A Comparative Study of FFT, STFT and Wavelet Techniques for Induction Machine Fault Diagnostic Analysis

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Abstract:-Motor Current Signature Analysis (MCSA) has been successfully used for fault diagnosis in induction machines. The current spectrum of the induction machine for locating characteristic fault frequencies is used in MCSA. The spectrum is obtained using a Fast Fourier Transformation (FFT) that is performed on the signal under analysis. The fault frequencies occur in the motor current spectra are unique for different motor faults. However FFT does not always achieve good results with non-constant load torque. Other signal processing methods, such as Short-time Fourier Transform (STFT) and Wavelet transforms techniques may also be used for analysis. These techniques are capable of revealing aspects of data like trends, breakdown points, discontinuities in higher derivatives, and self-similarity which are not available in FFT analysis. In the present paper, the comparisons of various techniques are discussed to analyze the experimental results obtained.

Key-words:-Fast Fourier transforms, Short time Fourier transform, Wavelet transform

1 Introduction

Advances in digital signal processing technology have enabled researchers to process more data in less time. As a result, information that is not previously available can be extracted from the collected data. In the light of these developments, condition monitoring via MCSA has recently drawn more attention from researchers. MCSA focuses its efforts on the spectral analysis of the stator current and has been successfully used in the detection of broken rotor bars, bearing damage and the dynamic eccentricity [1]. MCSA analyzes the stator current in search of current harmonics directly related to new rotating flux components, which are caused by faults in the motor-flux distribution [2]. The advantage of this technique is that it is well recognized nowadays as a standard due to its simplicity: It needs only one current sensor per machine and is based on straightforward signal-processing techniques such as Fast Fourier transforms (FFT). But, Fourier analysis has also some other serious drawbacks. One of them may be that time information is lost in transforming to the frequency domain. When looking at a Fourier transform of a signal, it is impossible to tell when a particular event has taken place. If it is a stationary signal - this drawback isn't very important. However, most interesting signals contain numerous non-stationary or transitory characteristics: drift, trends, abrupt changes, and beginnings and ends of events. These characteristics are often the most important part of the signal, and Fourier analysis is not suitable in detecting them. In an effort to correct this deficiency, Dennis Gabor (1946) adapted the Fourier transform to analyze only a small section of the signal at a time -- a technique called windowing the signal. Gabor's adaptation, called the Short-Time Fourier Transform (STFT), maps a signal into a two-dimensional function of time and frequency as shown in figure 1.

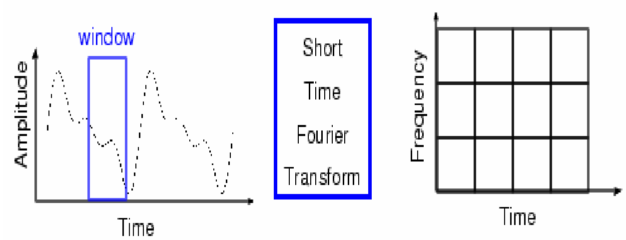


Fig. 1: Short time Fourier transform

In STFT one particular size of the time window is selected for all the frequencies, which restricts the flexibilities. Many signals require a more flexible approach -one where we can vary the window size to determine more accurately either time or frequency. For this, wavelet analysis can be used. Thus, Wavelet analysis represents the next logical step: a windowing technique with variable-sized regions. Wavelet analysis allows the use of following:

- long time intervals where more precise low-frequency information is required
- Shorter regions where high-frequency information is required.

The aim of this paper is to discuss the importance of FFT, STFT and wavelet transforms methods for stator-current analysis to detect the faults in induction machines.

2 Fault diagnosis using Fast Fourier transforms (FFT)

To diagnose the fault, spectrum is obtained using a Fast Fourier Transformation (FFT) that is performed on the signal under analysis. But, the FFT in the stator current is quite difficult to apply with accuracy due to problems such as frequency resolution, magnitude accuracy at steady state, and more generally, due to data processing [3]. The present paper discusses new methods (Short Time Fourier Transform, Wavelet transform) based on stator-current analysis for online fault detection in induction machines, which would overcome the averaging problems of classical FFT. This section also discusses some common faults of induction motors which can be online diagnosed with help of MCSA.

2.1 Rotor bar analysis

In the three-phase induction motor under perfectly balanced conditions (healthy motor) only a forward rotating magnetic field is produced, which rotates at synchronous speed, $n_1 = f_1.p$, where *f*1 is the supply frequency and *p* the pole-pairs of the stator windings. The rotor of the induction motor always rotates at a speed (*n*) less than the synchronous speed. The slip, $s = (n_1 - n)n_1$, is the measure of the slipping back of the rotor regarding to the rotating field. The slip speed $\left(n_2 = n_1 - n = s.n_1\right)$ is the actual difference in between the speed of the rotating magnetic field and the actual speed of the rotor. The frequency of the rotor currents is called the slip frequency and is given by:

$$f_2 = n_2.p = s.n_{1.}p \quad (1)$$

The speed of the rotating magnetic field produced by the current carrying rotor conductors with respect to the stationary stator winding is given by:

$$n + n_2 = n + n_1 - n = n_1 \quad (2)$$

With respect to a stationary observer on the fixed stator winding, then the speed of the rotating magnetic field from the rotor equals the speed of the stator rotating magnetic field, namely, the synchronous speed. Both mentioned fields are locked together to give a steady torque production by the induction motor. With broken rotor bars in the motor there is an additional, backward rotating magnetic field produced, which is rotating at the slip speed with respect to the rotor. The backward rotating magnetic field speed produced by the rotor due to broken bars and with respect to the rotor is:

$$n_b = n - n_2 = n_1.(1-s) - s.n_1 = n_{1.}(1-2s) \quad (3)$$

The stationary stator winding now sees a rotating field at:

$$n_b = n_1(1-2s) \quad (4)$$

or expressed in terms of frequency: $f_b = f_1(1-2s)$

This means that a rotating magnetic field at that frequency cuts the stator windings and induces a current at that frequency (f_b). This in fact means that f_b is a twice slip frequency component spaced $2s\ f_1$ down from f_1. Thus speed and torque oscillations occur at $2s\ f_1$ and this induces an upper sideband at $2s\ f_1$ above f_1 .Classical twice slip frequency sidebands therefore occur at $\pm\ 2s\ f_1$ around the supply frequency:

$$f_b = (1 \pm 2s)\, f_1 \quad (5)$$

While the lower sideband is specifically due to broken bar, the upper sideband is due to consequent speed oscillation. In fact, several papers show that broken bars actually give rise to a sequence of such sidebands given by [2]:

$$f_b = (1 \pm 2ks)\, f_1 \qquad k = 1, 2, 3 \quad \ldots..k \quad (6)$$

Therefore the appearance in the harmonic spectrum of the sidebands frequencies given by (5) or (6) clearly indicates a rotor fault of the induction machine.

2.2 Stator-Winding Faults

Inter-turn short circuit is the second type of motor fault investigated in this paper. The inter-turn short circuit of the stator winding is the starting point of winding faults such as turn loss of phase windings. The short-circuit current flows in the inter-turn short-circuit windings. This initiates a negative MMF, which reduces the net MMF of the motor phase. Therefore, the waveform of air-gap flux, which is changed by the distortion of the net MMF, induces harmonic frequencies in a stator-winding current as [13]:

$$f_{stator} = \left\{ \frac{n}{p}(1-s) \pm k \right\} f_1 \qquad \ldots\ldots\ldots\ldots (7)$$

Where *p* is the number of pole pairs, n = 1, 2, 3, . . ., and *k* = 1, 3, 5, . . ., respectively.

2.3 System under analysis

A case-study 3-phase, 440-V, 60-Hz, 5-hp, squirrel-cage induction motor, was tested in the laboratory. This motor was tested under healthy and one through four broken bars of rotor faulty conditions while another 3- phase, 5-hp squirrel cage, induction motor was tested under inter-turn shorts faults in one phase of the stator windings.

2.4 Result and analysis

Fig. 2 shows a comparison between the current spectrum for a fault free machine and broken rotor bar. The spectral analysis clearly shows that if a rotor fault is present, some components appear at the fault's characteristic frequencies in the spectrum. These faults characteristic frequencies are directly related to the shaft rotating frequency and its sub-harmonics. All cases have 60 Hz line frequency a 0.5-Hz slip frequency with the 2-N- m constant load. From eqn. (6), the abnormal harmonic frequencies of rotor asymmetry are obtained as 58.8 and 61.2 Hz with the harmonic constant k = 1and the slip frequency 0.6 Hz. The power-spectrum magnitudes of left sidebands are shown that the healthy and broken rotor bar have −44 and −7.5 dB, respectively. In addition, the power-spectrum magnitudes of the right sidebands are −26 and −6.5 dB, respectively. Fig. 3 shows the power spectrum magnitudes of stator currents obtained by conducting an experiment on 5-hp three-phase squirrel-cage induction motors. From eqn. (7), the abnormal harmonic frequency of a stator-winding fault, as illustrated by Fig. 3(b), appeared at 334.6 Hz with the dominant harmonic numbers k = 1, n = 20, and a slip frequency f_{s1} = 4.6 Hz. Here, the inter-turn short circuit of stator winding was used to realize the condition of a stator-winding fault. In order to easily investigate abnormal harmonics, large slips were introduced by a heavy load.

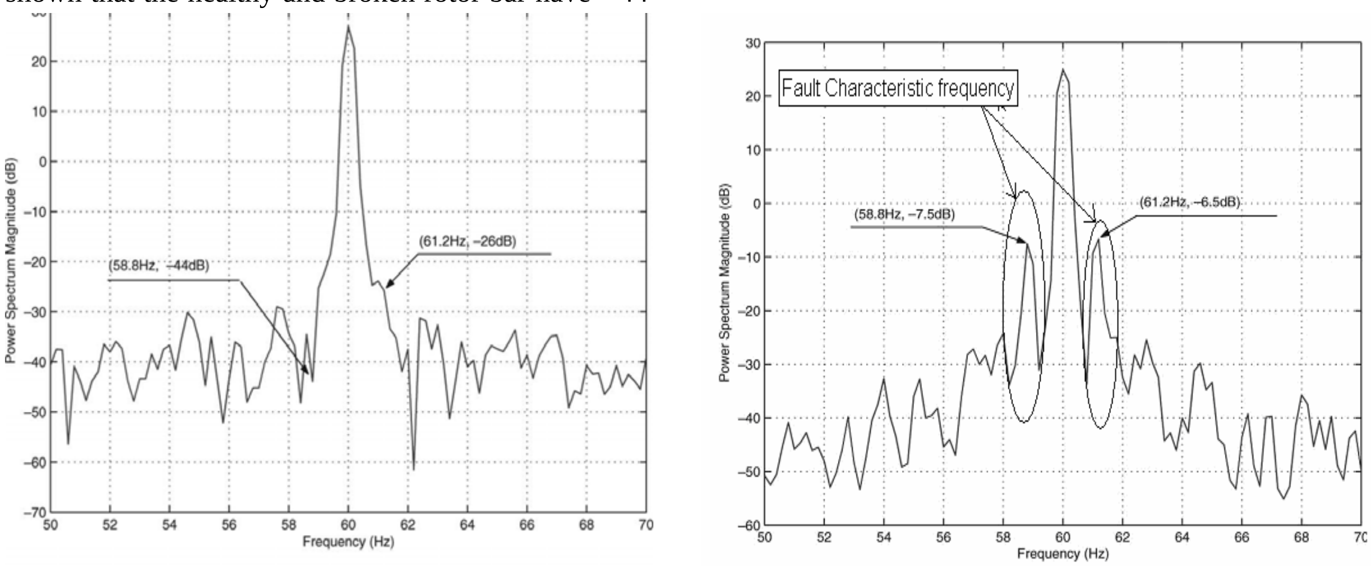


Fig. 2 (a): Spectrum of stator currents (Healthy rotor bar) (b): Spectrum of stator currents (Broken rotor Bar)

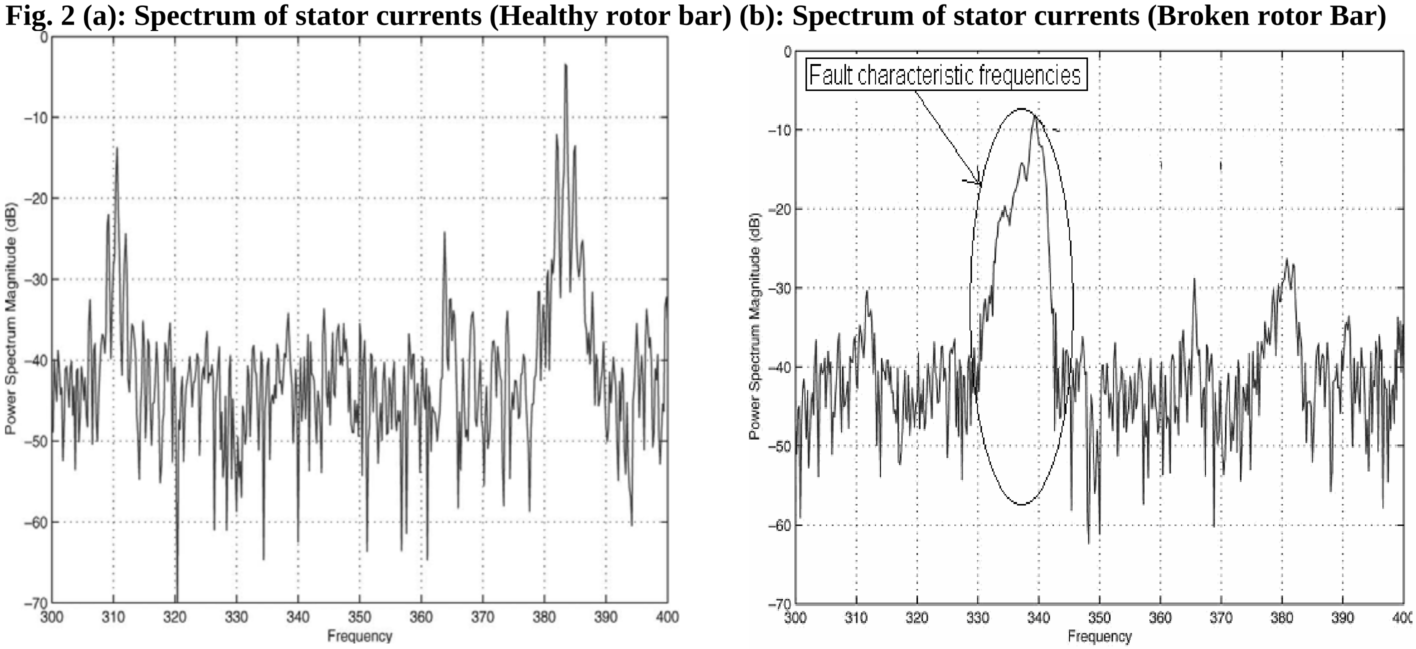


Fig.3 (a): Stator-winding-fault frequency spectra. (Healthy motor) **b)Stator-winding-fault frequency spectra (Stator-winding interturn short)**

3 Fault diagnosis using Short-Time Fourier Transformation (STFT)

It is the time-dependent Fourier transform for a sequence, and it is computed using a sliding window. The STFT is a Fourier-related transform that is used to determine the sinusoidal frequency and the phase content of the local sections of a signal as it changes over time [10]. In this method, the spectrogram is used to estimate the frequency content of a signal. The magnitude squared of the STFT yields the spectrogram of the function, which is usually represented like color plots as shown in fig. 4. In the case of non-constant load torque of an induction motor, the spectrogram could be used to show the changes in harmonic-current amplitudes.

3.1 System under analysis

A case-study 3-phase, 440-V, 6-poles, 5-hp, squirrel-cage induction motor, supplied by an AC drive operating under scalar (open-loop) constant Volts per Hertz control was tested in the laboratory. This motor has a cage with 45 bars, that is 7½ bars per pole pitch, and it has 240 stator winding turns per phase housed in a stator with 36 slots, that is six slots per pole, and hence two slots per pole per phase. This motor was tested under healthy and one through four broken bars of rotor faulty conditions.

3.2 Result and analysis

A short detail of the spectrogram and drawing the spectral distribution of a signal along time is shown in Fig. 4. The figure is scaled in decibels to obtain the best resolution. In case of a short circuit produced between turns in a stator phase, not only an unbalance appears in the currents but also fault harmonics due to it.

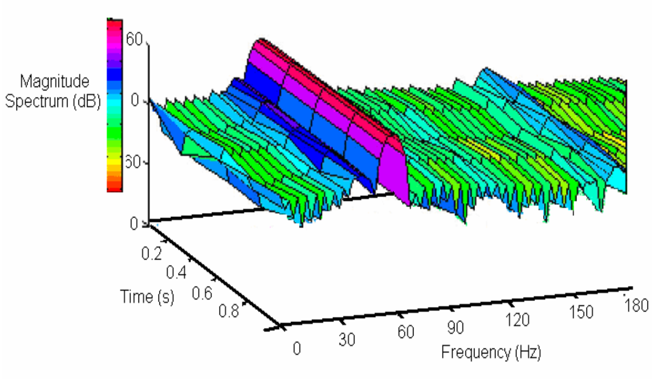


Fig. 4:Three-dimensional spectrogram details for the 0–180-Hz band, broken rotor bars

4 Fault diagnosis using wavelet transform

Fourier analysis uses the basic functions sin (t), cos(t), and exp(it). In the frequency domain, these functions are perfectly localized, but they are not localized in the time domain, resulting in a difficult to analyze or synthesize complex signals presenting fast local variations such as transients or abrupt changes [11]. To overcome the difficulties involved, it is possible to "window" the signal using a regular function, which is zero or nearly zero outside a time segment [-m, m]. The results in the windowed-Fourier transform [12]:

$$G_S(w,t) = \int s(u)g(t-u)e^{-iwu}du \qquad (8)$$

Shifting and scaling a different window function, called in this case mother wavelet, it is obtained the so called Wavelet Transform.

$$G_s(w,t) = \int s\left(\frac{1}{\sqrt{a}}\right)\varphi\left(\frac{t-u}{a}\right)du \qquad (9)$$

where a is the scale factor, u is the shift, $\varphi(t)$ is the mother wavelet and $G_S(w,t)$ is the wavelet transform of function s(t).

The discrete version of Wavelet Transform, DWT, consists in sampling not the signal or not the transform but sampling the scaling and shifted parameters. This result in high frequency resolution at low frequencies and high time resolution at high frequencies, removing the redundant information .
A discrete signal x[n] could be decomposed:

$$x[n] = \sum_k a_{jo,k}\phi_{jo,k}[n] + \sum_{j=j_o}^{j-1}\sum_k d_{j,k}\varphi_{j,k}[n] \ldots\ldots(10)$$

where $\phi[n]$ = scaling function

$\phi_{jo,k}[n] = 2^{j0/2}\phi(2^{jo}n-k)$: scaling function at scale $s=2^{jo}$ shifted by k.

$\varphi(n)$: mother wavelet

$\varphi_{jo,k}[n] = 2^{j/2}\varphi(2^j n-k)$: scaling function at scale $s=2^j$ shifted by k.

$a_{jo,k:}$: Coefficients of approximation at scale $s=2^{jo}$

$d_{j,k}$:Coefficients of detail at scale $s=2^j$

N= 2^j: being N the number of sample of samples of x[n]

In order words, a discrete signal could be constructed by means of a sum of a $j-jo$ details plus a one approximation of a signal at scale $s = 2^{jo}$.The details and the approximations at different scales could be obtained by means of a tree decomposition showed in Fig. 5.

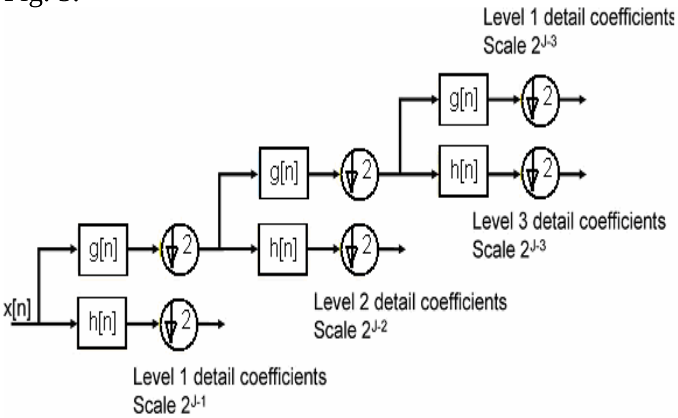


Fig. 5: Wavelet tree decomposition with three-detail levels.

4.1 System under analysis

In this experiment, two induction motors 1.5 kw, 440V was investigated for monitoring and diagnosis of broken rotor bars which were artificially damaged. The fig. 7 presents the results of an experiment

The motors were tested both under constant and non-constant load torque. Under non-constant load torque, it was expected that the amplitude of the harmonics and their frequencies over the spectrum will change continuously. The wavelet analysis breaks up the signal in several details and one final approximation. The different components cover the entire frequency spectrum with different bandwidths. The frequency bands depend on the sampling frequency and decrease as shown in Fig. 6. The highest band, which corresponds to level-one decomposition, covers from $f_s/2$ to $f_s/4$. For the next decomposition level, both the center frequency and the bandwidth divided into two.

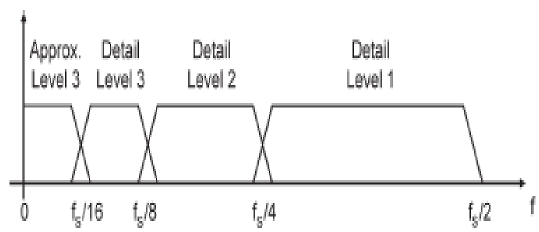


Fig. 6: Frequency ranges cover for details and final approximation.

4.2 Result and analysis

Figs. 7 (a) and (b) show the wavelet decomposition, from levels five to seven, for a healthy motor and for a faulty motor, respectively. For the lower decomposition levels (high frequency bands), there is no information about signal variation available, and the wavelet decomposition appears virtually only as a ground line. Low frequency details five to seven are much more relevant for fault detection, because they cover the frequency band corresponding to the supply and the fault frequency [11].Detail seven is primarily tuned with the fault harmonic band, and it should be the preferred option in diagnosing the condition of the motor.

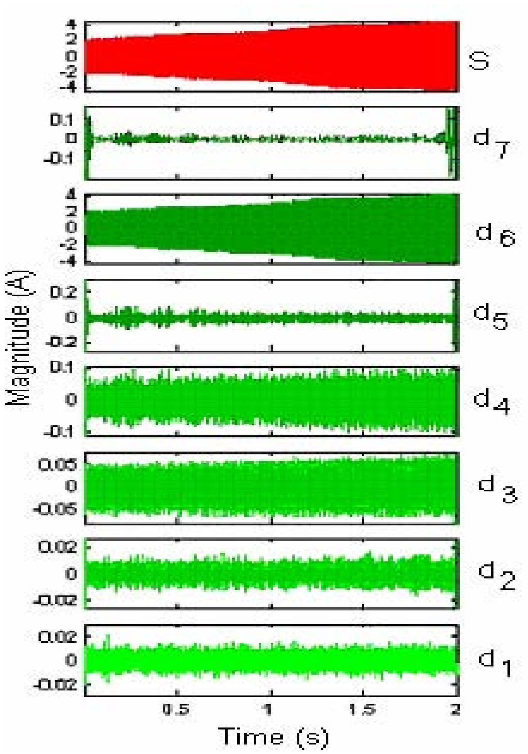
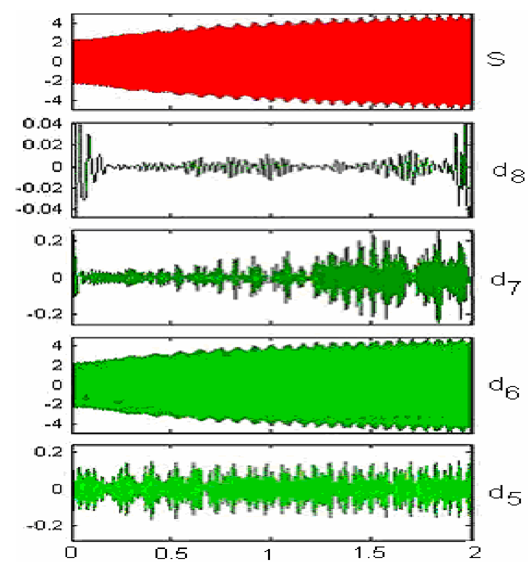


Fig 7(a): Wavelet decomposition (Healthy motor)



(b) Wavelet decomposition (Broken rotor bar)

5. Conclusion

In this paper, Motor current signature analysis for the detection of induction motor faults based on FFT, STFT, and wavelet analysis of stator current are discussed with some experimental results which are useful for online diagnosis in industrial applications. MCSA detects changes in a machine's permeance by examining the current signals and uses the current spectrum of the machine for locating characteristic fault frequencies. The spectrum is obtained using a Fast Fourier Transformation (FFT) that is performed on the signal under analysis. The fault frequencies that occur in the motor current spectra are unique for different motor faults. However this method does not always achieve good results with not constant load torque. Therefore, this paper proposes a different signal processing methods, such as Short Time Fourier Transforms (STFT) and wavelet analysis. The STFT determines the sinusoidal frequency and the phase content of the local sections of a signal as it changes over time. In this method, spectrogram is used to estimate the frequency content of a signal. The magnitude squared of the STFT yields the spectrogram of the function, which is usually represented like color plots. On other hand, Wavelet transforms show changes on harmonics amplitude and distribution, and it is the suitable transform to be applied on non stationary signals. At last, we can conclude that the new methods such as Short-Time Fourier Transform (STFT) and wavelet analysis can effectively diagnose shorted turns and broken rotor bars in non-constant-load-torque induction-motor applications.

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