DWT Wavelet Transform for the Rotor Bars Faults Detection in Induction Motor

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***Abstract*-The detection of broken rotor bars faults based on the analysis techniques, such as the fast Fourier transform (FFT), the accuracy of these technique depend on the loading conditions of the machine, and the ability to maintain a constant speed. To over come this problem, the analysis of the envelope of the transient starting-current waveform using the wavelet transform has been investigated. In this paper, a method for the diagnosis of rotor bar failures for the induction machine has been presented. It is based on the analysis of the stator current, using the discrete wavelet transform (DWT) at the start-up electromagnetic torque. Using the simplified dynamic model taking account the faults of the squirrel cage induction motor and the discrete wavelet transform (DWT), in order to extract the different harmonics components of the stator currents. The performance presented by using of the DWT: its ability to provide a local representation of the non stationary current signals for the healthy machine and with fault (two adjacent broken rotor bars).**

Keywords- Fault diagnosis; induction motor; broken rotor bars; startup transient; discrete wavelet transform (DWT).

I. INTRODUCTION

Induction motors, especially the asynchronous motors, play an important part in the field of electromechanical energy conversion. It is well-known that an interruption of a manufacturing process due to a mechanical problem induces a serious financial loss for the firm. We know a variety of faults that can occur in induction machines, such as rotor faults (broken bars or end ring) or rotor–stator eccentricity. In fact, if faults are undetected, they may lead to potentially catastrophic failures. The consequences of a faulty rotor are excessive vibrations, poor starting performances, torque fluctuation, or higher thermal stress [1].

In order to preserve a high level of machine integrity, it is necessary to assess the condition of the machine. Many faults detection methods have been proposed, but their established techniques contain many aspects which can be improved.

The most popular methods of induction machine condition monitoring utilize the steady-state spectral components of the stator quantities. These stator spectral components can include voltage, current and power and are used to detect turn faults, broken rotor bars, bearing failures and air gap eccentricities. Presently, many techniques that are based on steady-state analysis are being applied induction machines [2], [3]. Diagnostic method to identify the above faults may involve several different types of fields of science and technology. Several methods are applied to detect the faults in induction motors such as Fourier transform and Wavelet transform analysis.

Wavelet transform is a method for time varying or non-stationary signal analysis, and a new description of spectral decomposition via the scaling concept. Wavelet theory provides a unified framework for a number of techniques, which have been developed for various signals processing application. One of its feature is multi-resolution signal analysis with a vigorous function of both time and frequency localization. This method is effective for stationary signal processing and non-stationary signal processing. Mallet's pyramidal algorithm based on convolutions with quadratic mirror filter is a fast method similar to FFT for signal decomposition of the original signal in an orthonormal wavelet bas is or as a decomposition of the signal a set of independent frequency bands. The independence is due to the orthogonality of the wavelet function [4], [5].

II. WAVELET TRANSFORM

Wavelet transform provides flexibility in describing signals that include regions of different frequency contents. It is important for power quality problems and variable load applications.

The wavelet transform is an expansion of a given waveform into a space defined by a set of orthogonal or orthonormal functions, namely the wavelets. Many different wavelet functions have been proposed. The functions can be continuous (continuous wavelet transform) or discrete (discrete wavelet transform) [6].

A. Discrete Wavelet Transforms Description (DWT)

The wavelet transformation is processes of determining how well a series of wavelet functions represent the signal being analyzed. The goodness of fitting of the function to the signal is described by the wavelet coefficients. The result is a bank of coefficients associated with two independent variables, dilation and translation. Translation typically represents time, while scale is a way of viewing the frequency content. Larger scale corresponds to lower frequency meaning there by better resolution. The most efficient and compact form of the wavelet analysis is accomplished by the decomposing a signal into a subset of translated and dilated parent wavelets, where these various scales and shifts in the parent wavelet are related based on powers of two. Full representation of a signal can be achieved using a vector coefficients the same length as the original signal.

Considering a signal consisting of 2^m data points, where m is an integer. DWT requires 2^m wavelet coefficients to fully describe the signal. DWT decomposes the signal into m+1 levels, where the level is denoted as j and the levels are numbered i= -1, 0, 1, 2, 3…, m-1. Each level i consists of $j=2^i$ wavelet translated and equally spaced $2^{m/j}$ intervals apart.

The $j=2^i$ wavelets at level i are dilated such that an individual wavelet spans n-1 of that level interval, where N is the order of wavelet being applied. Each of the $j = 2^i$ wavelets at level i is scaled by a coefficient $a_{i,j}$ determined by the convolution of the signal with the wavelet. Notation is such that i corresponds to wavelet dilation and j is the wavelet translation in level i [7-9]. The forward wavelet transform determines the wavelet coefficient $a_{i,j}$ of j wavelet at each level i. For the signal f(n), the DWT is:

$$a_{i,j} = \sum_{n} f(n).\psi_{i,j}(n) \quad (1)$$

The waveforms associated with fast electromagnetic transients are typically non-periodic signals which contain both high-frequency oscillations and localized impulses superimposed on the power frequency and its harmonics. These characteristics present a problem for the traditional discrete Fourier transform (DFT), because its use assumes a periodic signal. As power system disturbances are subject to transient and non-periodic components, the DFT alone can be an inadequate technique for signal analysis. If a signal is altered in a localized time instant, the entire frequency spectrum can be affected. To reduce the effect of non-periodic signals on the DFT, The wavelet transform is a powerful signal processing tool used in power systems and other areas. The WT, like the STFT, allows time localization of different frequency components of a given signal; however with one important difference: the STFT uses a fixed width windowing function. As a result, both frequency and time resolution of the resulting transform will be fixed but in the case of the WT, the analyzing functions, which are called wavelets, will adjust their time-widths to their frequencies in such a way that, higher frequency wavelets will be very narrow and lower frequency ones will be broader. Therefore, the WT can isolate the transient components in the upper frequency isolated in a shorter part of power frequency cycle. The ability of the WT to focus on short time intervals for high-frequency components and long intervals for low-frequency components improves the analysis of the signals with localized impulses and oscillations [10].

1) *Specification of the Number of Decomposition Levels:* The number of decomposition levels is determined by the low frequency components. For the extraction of the frequency components caused by rotor broken bras, the number of decomposition level should be equal or higher than that of the detail signal containing the fundamental frequency. This number of decomposition levels n_f is given by [11].

$$n_f = integer\left[\frac{\log(f_s / f)}{\log(2)}\right] \quad (2)$$

f_s, f the sampling frequency and fundamental frequency respectively

B. Continuous Wavelet Transforms Description (CWT)

While the DWT is most efficient and compact, its power of two relationships the scale fixes its frequency resolutions. Often it is desired to differentiate between smaller frequency bands than DWT allows. This is possible by using scales that are more closely spaced together than the 2^i relationship, and is the basis for the continuous wavelet transform (CWT) [12], [13].

For a signal f(t), CWT determines the coefficients as:

$$\alpha(i, j) = \int_{-\infty}^{+\infty} f(t).\psi(i, j, t)dt \quad (3)$$

Here ψ is mother wavelet.

The number of coefficients necessary to describe the signal may be larger than the signal strength, as the CWT over samples the signal [12].

III. MODEL WITH FAULT OF INDUCTION MOTOR

The model of the rotor as illustrate in figure 1.

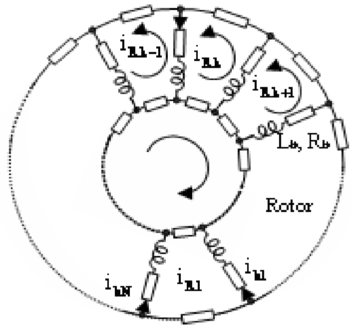

Figure 1. Rotor cage equivalent circuit

Using the extended park transformation in the (d, q) frame, the mathematical model for the induction motor taking account the rotor fault can be written as [14]:

$$[L]\frac{d[I]}{dt} = [V] - [R][I] \quad (4)$$

where:

$$[L] = \begin{bmatrix} L_{sc} & 0 & -\frac{N_r}{2}M_{sr} & 0 & 0 \\ 0 & L_{sc} & 0 & -\frac{N_r}{2}M_{sr} & 0 \\ -\frac{3}{2}M_{sr} & 0 & L_{rc} & 0 & 0 \\ 0 & -\frac{3}{2}M_{sr} & 0 & L_{rc} & 0 \\ 0 & 0 & 0 & 0 & L_e \end{bmatrix}$$

$$[R]=\begin{bmatrix} R_s & -L_{sc}\omega_r & 0 & \frac{N_r}{2}M_{sr}\omega_r & 0 \\ L_{sc}\omega_r & R_s & -\frac{N_r}{2}M_{sr}\omega_r & 0 & 0 \\ 0 & 0 & \lceil R_{rdd} & R_{rdq}\rceil & 0 \\ 0 & 0 & \lfloor R_{rqd} & R_{rqq}\rfloor & 0 \\ 0 & 0 & 0 & 0 & R_e \end{bmatrix}$$

$$L_{rc}=L_{rp}-M_{rr}+\frac{2.L_e}{N_r}+2.L_e\left(1-\cos(a)\right)$$

and

$$R_r=2\frac{R_e}{N_r}+2.R_b\left(1-\cos(a)\right)$$

where, the four terms are:

$$\begin{cases} R_{rdd,rqq}=R_r+\frac{2}{N_r}\left(1-\cos(a)\right)\sum_k R_{bfk}\left(1\mp\cos(2k-1)a\right) \\ R_{rdq,rqd}=-\frac{2}{N_r}\left(1-\cos(a)\right)\sum_k R_{bfk}\sin(2k-1)a \end{cases}$$

In this expression, the summation is applied to all bars that are in fault. R_{bfk} is the increased resistance of the bar index k from its initial value before the fault.

The expression of the torque is given by :

$$C_e=\frac{3}{2}p.N_r.M_{sr}\left(I_{ds}.I_{qr}-I_{qs}.I_{dr}\right) \quad (5)$$

IV. SIMULATION RESULTS

The simulations are realized for the induction motor model: 1.1 kW, 220 V, 50 Hz, 2-pole, rotor with 16 bars, for more detail about the simulation model of the machine found in [14-16].

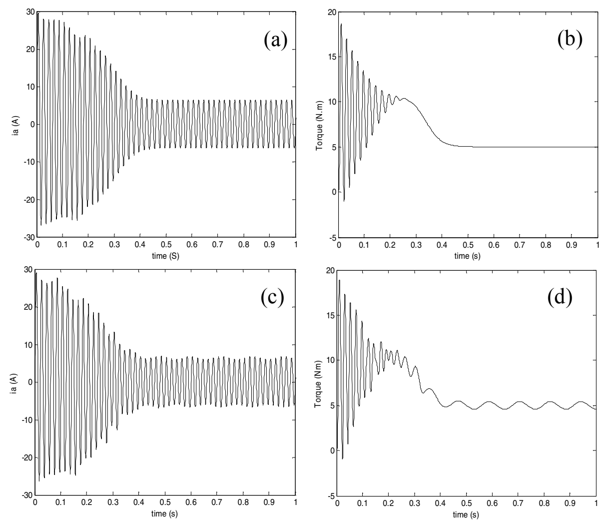

Figure 2. Stator current and electromagnetic torque for: (a, b) Healthy machine and (c, d) machine with two rotor broken bars

Figure 2 (a, b) shows that the stator current and the electromagnetic torque only contains transient fundamental component at the startup, and will be a DC component when the motor reaches the stable condition. The established regime for the torque is near the nominal load (full load). Figure 2 (c, d) indicate contain corresponding fault feature component for the rotor broken bar motors. The fault feature component is more significant after complete attenuation of the fundamental component.

According to the following analysis, rotor broken-bar fault can be easily detected by performing DWT on the fault feature component.

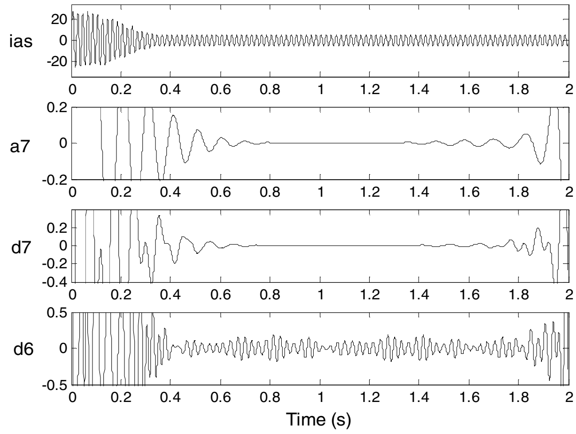

Figure 3. High-level wavelet signals results from the DWT signal analysis of transient stator current

Figure 3 shows the upper-level signals a7, d7 and d6 resulting from the wavelet decomposition of the startup stator current in a faulty machine (two broken rotor bars) operating with a nominal load, obtained from simulation with f_s=2500 samples/sec. The supply frequency in this paper is taken to be f=50 Hz.

TABLE I. Frequency Levels of Wavelet Coefficients

Level	Frequency band
d6	19.53 - 39.06 Hz
d7	9.76 - 19.53 Hz
a7	0 – 9.76 Hz

Table 1 shows the frequency levels of the wavelet function coefficients. Daubechies-40 wavelet is used in this paper as a mother wavelet. The efficiency of Daubechies wavelets based on the accurate reconstruction of power system transient signals as described in [8], [17]. Moreover, according to [18] use of high-order wavelets such as Daubechies-40 can improve the precision of diagnosis of the broken rotor bars.

A. Healthy Machine under Full Load (s= 6.6%): Stator Current Analysis

In figure 4 is displayed, the DWT of startup electromagnetic torque. The wavelet analysis shows that the upper-level signals (a7, d7 and d6) associated with frequency bands below 50 Hz do not have any important variation, once the electromagnetic transient finishes.

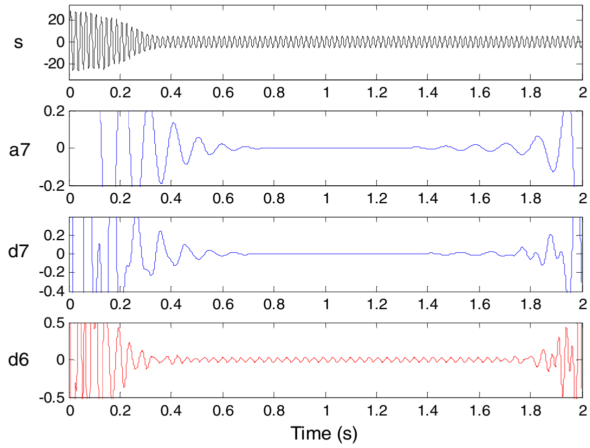

Figure 4. Wavelet analysis stator current at startup electromagnetic torque for healthy machine under full load.

B. Machine under Full Load with Two Broken Rotor Bars (s=6.6%).

1) *Stator Current Analysis:* The comparison between figure 4 and figure 5 shows clearly the fault (broken rotor bars) and can be identified by means of the "perturbations" that appear clearly in high-level d6. Oscillations "perturbations" not considered since they are due to the electromagnetic transient and can be found even after the stability of the machine.

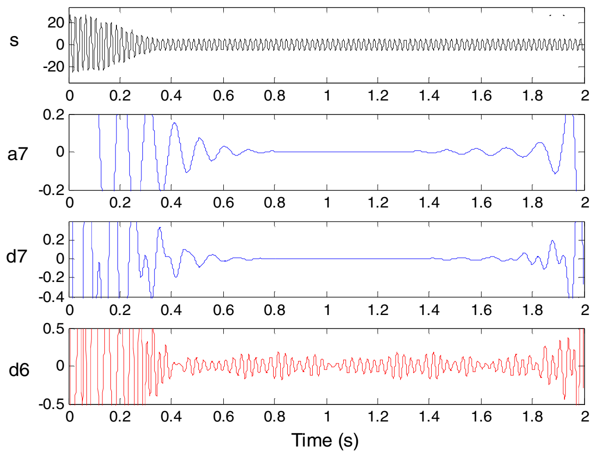

Figure 5. Wavelet analysis current stator at startup electromagnetic torque at full load with two broken bars

2) *Electromagnetic Torque Analysis:* Figure 6 (b) shows, the Wavelet transform for the torque in the cases the machine present two broken bars. In this case, the faults increase the magnitude values of the frequency band d7, and a7, but less in magnitude as compared with healthy machine (figure 6 a).

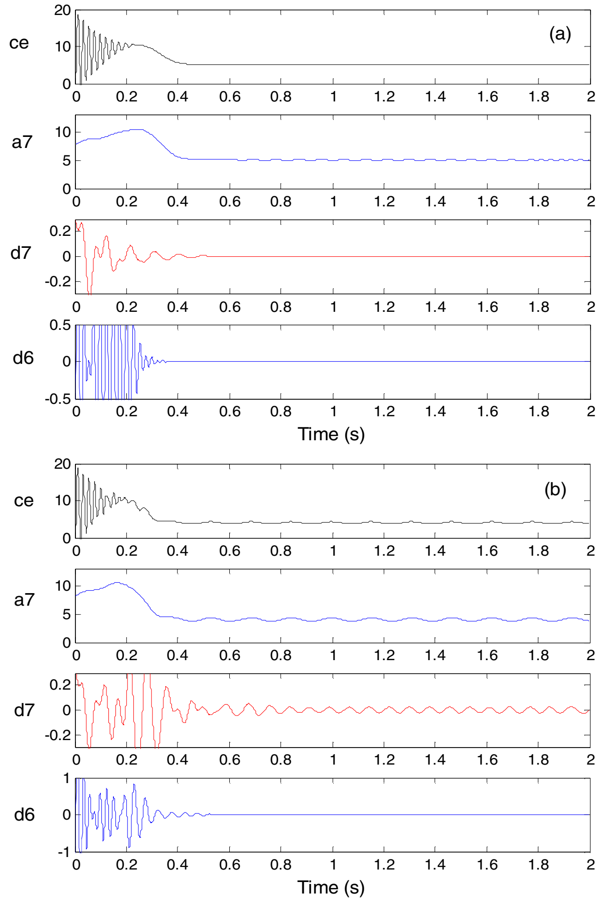

Figure 6. Wavelet analysis torque at startup electromagnetic torque at ful load: (a) Healthy machine, (b) machine with two broken bars

V. CONCLUSIONS

This paper has investigated the detection of broken rotor bars using wavelet analysis of the current and the torque. The wavelet technique presented here is able to extract useful characteristics from the starting current and torque of an induction motor.

The results of wavelet transformation give the advantageous information to decide the faulty situation, particularly in the presence of broken rotor bars at startup torque and the number of acquisition points is very reduce. This method can clearly exhibit the time-frequency characteristic of fault signals. By increasing the peaks of the time domain waveform of analysis function, misdiagnosis caused by frequency aliasing can be effectively eliminated. The proposed method provides a promising way for the mixed-faults diagnosis of induction motors.

VI. APPENDIX

For the simulated induction motor

P_n: Output power	1.1kW
V_s: Stator voltage	220 V
f_s: Stator frequency	50 Hz

P:	Pole number	1
R_s:	Stator resistance	7.58 Ω
R_r:	Rotor resistance	6.3 Ω
R_b:	Rotor bar resistance	0.15 mΩ
R_e:	Resistance of end ring segment	0.15 mΩ
L_b:	Rotor bar inductance	0.1 μH
L_e:	inductance of end ring	0.1 μH
L_{sf}:	Leakage inductance of stator	26.5 mH
M_{sr}:	Mutual inductance	46.42 mH
N_s:	Number of turns per stator phase	160
N_r:	Number of rotor bars	16
L:	Length of the rotor	65 mm
e :	Air-gap mean diameter	2.5 mm
J:	Inertia moment	0.0054 $kg.m^2$

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