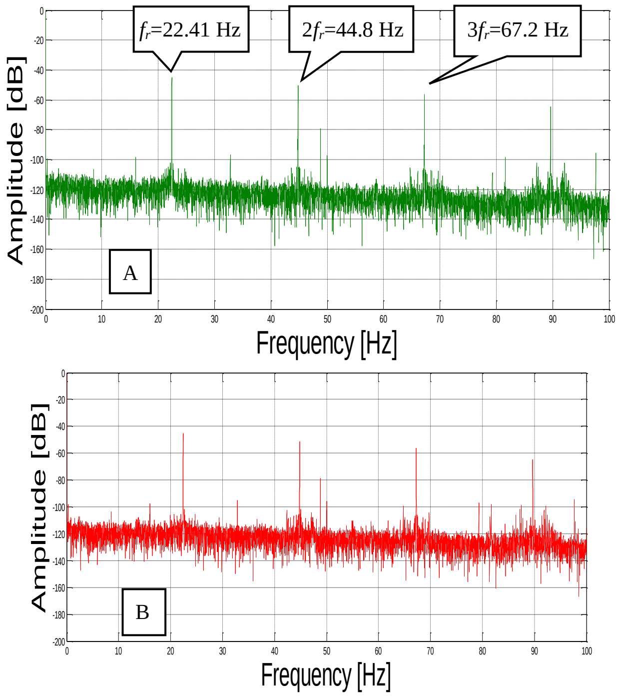


Figure 5. Fourier transform of modulated signal:
A. healthy conditions, B. faulty conditions

Based on Figure 5, faulty conditions of gearbox have been recognized from demodulation of modulated original stator current signal. In fact, there is no need to diagnosis gearbox fault from Fourier transform. Online Fourier transform calculations are difficulty and time consuming process to fault detection and this problem will damage Induction machine. Amplitude demodulation of stator current in faulty and healthy conditions is shown in Figure 6. Also, Phase demodulation of modulated stator current signal shown in Figure 7. The frequency demodulation of modulated stator current signal shown in Figure 8.

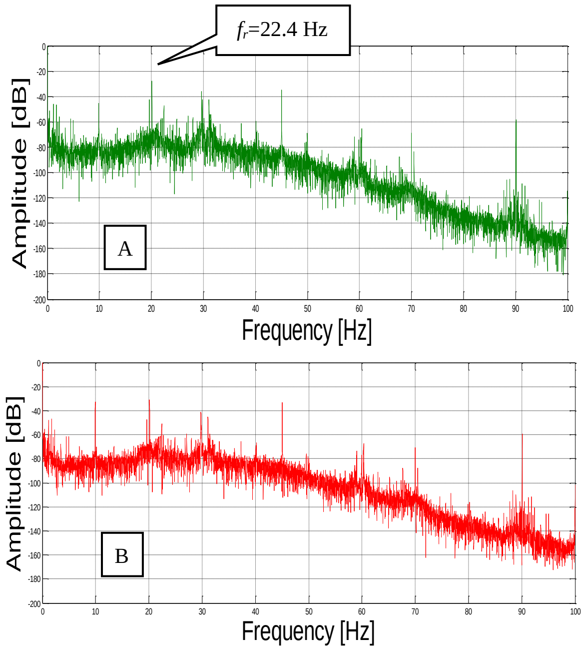


Figure 6. Amplitude demodulation of stator current:
A. healthy gearbox, B. faulty gearbox

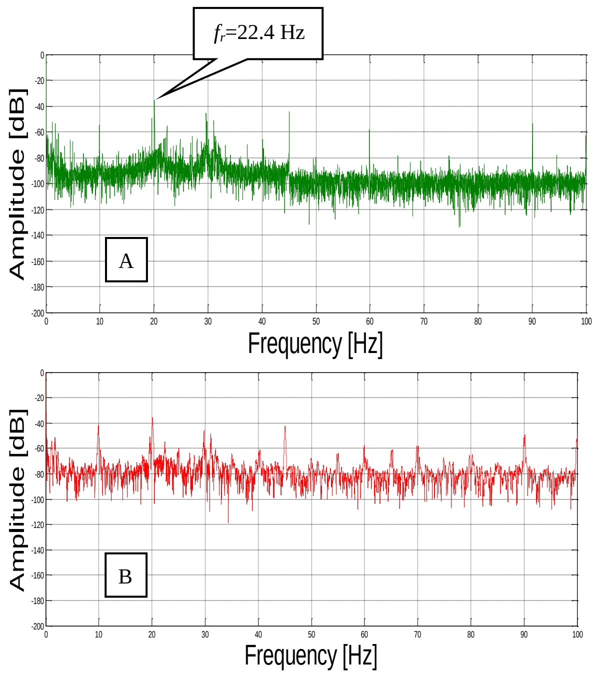
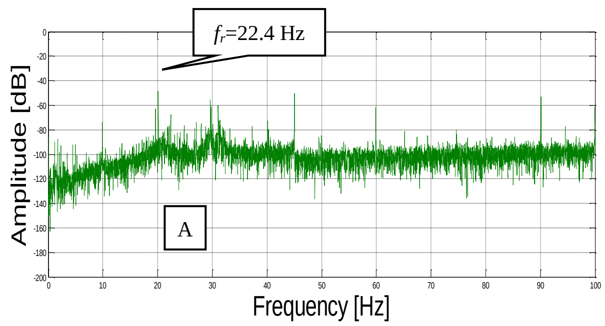


Figure 7. Phase demodulation of stator current:
A. healthy gearbox, B. faulty gearbox



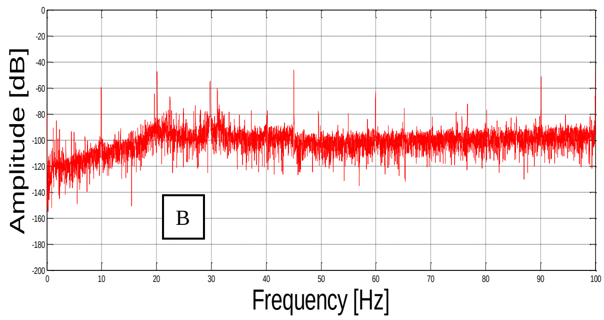


Figure 8. Frequency demodulation of stator current:
A. healthy gearbox, B. faulty gearbox

Based on the results obtained from Amplitude, Phase and Frequency demodulation, original frequency of rotor rotation in healthy conditions of gear box is 22.41 Hz and in faulty conditions is 22.42 Hz which coincident with Fourier transform method results. Simplified results of gearbox fault detection are listed in Table 4.

Table 4. Simplified results of stator current signal demodulation method

	Healthy conditions		Faulty conditions	
	Amplitude dB	Frequency Hz	Amplitude dB	Frequency Hz
Amplitude demodulation	-47.40	22.41	-51.00	22.42
Phase demodulation	-55.50	22.41	-54.89	22.42
Frequency demodulation	-67.44	22.41	-67.10	22.42

V. CONCLUSIONS

The wide range of using induction machine in industrial activities is cause to importance of fault detection in these machines. As mentioned, one of the important methods to fault detection is Fourier transform which that is time consuming and difficulty to online monitoring. So, stator current signal demodulation has been proposed to overcome mentioned problems and the results confirm accuracy and performance of proposed method. In fact, this method confirms the results obtained from Fourier transform with fast online monitoring.

NOMENCLATURES

f_e : frequency of supply line fundamental
Ω : rotational speed of the motor
τ_e : electro-mechanical torque of the motor
τ_{load} : the loading torque applied to the system
k_m : a constant depending of the motor characteristics
$x[n]$: single-phase current of stator
$z[n]$: analytic signal

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BIOGRAPHIES

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