Fault Detection of Electric Motors Based on Frequency and Time-Frequency Analysis using Extended DFT

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Abstract

This paper proposes a method of fault analysis for induction motors. The method is based on frequency domain and time-frequency domain analysis. Extended Discrete-Furrier Transform or EDFT is a proposed technique of signal processing. The principle is that any fault either in the stator or the rotor may distort the sinusoidal response of the motor RPM and the main frequency. Because the EDFT relates to both amplitude and frequency of number of harmonics in a signal, hence the EDFT is expected to show some harmonics around the mains frequency and other frequencies which have ability to differentiate the faults. The EDFT is applied to analyze motor faults on both frequency and time-frequency domain. The method is tested on 3 different motor conditions: healthy, stator fault, and rotor fault motor at full load condition. The experiments show that it can differentiate conditions clearly by observing the change in harmonic amplitudes for frequency domain and the change in color indexes for time-frequency domain. The method can also indicate the level of the fault severity by observing the percent change in the harmonic amplitudes and color index numbers.

Keywords: *Extended Discrete-Furrier Transform, Frequency Analysis, Time-Frequency Analysis, Fault Detection, Induction Motors, Signal Processing*

1. Introduction

An induction motor is the popular electric drives applied in many groups of industries such as chemical industries, car production industries, and agricultural industries and so on. Thus, the motor is the important mechanism driver in processes of the industries. It can be called the industrial electric motor because of their high level of reliability, efficiency and safety. However, the motor can be suffered with undesirable environments, wrong application and overload uses during operation. Hence it may lead the motor to early-stage failure or increase to server problems until the motor's breakdown which it is an important issue to stop all the mechanism processes of line production.

Some researchers have surveyed the failure that has often occurred in the motor. The research has shown that 30-40% of all recorded faults happening in the stator or armature faults caused due to the shorting of stator phase winding and 5-10% fault happening in the rotor broken bar and/or end ring fault [1]. Online condition monitoring is an important technique used to check the health of the motor during its operation at the early stage. The information that we obtain from the technique will be used for maintenance planning so that the remedial action can be done in much planned way to reduce the machine downtime and to maintain the overall plant safety. Signal processing is one of effective tools used to monitor the motor condition. One of them is called Motor Current Signature Analysis (MCSA) which is one of the most spread techniques for condition monitoring of the motor since decades. The main reason is that the other techniques need invasive sensor accessing to the motor and they also need extra equipment/sensors for measuring the required signals. Popularly, the MCSA is mostly based on frequency analysis. Sometime it is called spectrum method. Some researchers have applied the spectrum for stator fault [2-6] and the rotor fault [7-12] by which the principle was generally based on the observation of the side band, its harmonics around the main frequency, or its other harmonics. However from the previous research [13], the spectrum method cannot show the side band clearly for detecting both rotor and stator by which the stator phase current signals were used as input data. It also has a limitation for identifying the level of fault severity.

Thus from the limitation, this paper proposes a new method of motor condition monitoring. The proposed method is expected to differentiate the motor condition clearly and also be able to identify the level of the faults severity with high accuracy. Extended Discrete Furrier Transform or EDFT is used as a technique for fault quantification in this paper. It is extended from DFT in the purpose of using with limited-signal. Because the EDFT relates to both amplitude and frequency of number of harmonics in a signal, hence it is expected to show some harmonics around the mains frequency and some frequencies which has ability to differentiate the faults. The EDFT is used to analyze the motor faults on both frequency domain and time-frequency domain. There are the motor faults used to test the proposed method in this research: healthy, stator short turn circuit and broken rotor bar faults of 3 phase induction motors. Following section, this paper introduces the concept of the EDFT. The EDFT results of the experimental cases are presented. Finally, the discussion and conclusion are shown

2. Related Mathematical Theories

2.1 Extended Discrete-Fourier Transform

Extended Discrete Fourier Transform or EDFT algorithm produces N-point DFT of sequence X (input data) where N is greater than the length of input data. Unlike the Fast Fourier Transform (FFT), where unknown readings outside of X are zero-padded, the EDFT algorithm for calculation of the DFT using only available data and the extended frequency set (therefore, named 'Extended DFT'). The EDFT is one of signal processing techniques which has been mainly adopted from DFT in order to use it with a limitation of a signal input. The EDFT can increase frequency resolution. Because it is well known that zero-padding do not increase frequency resolution by DFT technique, therefore the resolution of the FFT algorithm is limited at N for all frequencies, while EDFT is able to increase the resolution on some frequencies and decrease on others. The EDFT can estimate amplitudes and phases of sinusoidal components in sequence X. the EDFT can be separated for continuous and discrete frequency. The calculation of the EDTFT for continuous frequency can be shown as [13]

$$F_{\alpha}(\omega) = |S(\omega)|^2 XR^{-1}E_{\omega}, -\Omega \le \omega \le \Omega, \quad (1)$$

$$x_{\alpha}(\omega) = XR^{-1}E_{t}, -\infty < t < \infty\infty, \quad (2)$$

$$S_{\alpha}(\omega) = \frac{XR^{-1}E_{\omega}}{E_{\omega}^{H}R^{-1}E_{\omega}} \quad (3)$$

where $S_\alpha(\omega)$ is the signal amplitude spectrum, $F_\alpha(\omega)$ is the power spectrum density, $x_\alpha(\omega)$ is relative frequency resolution at $\omega_0 = \omega$. X is data input of a signal. R is a unit matrix. E is Fourier transform basis matrix. For discrete frequency set $-\Omega \leq 2\pi f_n < \Omega$, $n = 0,1,2,\ldots,N-1$, The EDFT can be expressed by the following iterative algorithm

$$x = \frac{1}{N} E W^{(i)} E^H \quad (4)$$
$$F^{(i)} = X R^{-1} E W^{(i)} \quad (5)$$
$$S^{(i)} = \frac{X R^{-1} E}{\mathrm{diag}(E R^{-1} E)} \quad (6)$$

where the iteration number $i = 1,2,3,\ldots I$. The diagonal weight matrix $W^{(i)}$ (NxN) for the first iteration is a unit matrix, $W^{(i)}$ = I, and for the next iterations are derived from the amplitude spectrum$W^{(i+1)} = \mathrm{diag}|S^{(i)}|^2$. The matrix E (KxN) has elementse $^{-j2\pi f_n t_k}$. The $\mathrm{diag}(E^H R^{-1} E)$ $(1xN)$ means extracting the main diagonal elements from quadratic matrix. The EDFT output $F(1xN)$ and $S(1xN)$ are calculated from the results of the last performed iteration I.

2.2 Color Index Transformation for Time-Frequency Analysis

The transformation of color indexes is proposed for time-frequency analysis. The functions are to transform the colors results from the STFT of stator phase plotting. The equations can be divided into functions for rotor faults and stator faults. For rotor fault detection, the function can be expressed here as

$$CI_{BRK}(f) = \mathrm{TRANS}[\mathrm{Color}(f_e \mp s)] \quad (7)$$

And for stator fault detection, the function can be expressed here as

$$CI_{SC}(f) = \mathrm{TRANS}[\mathrm{Color}(3 * f_e)] \quad (8)$$

where f is any specific frequency, f_e is electrical frequency or main frequency, s is frequency slip calculated from mechanical frequency and electrical frequency. Hence Eq (7) and Eq. (8) are a proposed function of color index transformation (TRANS)

3. Experimental Verification

The structure of the test rig is shown in Fig. 1. The test rig consists of an induction motor (4kW, 1400RPM) with load cell with a facility to collect the 3-phase current data directly to the PC at the user define sampling frequency. The motors in the test rig used in this experiment can be divided into 3 different conditions – Healthy, Stator Fault (short circuits) and Rotor Faults (broken rotor bars). The load of the motors is set at full load conditions. The data are collected at the sampling frequency of 1280 samples/s. The stator fault motor can be adjusted into 3 server level of the short circuits - 5 turn shot circuit, 10 turn short circuit and 15 turn short circuit while the rotor fault motor is one broken rotor bar.

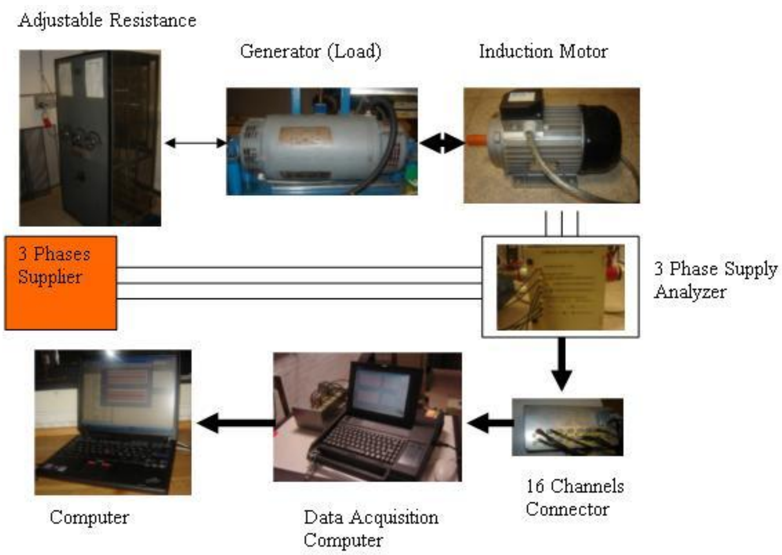

Fig. 1. Schematic of the Test Rig of an Induction Motor (4kW, 1400RPM) with Load Cell

4. Frequency-Amplitude Analysis

A typical stator phase current plot for the healthy motor operating at 100% load is shown in Fig. 2. The rated current for the motor is close to 10 Ampere. The frequency analysis and the time-frequency analysis methods have also been estimated for all the experimental data. The frequency resolution was kept 1.25Hz with 90% overlap and number of average 82 for all the signal processing. The computation time using the Pentium-IV PC for both frequency and time-frequency analysis was less than 25 sec which is definitely quick process for the health monitoring purpose. Firstly, the EDFT is plotted easily on frequency domain (as seen in Fig. 2-B). The first harmonic can be seen 50 Hz (main frequency) and followed by 150 Hz (generally used for stator fault detection). The harmonics at frequency 25 Hz and 75 Hz is sideband (generally used for rotor fault detection)

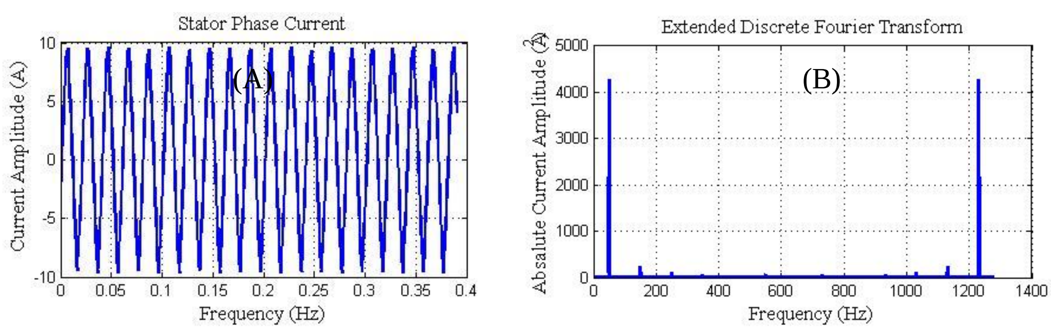

Fig. 2 (A) A typical Stator Phase Current Plot (B), The EDFT Plot on Frequency Domain for the Healthy Motor

Following experiment, the EDFT with Power spectrum estimation, power spectrum density and relative frequency resolutions based on the EDFT are used to classify the motor condition. The power spectrum shows relation between normalize frequency and $10 * log[abs(S)^2]$ which S is amplitude spectrum in square of Ampere unit. The power spectrum density shows relation between normalize frequency and $10 * log[abs(F)^2/N]$ which F is stator phase current on frequency domain processed by the EDFT. The relative frequency resolutions shows relation between normalize frequency and $(\frac{F}{S})/K$.

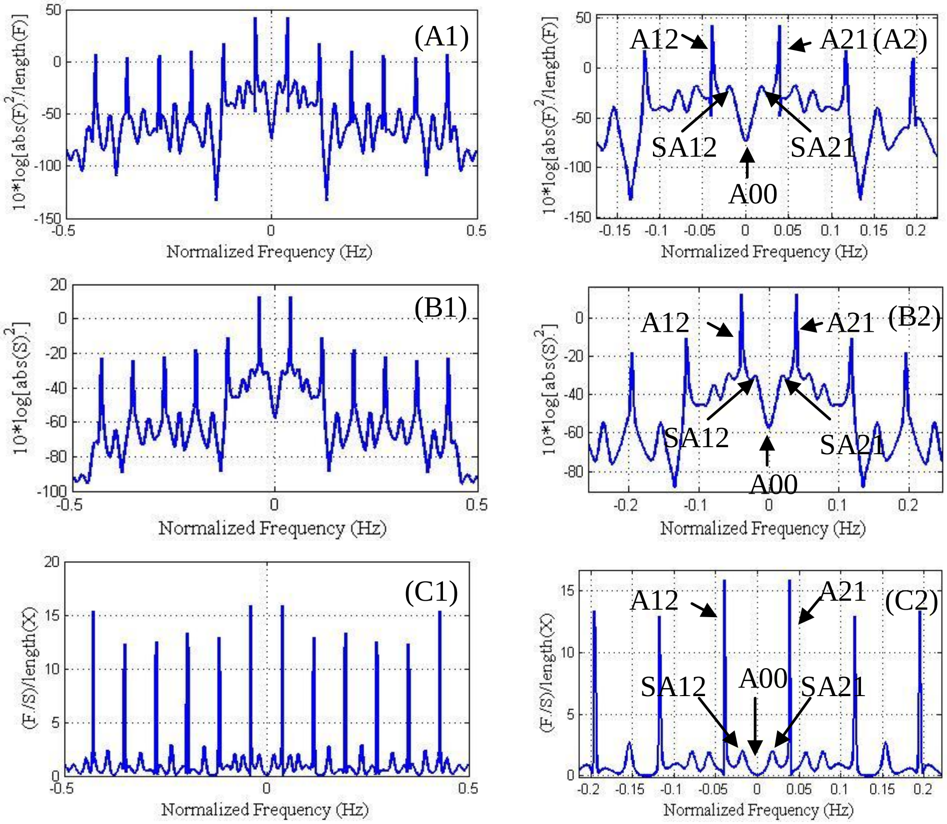

Fig. 3 The EDFT Results from Healthy Motor: (A) Power Spectrum, (B) Power Spectrum Density, (C) Relative Frequency Resolution

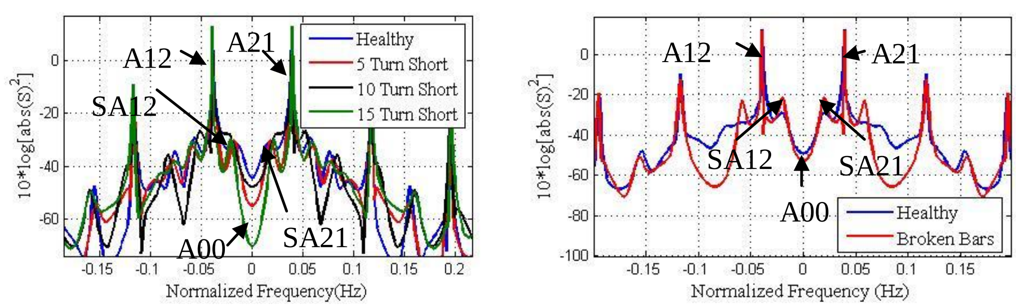

Fig. 4 Plotting Comparison: (A) Power Spectrum Comparison (healthy, 5 turn short, 10 turn short, and 15 turn short), (D) Power Spectrum Comparison (healthy, broken bars)

The power spectrum, power spectrum density and relative frequency resolutions of stator currents from healthy motor condition can be seen in Fig. 3 (A-C). Assume that A00 is a harmonic appearing at zero frequency or called ‘main frequency’, A12 (=A21) is a harmonic appearing next to main frequency and SA12 (=SA21) is a sideband appearing around main frequency.

Table 1 Harmonic Height of Power Spectrum at Interested Frequencies

Conditions	A00	A12 =A21	SA12=SA21
healthy	-68.13	12.51	-30.65
Broken bar	-59.30	12.43	-10.68
5 Turn short	-54.22	12.83	-29.52
10 Turn short	-61.58	13.31	-33.85
15 Turn short	-70.34	14.03	-29.99

Table 2 Harmonic Height of Power Spectral Density at Interested Frequencies

Condition	A00	A12 =A21	SA12=SA21
Healthy	-116.01	42.53	-22.31
Broken bar	-72.43	42.41	-1.40
5 Turn short	-63.04	42.83	-18.55
10 Turn short	-80.53	43.31	-24.48
15 Turn short	-96.73	44.09	-19.36

Table 3 Harmonic Height of Relative Frequency Resolution at Interested Frequencies

Condition	A00	A12 =A21	SA12=SA21
healthy	0.002	16.50	1.305
Broken bar	0.110	16.41	4.600
5 Turn short	0.181	17.25	1.767
10 Turn short	0.056	17.92	1.470
15 Turn short	0.023	18.77	1.392

From the tests, the EDFT seems to identify the faults clearly as can be seen in Fig. 3 and 4. Fig. 3 shows the plotting of spectrum estimation, power spectrum density, and relative frequency resolution. Fig. 4-A shows the plotting of power spectrum estimation between healthy condition and 3 different severities of stator faults. The harmonic A12 (=A21) seem to grow when the number of the short circuit turns increases (around 2.55% for 5 turns short, 6.39% for turns short, 12.15% for turns short compared to healthy condition) while the harmonic A12 of the rotor faults seems to remain (as can be seen in Table 1). The harmonic A12 (=A21) of the power spectrum density and relative frequency resolution for stator faults also increase compared to the healthy condition (as seen in Table 2 and 3).

The power spectrum estimation (Fig. 4-B) is plotted by comparing the results between healthy and broken bar motor. It can be observed that the sideband SA12 (=SA21) has increased when the broken rotor bar happens (around 65.15 %) while the sideband SA12 of the stator faults seem to remain. Additionally, the harmonics of the sideband SA12 (=SA21) of power spectrum density and relative frequency resolution can also show the growth in the same way (around 93.72% for the power spectrum density and 253.84% for the relative frequency resolution compared to the healthy condition). The proposed method has been tested with several sets of the motor data in each condition which all the tests are able to provide similar results. But, the measurement noises may slightly affect the accuracy of the results.

5. Time-Frequency Analysis

From the experiments, the EDFT of stator phase currents on time-frequency domain from different motor conditions is possible to identify the faults as shown in Fig. 5-6.

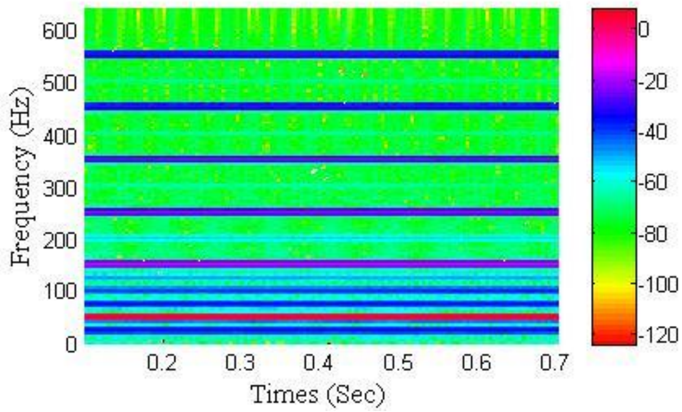

Fig. 5 The EDFT Results on Time-Frequency Analysis from Healthy Motor

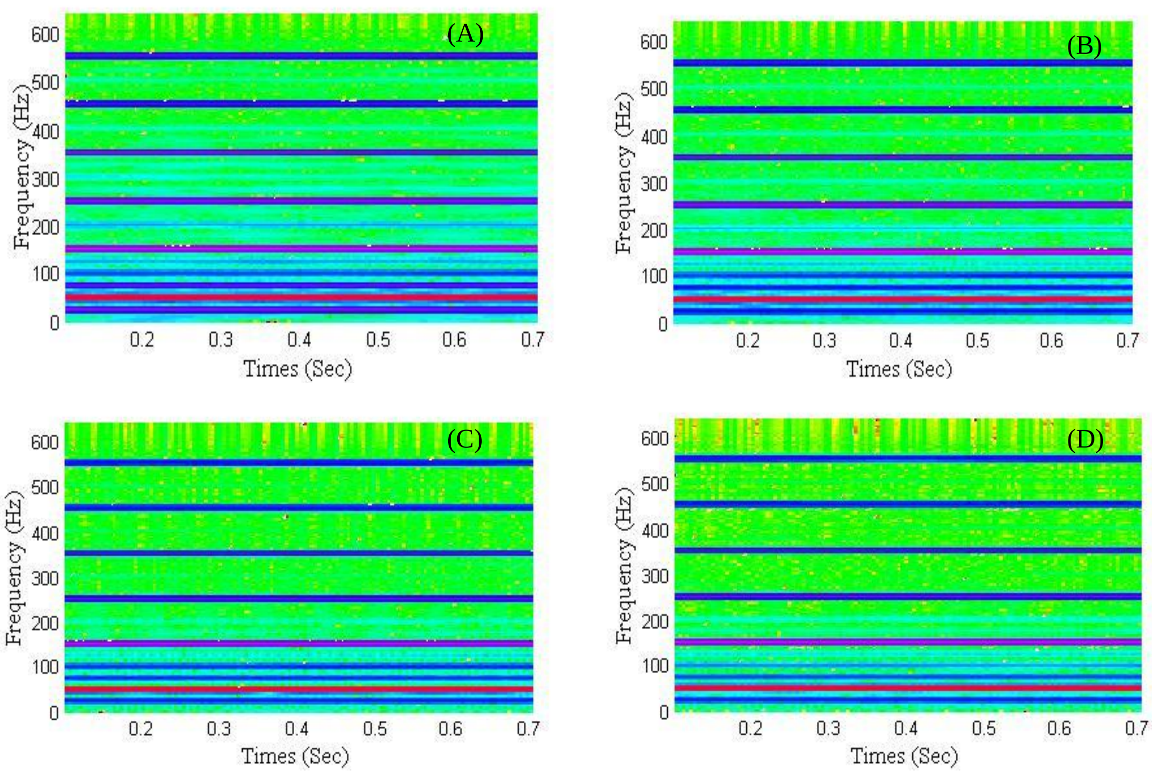

Fig. 6 The EDFT Results on Time-Frequency Analysis from: (A) Broken Bars, (B) 5 Turn Short, (C) 10 Turn Short, (D), 15 Turn Short

The time-frequency analysis is plotted in color shade (as can be seen in Fig. 5-6). The principle is that the color shades at interested frequencies are applied for motor condition classification. The interested frequencies are concentrated on 25 Hz, 50 Hz, 75 Hz, 150 Hz, 250 Hz and 350 Hz. Based on the observation, It can be seen that the color shade at some frequencies have changed when the stator phase current of different motor conditions has been processed. The color shades of the broken rotor bar motor at 25 Hz and 75 Hz can show different color shades compared to the result from healthy condition. Additionally, the color shades of the stator short circuit motor at 150 Hz can shows different color shades when the number of short circuit turns increase. Because it is difficult to differentiate the color shades by naked-eye from each condition, the color shades are necessary to be transformed into numbers from Eq. 7 and 8. Beside Fig. 5 shows color shade and among numbers which indicate index numbers of each color. The result of color indexes in different conditions and frequencies is shown in Table 4.

Table 4 Color Indexes of Different Conditions at Interested Frequency

Condition	25 Hz	50 Hz	75 Hz	150 Hz	250 Hz	350 Hz
healthy	-33	+10	-33	-22	-24	-32
Broken bar	-23	+9	-23	-21	-20	-32
5 Turn short	-32	+9	-32	-20	-21	-31
10 Turn short	-33	+9	-33	-18	-20	-31
15 Turn short	-33	+9	-33	-17	-20	-31

It can be seen that the color indexes at 150 Hz from healthy condition to 15 turn short circuit have increased when the number of short circuit turn increase. At the frequencies 25 Hz and 75 Hz, the color indexes of broken rotor bar motor have been increased significantly (around 1.4 times) when compare with the color indexes of healthy condition.

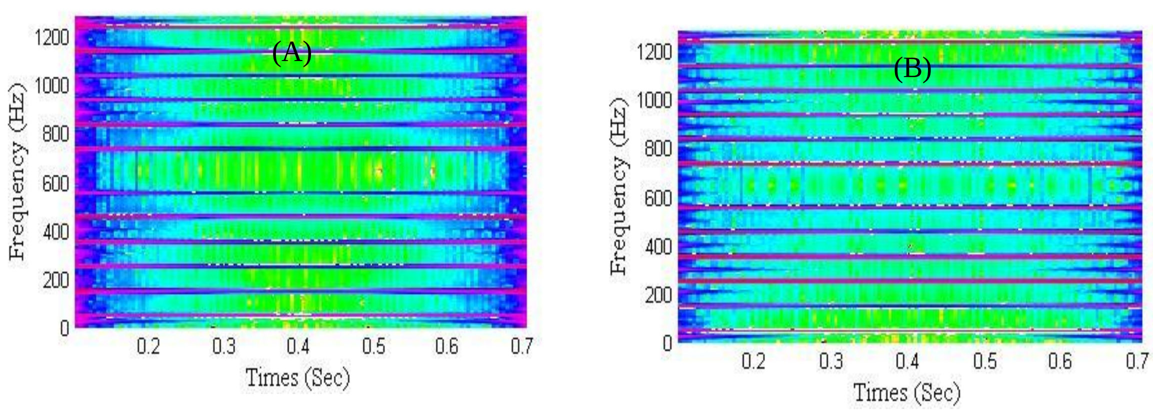

Fig. 8 The EDFT Results of Power Spectrum on Time-Frequency Analysis from: (A) Broken Rotor Bars, (B) 15 Turn Short Circuit

The EDFT results of power spectrum, power spectrum density and relative frequency resolutions of stator currents on time-frequency analysis have also been used for motor condition classification in this experiment. Fig. 8 shows The EDFT results of power spectrum on time-frequency analysis from broken rotor bars (Fig. 8-A) and 15 turn short circuit (Fig. 8-B). Based on the experiment, the color shade from power spectrum, power spectrum density and relative frequency resolutions is difficult to transform to color indexes. Hence it is difficult to differentiate the motor condition.

6. Conclusion

Because any fault either in the stator or the rotor may distort the sinusoidal response of the motor phase current signal which results in number of harmonics of the motor RPM and the mains frequency, hence the Extended Discrete-Furrier Transform or EDFT is proposed here for the motor fault detection (The EDFT is the modification of the DFT extended in the purpose of using with limited-signal). Because the EDFT is a tool which can show the relation between amplitude and frequency of number of harmonics in a signal, hence the EDFT is expected to show some harmonics around the mains frequency and some frequencies which have ability to differentiate the faults. The EDFT is applied for fault classification on both frequency and time frequency domain. Based on The experiments, the EDFT can differentiate the motor condition clearly with the harmonic amplitude for frequency domain and with color indexes for time-frequency domain. The method can also indicate the level of the fault severity by observing the percent change in the measured height of the harmonic amplitudes and color index changes. Thus, it concludes that the EDFT method is a tool which has ability to use for fault detection and quantification. However base on observation, the accuracy of the method may be affected by measurement noises. Further modification of the method is planned for future work.

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