

Fault Quantification of Industrial Electric Motors using Extended Discrete Fourier Transform

Juggrapong Treerong¹

บทคัดย่อ

บทความนี้นำเสนอวิธีการใหม่ของการตรวจจับและการวัดระดับการเสียหายของมอเตอร์ไฟฟ้าแบบเหนี่ยวนำชนิดสามเฟส โดยวิธีที่ใช้ในการตรวจจับคือเทคนิคการประมวลสัญญาณของการแปลงฟูเรียร์กินทนะแบบขยาย กระแสไฟฟ้าของสเตเตอร์ถูกใช้เป็นข้อมูลอินพุตในการประมวลผลของสัญญาณ เพื่อตรวจสอบและการวัดระดับการเสียหายของมอเตอร์ วิธีนี้ได้ถูกทดลองกับมอเตอร์ 3 ชนิดของการเสียหาย คือ มอเตอร์สภาพดี มอเตอร์ที่สเตเตอร์เสีย (ขดลวดเกิดการช็อต) และมอเตอร์ที่โรเตอร์เสีย (บาร์ของโรเตอร์แตก) โดยวิธีการแปลงฟูเรียร์กินทนะแบบขยาย จะใช้ในการแยกความแตกต่างของการเสียหายของมอเตอร์ โดยแสดงความสัมพันธ์ แบ่งออกเป็น 3 รูปแบบคือ สเปกตรัมของกำลัง ความหนาแน่นของสเปกตรัมของกำลัง และความถี่เชิงสัมพันธ์ ซึ่งทั้ง 3 รูปแบบแสดงความสัมพันธ์ของความถี่และแอมพลิจูด จากการทดลองพบว่าวิธีใหม่นี้สามารถแยกสภาพของมอเตอร์ได้อย่างมีประสิทธิภาพ แต่อาจได้รับผลกระทบจากสัญญาณรบกวนจากการวัดบ้าง อย่างไรก็ตามจากการสังเกตการทดลอง วิธีที่นำเสนอใหม่นี้ มีความสามารถสำหรับการตรวจจับและวัดระดับความรุนแรงของการเสียหายของมอเตอร์ด้วยความแม่นยำ

คำสำคัญ: การตรวจสอบสภาพ การตรวจจับความเสียหาย มอเตอร์ไฟฟ้าแบบเหนี่ยวนำ การแปลงฟูเรียร์กินทนะแบบขยาย การประมวลผลของสัญญาณ

Abstract

This paper proposes a new method of fault detection and quantification for induction motors. The method is based on Extended Discrete-Fourier Transform (EDFT). Stator phase currents of 3 phase induction motors are used as inputs. The method is verified on experimental test with 3 different motor conditions: healthy, stator fault, and rotor fault motor at full load condition. The method plots the relation between normalized frequency and absolute amplitude (power spectrum). The plots of power spectrum density and relative frequency resolutions of stator currents are also applied to differentiate the faults. The experimental tests show that the proposed method can differentiate each condition clearly by observing the change in specific harmonics. The method can also show the level of fault

¹ Lecturer, Department of Teacher Training in Mechanical Engineering, Faculty of Technical Education, King Mongkut's University of Technology North Bangkok, Tel. 0-2913-2500 Ext.3248, E-mail: juggrapong@yahoo.com

severities by observing the percent of growth in the harmonics, but the measurement noises may slightly affect the fault differentiation. However, based on observation the proposed method can show ability of fault detection and quantification for this kind of the motor with good accuracy.

Keywords: Condition Monitoring, Fault Detection, Induction Motors, Extended Discrete-Fourier Transform, Extended DFT, Signal Processing

1. Introduction

Induction motors are the most widely used motors among different electric motors because of their high level of reliability, efficiency, reasonable prices and safety. However, these motors are often exposed to hostile environments during operation which leads the motors to early deterioration until the motors breakdown. It has also been observed that 30-40% of all recorded faults are generally related to the stator or armature faults caused due to the shorting of stator phase winding and 5-10% fault related to the rotor (broken bar and/or end ring fault) [1]. Hence the condition monitoring technique has generally been used to detect the fault at the early stage so that the remedial action can be done in much planned way to reduce the machine downtime and to maintain the overall plant safety.

Motor Current Signature Analysis (MCSA) is one of the most spread procedures for health monitoring of the motor since decades. One of the main reasons for using this method is that the other methods require invasive access to the motor and they also need extra equipment/sensors for measuring the required signals. Popularly, the

MCSA is mostly based on frequency domain or frequency analysis. Sometimes it can also be called spectrum method. There are numbers of the research studies that have used the spectrum of the stator phase current signal for the rotor fault [2]-[7] and stator fault [8]-[12], often based on the presence of the side band frequency (related to the slip frequency) and its harmonics around the power supply frequency or/and its harmonics. However, the spectrum method has a limitation for identifying the level of fault severity.

Thus, this paper proposes a new method of motor condition monitoring. The proposed method is expected to differentiate the motor condition clearly and also able to identify the level of the faults severity with high accuracy. Extended Discrete Furrier Transform or EDFT is proposed as a new technique for motor condition differentiation. It is extended from FT 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. 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. 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 can increase frequency resolution. It is well known, that zero-padding does not increase frequency resolution of DFT, 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 EDFT for continuous frequency can be shown as [13]

$$F_x(\omega) = |S(\omega)|^2 X R^{-1} E_\omega, -\Omega \leq \omega \leq \Omega, \quad (1)$$

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

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

where $S_\alpha(\omega)$ is the signal amplitude spectrum, is the power spectrum density, $F_x(\omega)$ is relative frequency resolution at $\omega = \omega_\alpha$. X is data input of a signal. R is a unit matrix. E is Fourier transform basis matrix.

For discrete frequency set $-\Omega \leq 2\pi f_n < \Omega$, $n = 0, 1, 2, \dots, N-1$, The EDFT can be expressed by the following iterative algorithm

$$x = \frac{1}{N} E W^{(i)} E^H, \quad (4)$$

$$F^{(i)} = X R^{-1} E W^{(i)} \quad (5)$$

$$S^{(i)} = \frac{X R^{-1} E}{\text{diag}(E R^{-1} E)} \quad (6)$$

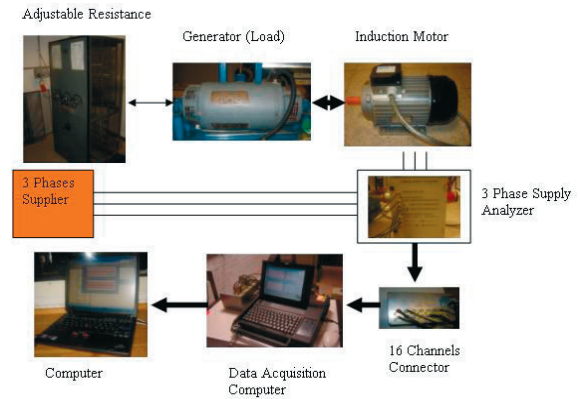


Figure 1 Schematic of the test rig.

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

3. Experimental Verification

The schematic of the test rig is shown in Figure 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 experiments were conducted for these 3 different conditions – Healthy, Stator Fault and Rotor Faults at different load conditions. The data were collected at the sampling frequency of 1280 samples/s. The stator fault was simulated by the short circuits: 5 turn short circuit, 10-turn, short circuit and 15 - turn short circuit whereas the rotor fault is broken rotor bars.

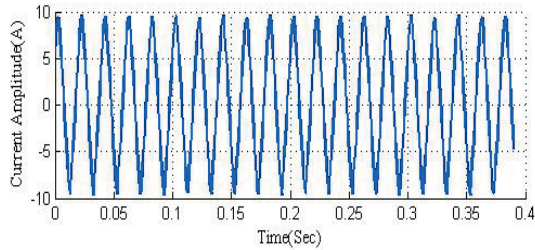


Figure 2 A typical stator phase current plot.

4. Results

A typical stator phase current plot for the healthy motor operating at 100% load is shown in Figure 2. The rated current for the motor is close to 10 Ampere. 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.

The proposed method is the Extended Discrete Furrier Transform or EDFT. 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 $10 \cdot \log[abs(S)^2]$ which S is amplitude spectrum in Ampere unit. The power spectrum density shows relation between normalize frequency and $10 \cdot \log[abs(F)^2/N]$. The relative frequency resolutions shows relation between normalize frequency and $(\frac{F}{S})/K$.

Stator phase currents are processed from 3 different motor conditions: healthy, stator short circuit, broken bar motors. The power spectrum, power spectrum density and relative frequency resolutions

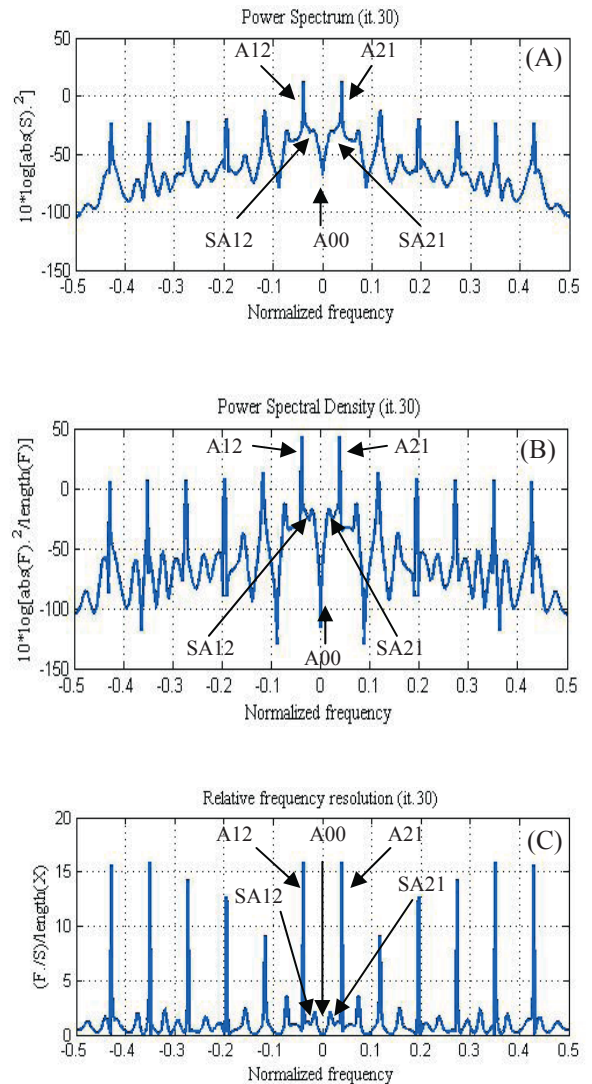


Figure 3 AThe EDFT of stator phase current of healthy motor: (A) Power Spectrum, (B) power Spectrum Density, (C) Relative frequency resolution.

of stator currents from healthy motor condition can be seen in Figure 3 (A-C). Assume that A00 is a harmonic appearing at zero frequency, A12 (=A21) is a couple harmonic appearing around zero frequency and SA12 (=SA21) is one of sidebands of the couple harmonic.

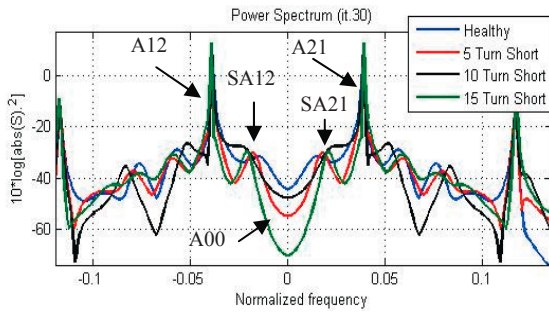


Figure 4 The power spectrum comparison of healthy, 5 turn short, 10 turn short, and 15 turn short.

From the experimental tests of the EDFT in different conditions, the EDFT seems to identify the faults clearly as can be seen in Figures 4 and 5. Figure 4 shows the plotting of power spectrum estimation with healthy condition and 3 different severities of stator faults. The couple harmonic (A12=A21) seems 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 couple harmonic of the rotor faults seems to remain (as can be seen in Table 1). The harmonics (A12=A21) of the power spectrum density and relative frequency resolution for stator faults also increase compared to the healthy condition (As seen in Tables 2 and 3). Figure 5 shows the plotting of spectrum estimation, power spectrum density, and relative frequency resolution. Firstly, the power spectrum estimation (Figure 5-A) 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 of the stator faults seem to remain. The harmonics of the sideband SA12 (=SA21) of power spectrum density and relative frequency resolution (Figure 5-B)

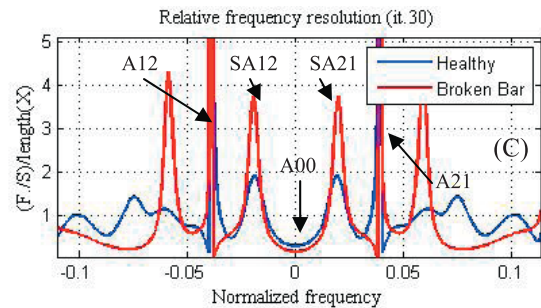
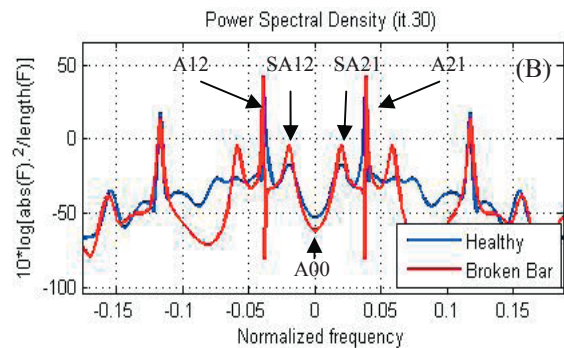
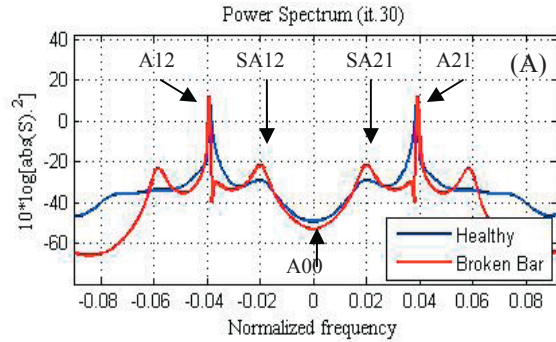


Figure 5 The comparison between healthy and broken bar motor of: (A) power spectrum, (B) power spectrum Density, (C) relative frequency resolution.

and 5-C) 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).

From the Table 1-3, it can be seen that the height of harmonic A12 (=A21) has increased when the

number of short circuit turn increases from healthy condition to 15 turn short circuit. The measured height of sideband SA12 (=SA21) has increased when the broken rotor bar happen. Hence the based on the observation from the experiments, it can be concluded that the EDFT of the phase current signal can identify and distinguish the rotor fault and stator fault of the electric motor. It has also been observed that the growth of the interested harmonics can be used for measuring the level of fault severities.

Table 1 Harmonic height of power spectrum at specific frequency

Condition	A00	A12 =A21	SA12=SA21
healthy	-68.13	12.51	-30.65
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
Broken bar	-59.30	12.43	-10.68

Table 2 Harmonic height of power spectral density at specific frequency

Condition	A00	A12 =A21	SA12=SA21
healthy	-116.01	42.53	-22.31
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
Broken bar	-72.43	42.41	-1.40

Table 3 Harmonic height of Relative frequency resolution at specific frequency

Condition	A00	A12 =A21	SA12=SA21
healthy	0.002	16.50	1.305
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
Broken bar	0.110	16.41	4.600

5. Conclusion

A new method of fault detection for induction motors has been proposed. The method is based on Signal Processing called ‘Extended Discrete Furrier Transform or EDFT’. The method has been tested on 3 different motor conditions (healthy, stator faults and rotor faults) at full load condition. It can be seen that the measured height of harmonic A12 (=A21) has increased when the number of short circuit turn increases from healthy condition to 15 turn short circuit. The measured height of sideband SA12 (=SA21) has increased when the broken rotor bar happen. The experimental tests have shown that the method can differentiate the motor condition clearly and the method can also show the level of the fault severity. The severity level of the faults can be observed the change in the measured height of the harmonics. Thus, it concludes that the proposed method can provide good accuracy of fault detection and quantification. However, the accuracy of the method may be affected by measurement noises. Further modification of the method is planned for future work.

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] R.R. Schoen and T.G. Habetler, “Effects of time-varying loads on rotor fault detection in induction machines,” *Industry Applications, IEEE Transactions*, vol. 31, no.4, pp. 900 – 906, 1995.
- [3] A. Bellini, F. Filippetti, G. Franceschini, C.Tassoni, and G.B. Kliman, “Quantitative evaluation of induction motor broken bars by means of

- electrical signature analysis,' *Industry Applications, IEEE Transactions*, vol. 37, no.5, pp. 1248 – 1255, 2001.
- [4] B. Ayhan, M.Y. Chow, and M.H. Song, "Multiple Signature Processing-Based Fault Detection Schemes for Broken Rotor Bar in Induction Motors," *Energy Conversion, IEEE Transactions*, vol. 20, no.2, pp. 336-343, 2005.
- [5] H. Henao, H. Razik, and G.-A. Capolino, "Analytical approach of the stator current frequency harmonics computation for detection of induction machine rotor faults," *Industry Applications, IEEE Transactions*, vol. 41, no. 3, pp. 801 – 807, 2005.
- [6] G. Didier, E. Ternisien, O. Caspary, and H. Razik, "A new approach to detect broken rotor bars in induction machines by current spectrum analysis," *Mechanical Systems and Signal Processing*, vol. 21, pp. 1127–1142, 2007.
- [7] S.H. Kia, H. Henao, and G.-A. Capolino, "A High-Resolution Frequency Estimation Method for Three-Phase Induction Machine Fault Detection," *Industrial Electronics, IEEE Transactions*, vol. 54, no.4, pp. 2305 – 2314, 2007.
- [8] A.J. Marques Cardoso, S.M.A. Cruz, and D.S.B. Fonseca, "Inter-turn stator winding fault diagnosis in three-phase induction motors' by Park's vector approach," *Energy Conversion, IEEE Transaction*, vol. 14, no. 3, pp. 595 – 598, 1999.
- [9] A. Bellini, F. Filippetti, G. Franceschini, and C. Tassoni, "Closed-loop control impact on the diagnosis of induction motors faults," *Industry Applications, IEEE Transactions*, vol. 36, no.5, pp. 1318 – 1329, 2000.
- [10] R.M. Tallam, T.G. Habetler, and R.G. Harley, "Stator winding turn-fault detection for closed-loop induction motor drives," *Industry Applications, IEEE Transactions*, vol. 39, no.3, pp. 720 – 724, 2003.
- [11] H. Henao, C. Martis, and G.-A. Capolino, "An equivalent internal circuit of the induction machine for advanced spectral analysis," *Industry Applications, IEEE Transactions*, vol. 40, no.3, pp. 726 – 734, 2004.
- [12] G. Aroquiadassou, H. Henao, and G.-A. Capolino, "Experimental Analysis of the dq0 Stator Current Component Spectra of a 42V Fault-Tolerant Six-Phase Induction Machine Drive with Opened Stator Phases," In *IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives (SDEMPED 2007)*, 6-8 Sept. 2007, pp. 52 – 57.
- [13] Vilnis Liepins, "Extended Fourier analysis of signals," PhD dissertation, University of Latvia, 1998.