Fault Quantifications of Induction Motor Based on Time Frequency Analysis

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บทคัดย่อ

สเปคตรัมเป็นวิธีที่ได้รับนิยมใช้ในปัจจุบันในการตรวจสอบการเสียหายของมอเตอร์ไฟฟ้า โดยการอาศัยหลักการการวิเคราะห์สัญญาณบนโดเมนความถี่และสังเกตุการเกิดอาร์โมนิกที่ความถี่ด้านข้าง ความถี่หลักหรือความถี่ที่ตำแหน่งอื่นๆ แต่อย่างไรก็ตามจากการทดลองพบว่าวิธีสเปคตรัมมีความสามารถในการแยกสภาพของมอเตอร์ได้อย่างแม่นยำระดับหนึ่ง แต่ระดับความรุนแรงของการเสียหายไม่สามารถวัดได้ ดังนั้นบทความนี้ได้นำเสนอวิธีการใหม่ที่เรียกว่า การวิเคราะห์บนโดเมนเวลา-ความถี่ หรือสเปคโตรแกรม วิธีนี้ถูกคาดหวังว่าจะสามารถสร้างความสัมพันธ์ระหว่างสัญญาณกระแสไฟฟ้าเฟสและระดับความรุนแรงของการเสียหาย ซึ่งจะทำให้สามารถตรวจจับและวัดระดับความรุนแรงของการเสียหายของมอเตอร์ วิธีวิเคราะห์ใหม่ได้ทำการทดลองกับ 3 สภาพของมอเตอร์ สภาพแบบปกติ สภาพแบบสเตเตอร์เสียหาย และสภาพโรเตอร์เสียหาย จากการทดลองพบว่าวิธีนี้สามารถให้ความแม่นยำในการตรวจสอบความเสียหายและวัดระดับความเสียหายโดยอาศัยการเปลี่ยนแปลงตัวเลขของค่าสัมประสิทธิ์ของสี ดังนั้นสามารถสรุปได้ว่าวิธีนี้สามารถเป็นเครื่องมือที่มีประสิทธิภาพ สำหรับการวิเคราะห์สภาพของมอเตอร์

คำสำคัญ: มอเตอร์ไฟฟ้าแบบเหนี่ยวนำ การประมวลผลสัญญาณ การตรวจสภาพมอเตอร์ สเปคโตรเกรม โดเมนเวลาและความถี่

Abstract

The spectrum method has popularly been applied to fault detection bases on frequency analysis by observing the side band, its harmonics around the main frequencies or its other harmonics. Based on the present experiments, the spectrum method with the FFT function has the ability to distinguish the motor condition. However, the fault severity levels were not analyzed. Therefore a time-frequency analysis (or spectrogram) of the stator phase currents is proposed here. This method is expected to show the relationship between the phase current signals and the fault levels, enabling it to detect the faults and also to indicate the fault levels. The method is tested on 3 different motor conditions: healthy, stator fault, and rotor fault motor at full load conditions. The experiments show that the proposed method can provide accurate fault prediction and fault level quantification by observing the change in the color index at specific frequencies. Hence it can be concluded that the propose method is an effective tool for motor fault analysis.

Keywords: Induction Motors, Signal Processing, Fault Detection, Spectrogram, Time Frequency Domain

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1. Introduction

An induction motor is one the most popular electric motor drives used in industries. Because the motor is an important mechanism driver in industrial processes, it is so popular because of its high level of reliability, efficiency and safety. However, the motor can suffered from undesirable environments, and wrong application and overloads during operation. Hence it may lead the motor to early-stage failure an increase in server problems or the motor's breakdown which is an important issue causing a stop in all the mechanism processes of line production.

Some researchers have found that failure has often occurred in the motor, and research has shown that 30-40% of all recorded faults occur in the stator or armature faults caused by a short in the stator phase winding and that 5-10% of faults occur in the rotor (a broken bar and/or an end ring fault) [1]. Online condition monitoring is an important technique used to check the health of the motor during its operation during the early stage. The information that we obtained from the technique will be used for maintenance planning so that remedial action can be carried out from the planning to eradicate the machine downtime and to maintain overall plant safety. Signal processing is one of the effective tools used to monitor the motor condition. One of them is called Motor Current Signature Analysis (MCSA) which has been one of the most popular techniques for condition monitoring of the motor for decades. The main reason is that the other techniques require invasive sensor accessing to the motor and they also require extra equipment/sensors for measuring the required signals.

Generally, the MCSA is mostly based on frequency analysis or what is called the spectrum method. Some research studies that have applied the spectrum to stator fault [8]-[12] and rotor fault [2]-[7] where they were generally based on the observation of the side band and the harmonics around main frequencies or its other harmonics. However according to the experiments in this paper, the spectrum method with the FFT function exhibited the ability to distinguish the motor condition, but, the fault severity level could not be observed from the method. This is because the method did not indicate a relationship between spectrum amplitudes and fault severity levels. Additionally, it may also be affected by measurement noise resulting in harmonic components.

Thus from these limitations, this paper proposes a new method based on time frequency analysis called the spectrogram. Some researchers have applied time frequency analysis to fault detection of the motor [13]-[16] which mostly concentrates on mechanical faults such as rotor, bearing, and load faults. The principle was generally based on the observation of image differentiation which makes it difficult to quantify the fault severity. Thus, the proposed method was introduced. The main principle is to transform the colors of graphic plotting results from the time frequency analysis into numbers. The Short-Time Fourier Transform (STFT) was used as a technique and the faults were concentrated: stator short circuit and broken rotor bar. First, the paper introduces the concept of the time frequency analysis or 'spectrogram' and presents the results of the experiments. Finally a brief conclusion is offered.

2. Related Mathematical Theories

2.1 Times-Frequency Analysis

Short-Time Fourier Transform (STFT) or Windowed Fourier Transform can be called the time-dependent Fourier Transform. The STFT is used to analyze only a small section of the signal at a time. If it is assume that x(n) is a signal of data input, the STFT of a signal x(n) is a function of two variables: time and frequency. Thus, the equation of the STFT can be written as follows:

$$X_{STFT}(e^{j\omega}, m) = STFT(x(n) := DTFT(x(n-m)W(n))$$

$$X_{STFT}(e^{j\omega}, m) = \sum_{m=-\infty}^{\infty} x(n-m)W(m)e^{-j\omega m} \quad (1)$$

W(n) is the window function of length R (R = Block length) used to divide a signal X(n) into short sections, n is a variable of time, and ω is a variable of continuous frequency. The block length is determined by the support of window function W (n). A graphical display of the magnitude of the STFT is called the spectrogram of the signal. It shows in z direction on the x-y plane. From Eq. (1), to numerically evaluate the STFT, one sample the frequency axis ω in N equally spaced samples from ω = 0 to ω = 2¶. Thus, Eq. (1) can be rewritten as

$$X_{STFT}(k, n) = XSTFT(e^{j\omega})|_{\omega=2\pi k/n}$$
$$= \sum_{m=-0}^{R-1} X(n-m)W(m)e^{-j\frac{2\pi}{N}km} \quad (2)$$

According to which $0 \leq k \leq N - 1$ when N is the number of point for the DFT (Discrete- Fourier Transform) calculation and W(n) have distance equal to R by which N≥R. One can choose the block length. A long block length will provide a higher frequency resolution (because the main-lobe of the window function will be narrow). A short block length will provide higher time resolution because less averaging across samples is performed for each STFT value.

2.2 Color Transformation Function

The transformation of color indexes is proposed in this paper. The functions are to transform the colors results from the STFT of the stator phase plotting. The equations can be divided into functions for rotor faults and stator faults.

For the rotor fault detection, the function can be expressed here as:

$$CI_{BRK}(f) = TRANS[Color(f_e \pm s)] \quad (3)$$

For the stator fault detection, the function can be expressed here as:

$$CI_{SC}(f) = TRANS[Color(3f_e)] \quad (4)$$

Where f is any specific frequency, f_e is the electrical frequency or main frequency, s is the frequency slip calculated from the mechanical frequency and electrical frequency. Hence Eq. (3) and Eq. (4) are a proposed function of the color index transformation (TRANS)

3. Experimental Verification

The structure of the test rig is shown in Figure 1. The test rig consists of an induction motor (4kW, 1400RPM) with a 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 are divided into 3 different conditions Healthy, Stator Fault (short circuits), and Rotor Faults (broken rotor bars). The load of the motors was set at full load conditions. The data were collected at the sampling frequency of 1280 samples/s. The stator fault motor was adjusted into 3 server level of the short circuits: a 5-turn shot circuit, a 10-turn short circuit, and 15-turn short circuit, while the rotor fault motor was one broken rotor bar.

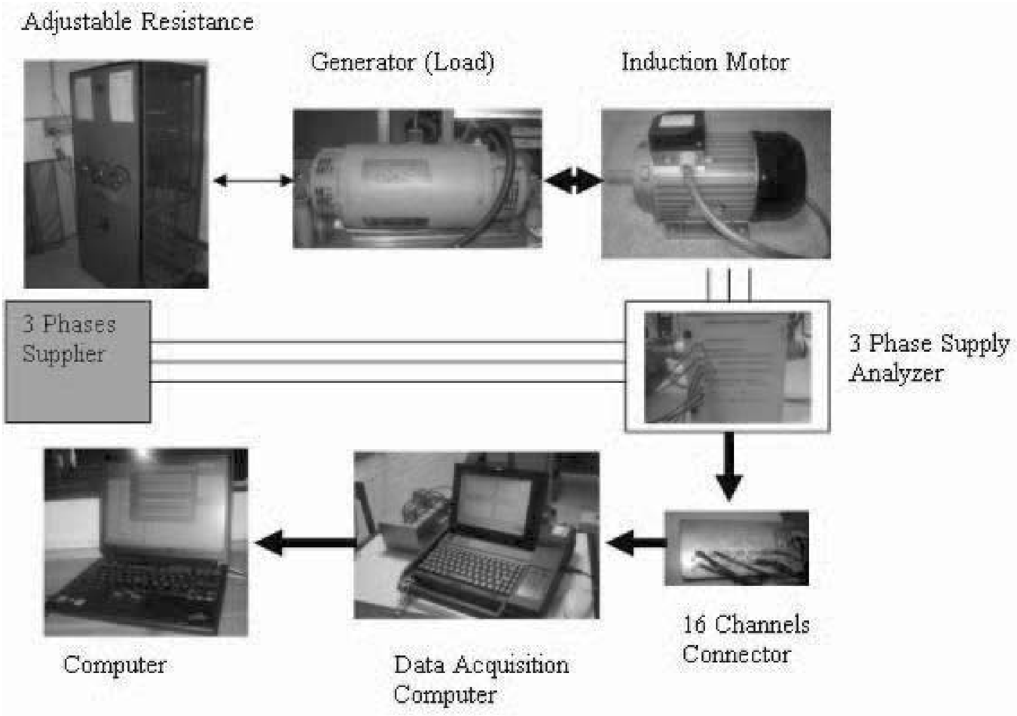

Figure 1 Schematic of the test rig.

4. Results

A typical stator phase current plot for a healthy motor at 100% or full load, as shown in Figure 2. The rated current for the motor was around 10 Amperes. The frequency resolution was kept at 1.25 Hz with 90% overlap and at an average of 82 for all of the signal processing. The computation time using the Pentium-M PC for the method was less than 10 sec. hence it is to differentiate motor conditions which is rather than quick process.

As can be seen in Figure 3-4, the FFT was also been used in this paper. The spectrum of the motor current showed clearly for the motor condition differentiation. The letter 'A' represents the amplitude of each harmonic. The machine's RPM (50 Hz)

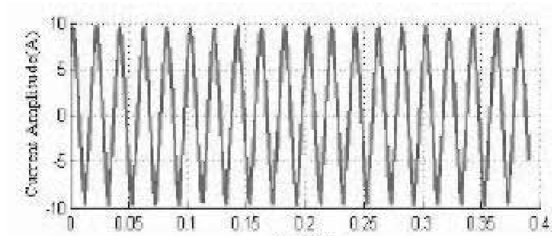

Figure 2 A typical stator phase current plot.

(1x or A2) component and its higher harmonics (2x, 3x,…or A4, A5,…) were present. The harmonics grdw at frequency A1 (x/2) and A3 (3x/2) (sideband of main frequency) when the electric current of the broken rotor bar motor was processed. Thus, it can be concluded that the harmonics at A2 ± s Hz were able to identify the rotor faults by which s was the frequency

A. Frequency Analysis

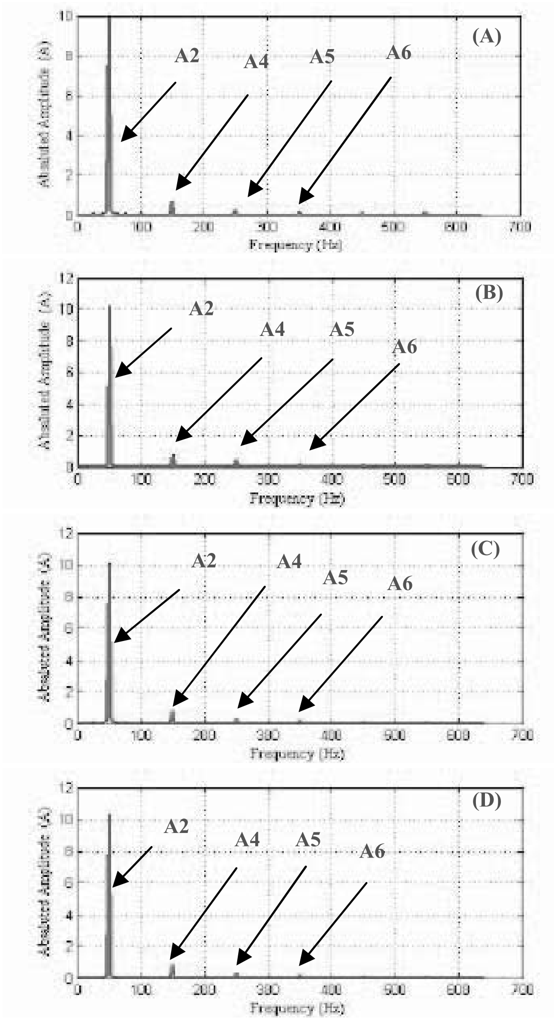

Figure 3 Frequency analysis: (A) Healthy Motor, (B) 5-Turn Short circuit, (C) 10- Turn Short circuit, (D) 15- Turn Short circuit.

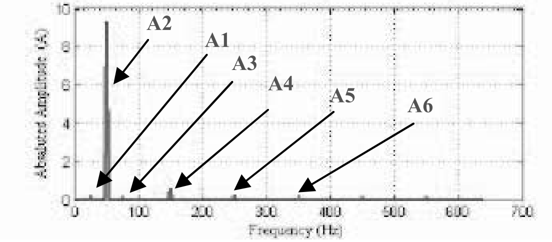

Figure 4 Frequency analysis: Broken Roter Bar.

slip (25%). The electric currents of the stator short turn circuits motor were also processed by the FFT. The results show that the harmonics at frequency A4 increased when the number of short circuit turns happened. The FFT method could identify the faults but the severity level of the faults was not clearly seen. This is because the method did not provide a relation between spectrum amplitudes and fault severity levels. Additionally, it may be affected by measurement noise resulting in the harmonic components.

According to the experiments, the spectrogram of the stator phase currents from the different motor conditions was able to identify the faults as shown in Figure 5-6. The spectrogram plots are indicated by C1, C2, C3 and so on. The spectrogram as plotted in a color shade. The spectrogram plots at frequency C1 = 25 Hz, C2=50 Hz, C3=75 Hz, C4=150 Hz, C5=250 Hz and C6=350 Hz showed different color shades for different motor faults. It can be seen that the color shade at a specific frequency changed when the electric current of the different motor conditions was processed. The spectrogram of the broken rotor bar motor at 25 Hz and 75 Hz exhibited different color shades compared to the result from the healthy condition. Additionally, the spectrogram of the stator short circuit motor at 150 Hz showed different color shades when the number of short circuit turns increased.

Because it is difficult to differentiate the color shades with the naked eye from each condition, it was necessary to transform to numbers. Figure 7 shows the relation between color shade and color index that was used in this paper. The color indexes are set from 1 to 64 following the color shades. The color indexes are transferred from color shades into numbers from Eq. 3 and 4. The result for different conditions and frequencies are shown in Table 1.

B. Time-Frequency Analysis

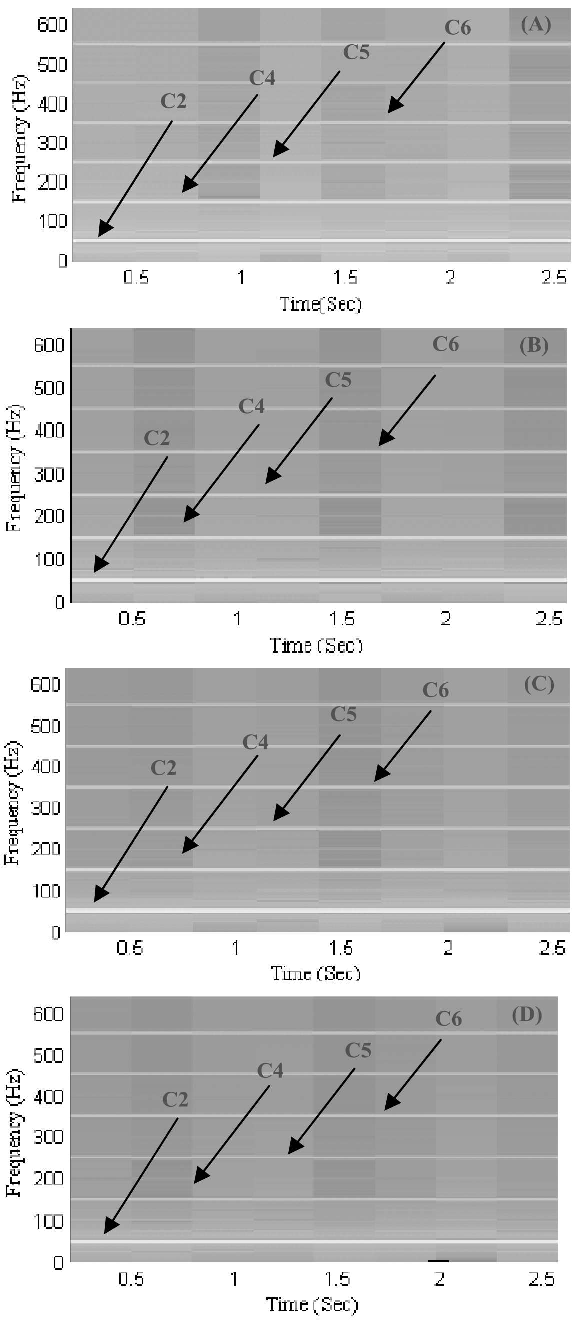

Figure 5 Time-Frequency analysis: (A) Healthy Motor, (B) 5 Turn Short circuit, (C) 10 Turn Short circuit, (D) 15 Turn Short circuit.

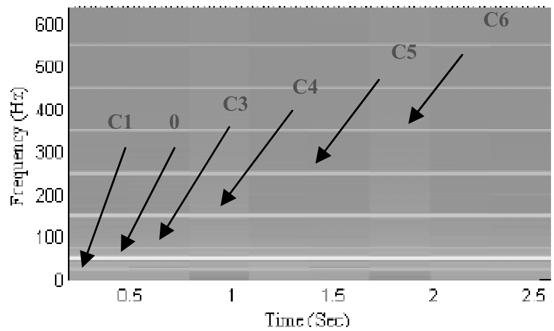

Figure 6 Time-Frequency analysis: Broken Rotor Bar.

Figure 7 Color indexes.

Table 1 Color indexes of different conditions at each frequency

Condition\Color Indexes	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Healthy	40	64	40	56	49	44
5Turn Short	41	64	41	58	48	45
10 Turn Short	41	64	41	59	49	44
15 Turn Short	40	64	40	61	58	43
Broken Rotor	55	64	55	56	47	44

It can be seen that the color indexes at C4 (150 Hz) from the healthy condition to 15 turn short circuit increased when the number of short circuit turn increased. At frequency C1 (25 Hz) and C3 (75 Hz), the color indexes of the broken rotor bar motor increased significantly (almost 1.4 times) when compared with the color indexes of the healthy condition. At the other frequency it seemed to fluctuate which they cannot be applied for fault prediction.

6. Conclusion

Based on the present experiment, the spectrum method using the FFT function had the ability to distinguish the motor condition. However, the fault severity levels seemed to be not clear for measuring. Hence from this limitation, a time-frequency analysis (or spectrogram) of the stator phase curents was proposed. The Short-Time Fourier Transform or STFT was used as a technique for signal processing. The method was expected to show a relation between the phase current signals and the fault levels, which gives it the capability to detect faults and indicate fault levels. The method was tested on different motor conditions (healthy, stator faults and rotor faults) at full load conditions. The results seem to be clear for C1 and C3 in the case of broken bar faults and for C4 in the case of the short turn circuit (stator faults). The changes among the color indexes can be applied to be fault severity levels. Thus, it can be concluded that the proposed method is an effective tool for fault detection and quantification.

References

[1] S. Nandi, H.A. Toliyat, and X. Li, "Condition Monitoring and Fault Diagnosis of Electrical Motors-A Review," *Energy Conversion, IEEE Transactions*, vol. 20, no. 4, pp. 719-729, 2005.

[2] H. Henao, H. Razik, and G.-A. Capolino, "Analytical approach of the stator current frequency harmonics computation for detection of induction machine rotor faults," *IEEE Transactions on Industry Applications*, vol. 41-3, pp. 801-807, May-June 2005.

[3] A. Yazidi, H. Henao, and G.-A. Capolino, "Broken rotor bars fault detection in squirrel cage induction machines." *2005 IEEE International Conference on Electric Machines and Drives*, 15-18 May 2005, pp. 741-747.

[4] A. Bellini, C. Concari, G. Franceschini, E. Lorenzani, C. Tassoni, and A. Toscani, "Thorough Understanding and Experimental Validation of Current Sideband Components in Induction Machines Rotor Monitoring," *32nd Annual IEEE Conference on Industrial Electronics (IECON 2006),* Nov. 2006, pp. 4957-4962.

[5] C. Kral, H. Kapeller, F. Pirker, and G. Pascoli, "Discrimination of Rotor Faults and Low Frequency Load Torque Modulations of Squirrel Cage Induction Machines by means of the Vienna Monitoring Method," *IEEE 36th Power Electronics Specialists Conference 2005 (PESC '05)*, pp. 2861-2866.

[6] C. Kral, T.G. Habetler, R.G. Harley, F. Pirker, G. Pascoli, H. Oberguggenberger, and C.J.M. Fenz, "A comparison of rotor fault detection techniques with respect to the assessment of fault severity," *4th IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives 2003 (SDEMPED 2003)*, 24-26 Aug. 2003, pp. 265-270.

[7] M. Drif and A.J. Marques Cardoso, "Rotor Cage Fault Diagnostics in Three-Phase Induction Motors, by the Instantaneous Non-Active Power Signature Analysis," *IEEE International Symposium on Industrial Electronics 2007 (ISIE 2007)*, 4-7 June 2007, pp. 1050-1055.

[8] R.S. Miranda, H.A.Toliyat, C.B. Jacobina, and A.M.N. Lima, "Short-Circuit Fault Mitigation in Six-Phase Induction Machine Drives," *IEEE Vehicle Power and Propulsion Conference 2007 (VPPC 2007)*, 9-12 Sept. 2007, pp. 370-376.

[9] A.J. Marques Cardoso, M.A. Cruz S, and D.S.B. Fonseca, "Inter-turn stator winding fault diagnosis in three-phase induction motors, by

Park's vector approach," *IEEE Transaction on Energy Conversion*, vol.14-3, pp. 595-598, Sept. 1999.

[10] H. S. Lim, K.T. Chong, and H. Su, "motor fault detection method for vibration signal using FFT residuals," *International journal of Applied Electromagnetics and Mechanics*, vol. 24, pp. 209-223, 2006.

[11] S.M.A. Cruz and A.J.M. Cardoso, "Diagnosis of stator inter-turn short circuits in DTC induction motor drives," *IEEE Transactions on Industry Applications*, vol.40-5, pp.1349-1360, Sept.-Oct. 2004.

[12] A. Siddique, G.S. Yadava, and B. Singh "A review of stator fault monitoring techniques of induction motors," *IEEE Transaction on Energy Conversion*, vol.20-1, pp. 106-114, Mar 2005.

[13] B. Yazici and G.B.Kliman, "An adaptive statistical time-frequency method for detection of broken bars and bearing faults in motors using stator current," *IEEE Transactions on Industry Applications*, vol. 35-2, pp. 442-452.

[14] B. Yazici, G.B. Kliman, W.J. Premerlani,and R.A. Koegl, "An adaptive, on-line, statistical method for bearing fault detection using stator current," *the 1997 IEEE Conference on Industry Applications, 1997*, vol.1, pp. 213-220.

[15] J. Rosero, J. Cusido, A. Garcia Espinosa, J.A. Ortega, and L. Romeral, "Broken Bearings Fault Detection for a Permanent Magnet Synchronous Motor under non-constant working conditions by means of a Joint Time Frequency Analysis," *2007 IEEE International Symposium on Industrial Electronics (ISIE 2007)*, pp. 3415-3419.

[16] S. Rajagopalan, J.A. Restrepo, J.M. Aller, T.G. Habetler, and R.G. Harley, "Nonstationary Motor Fault Detection Using Recent Quadratic Time-Frequency Representations," *IEEE Transactions on Industry Applications*, vol. 44-2, pp. 735-744.