Application of Signal Processing for Motor Condition Monitoring Based on Filtered-signals and Eliminated-signals

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บทคัดย่อ

บทความนี้นำเสนอวิธีการใหม่ของการตรวจจับการเสียหายของมอเตอร์ไฟฟ้า วิธีการที่นำเสนอใหม่นี้จะใช้สัญญาณที่ถูกกรองแล้วและสัญญาณที่ถูกขจัดทิ้ง ซึ่งโดยทั่วไปแล้วกระแสไฟฟ้าที่บันทึกโดยตรงกับมอเตอร์เริ่มแรกจะขจัดสัญญาณรบกวนทิ้งก่อน ถ้าสมมุติว่าสัญญาณใหม่ที่ได้ถูกเรียกว่า “สัญญาณที่ถูกกรองแล้ว” และสมมุติว่าสัญญาณที่ถูกขจัดทิ้งที่เต็มไปด้วยสัญญาณรบกวนเรียกว่า “สัญญาณที่ถูกขจัด” โดยงานวิจัยนี้ได้เสนอ 2 วิธีในการตรวจจับการเสียหายของมอเตอร์ โดยการนำทั้งสัญญาณที่ถูกกรองแล้วและสัญญาณที่ถูกขจัดมาใช้ โดยวิธีแรกเป็นการนำสัญญาณที่ถูกกรองแล้วมาใช้เพื่อคำนวณหาค่าความชันของความหนาแน่นของสเปตรัม วิธีที่สองเป็นการนำสัญญาณที่ถูกขจัดทิ้งมาใช้สำหรับเพื่อคำนวณหาค่าสเปกตรัมของสัญญาณนี้ ทั้งสองวิธีนี้จะนำวิธีการประมวลผลสัญญาณของการแปลงฟูเรียร์ภินทนะแบบขยายมาใช้ในการวิเคราะห์ งานวิจัยนี้ได้ทำการทดลองกับ 3 ชนิดของสภาพมอเตอร์คือ สภาพดี สภาพที่สเตเตอร์เสีย (ขดลวดลัดวงจร) และสภาพที่โรเตอร์เสีย (โรเตอร์บาร์แตก) จากการทดลองพบว่าวิธีที่นำเสนอทั้งสองนี้ สามารถแยกสภาพของมอเตอร์ได้อย่างแม่นยำ และยังสามารถตรวจสอบระดับความรุนแรงของการเสียหายได้อีกด้วย ดังนั้นทั้งสองวิธีใหม่นี้สามารถที่จะเป็นเครื่องมือที่มีประสิทธิภาพเมื่อนำไปใช้ตรวจจับความเสียหายของมอเตอร์พร้อมกัน

คำสำคัญ: การประมวลผลสัญญาณ การตรวจสภาพมอเตอร์ การตรวจจับการเสียหาย การแปลงฟูเรียร์ภินทนะแบบขยาย สัญญาณที่ปราศจากสัญญาณรบกวน สัญญาณที่ถูกขจัดทิ้ง

Abstract:

This paper proposes new procedures of motor fault detection. The proposed methods are based on filtered-signals and eliminated-signals. Generally, the raw stator phase currents obtained from a motor are initially filtered in order to get rid of disturbing signals. These new signals are called “filtered-signals” and those eliminated from the raw stator phase currents are called “eliminated-signals.” This paper proposes two methods of motor condition monitoring by processing the two types of signals mentioned above. For the first method, the filtered-signals were used to calculate the PSD slope of the spectrum, while in the second, the eliminated-signals were employed to calculate the spectrum itself. Extended DFT was applied to analyze both methods. Three different motor conditions; a healthy motor, a motor with stator fault, and another one with rotor fault were tested. The experiments showed that both methods could differentiate the motor

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conditions accurately. In addition, they could indicate the levels of fault severity. Thus, these two methods could be used simultaneously as an effective tool for monitoring motor faults.

Keywords: Signal Processing, Condition Monitoring, Fault Detection, Extended DFT, Filtered Signals, Eliminated Signals

1. Introduction

An induction motor is the popular electric drives applied in among industry groups 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. So it is a popular motor in the industries. 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.

Some researchers have surveyed the failure that has often occurred in the motor. One of 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. Because the faults (stator or rotor faults) can distort the sinusoidal phase currents and its main frequency, hence the spectrum method has generally been applied for motor fault detection (such as normal spectrum, power spectrum, power spectrum density). Some researchers have applied the spectrum method for stator fault [2]-[8] and the rotor fault [9]-[14] 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 [15]-[17], the spectrum method shows the side band unclearly for motor fault differentiation. It also has a limitation for identifying the level of fault severity.

Thus from the limitation, this paper proposes new methods of motor fault detection. The proposed methods are based on filtered-signal and eliminated-signal. Generally, the raw stator phase currents collected from the motors are firstly filtered in order to get rid of measurement noises. If the new signals are called "Filtered-Signals" and the signals eliminated from the raw stator phase currents are called "Eliminated-Signals" (which they also contain measurement noises), hence this paper proposes methods of motor condition monitoring by processing the both signals (filtered-signals and eliminated-signals). The first proposed procedure is to detect the motor faults by spectrum of PSD slope from the filtered-signals. The second proposed procedure is to detect the motor faults by spectrum of the eliminated-signals. The extended DFT is applied as a technique for signal processing for both methods. Firstly, the paper introduces the concept of the EDFT. The test rig of this experiment and the results are shown. Finally, the conclusion is briefed.

2. Related Mathematical Theories

2.1 Spectrum Based on EDFT

The spectrum is a powerful tool of signal analysis and representation of a time function in the frequency domain. Discrete Fourier Transform (DFT) is one of popular mathematical algorithms applied to represent a time function in frequency domain. It requires an input function that is discrete and produces a discrete frequency domain representation. If a time function which contains the sequence of N complex numbers x(0), x(1), ..., x(N-1) is transformed into a frequency domain which contain the sequence of N complex numbers X(0), X(1), ..., X(N-1). Hence the DFT of a signal can be calculated from

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-j\frac{2\pi}{N}kn} \quad ,k = 0, 1, 2, \ldots, N-1 \quad (1)$$

where j is the imaginary unit, $e^{-j\frac{2\pi}{N}kn}$ is a primitive n^{th} root of unity, x(n) is a time function at time n, and n is represent times by which it is between 0 and N-1

Extended Discrete Fourier Transform (EDFT) has mainly been adopted from DFT in order to use it with a limitation of a signal input. It produces N-point DFT of sequence X (input data) where N is greater than the length of input data. The DFT processes a signal based on using only available data. But the EDFT has been developed to extend frequencies [18]. Hence the EDFT can increase frequency resolution. The EDFT of a signal can be calculated from

$$S(\omega) = \frac{\sum_{n=0}^{N-1} x(nT)\alpha(\omega,nT)}{\sum_{n=0}^{N-1} e^{j\omega nT}\alpha(\omega,nT)} \quad (2)$$

where $S(\omega)$ is the signal amplitude spectrum at frequency ω, $\alpha(\omega, nT)$ is Transform basis functions, N is a discrete sequence length (n=0, 1, 2, …, N-1), and T is sampling period.

2.2 Power Spectrum Density Based on EDFT

The power spectral density (PSD is a positive real function of a frequency variable related to a stationary stochastic process or a deterministic function of time. It is used to describe how the power of a time signal is distributed with frequency. It is also called a frequency-domain plot of power per frequency. The PSD formula can be expressed [18] by

$$PSD(\omega) = |S(\omega)|^2 XR^{-1}E(\omega) \quad (3)$$

where $-\Omega \leq \omega \leq \Omega$, $PSD(\omega)$ is the power spectrum density at frequency ω , $E(\omega)$ is Fourier transform basis matrix, and R is a unit matrix

From the PSD formula, the slope of the PSD can be proposed in the paper by

$$Slope(i) = \frac{\log10(PSD(i+1)/PSD(i))}{\log10(f(i+1)/f(i))} \quad (4)$$

where $PSD(i)$ and $PSD(i+1)$ are PSD values at sequence i and $i+1$ respectively. $f(i)$ and $f(i+1)$ are frequency at sequence i and i+1 respectively,

3. Experimental Verification

The structure of the test rig is shown in Fig. 1. The test rig consists of an induction motor (4kW,

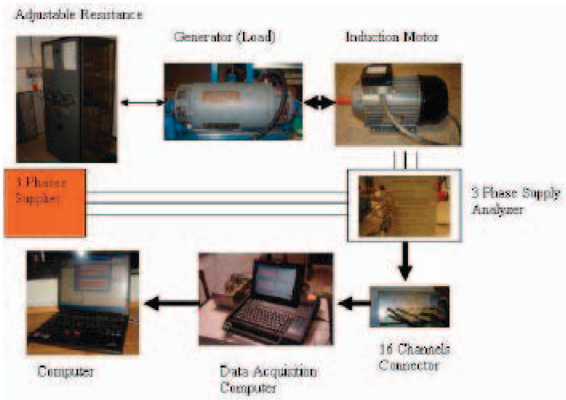

Figure 1 Schematic of the test rig.

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 faults (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 short circuit, 10 turn short circuit and 15 turn short circuit while the rotor fault motor is one broken rotor bar. There are the specifications of the 3 induction motors: 3 phases, 3 kW, 4 HP, 4 Pole, 50 Hz, line voltages 415 Volt.

4. Experimental Results

A typical stator phase current plot for the healthy motor at 100% or full load is shown in Fig. 2. The rated current for the motor is around 10 Amperes. The frequency resolution was kept 1.25Hz with 90% overlap and number of average 82 for all the signal processing.

4.1 Condition Monitoring Based on Spectrum of PSD Slope (Filtered-Signals)

This proposed procedure is the first method of motor condition monitoring by which the filtered-signals are applied to analyze the motor faults. The PSD values firstly are calculated from data of the stator phase currents (filtered-signals) by Eq. 3. The results can be seen in Fig. 3-(A). Then the slopes of the PSD along frequency are calculated by Eq. 4 which the results of the PSD slope can be seen in Fig. 3-(B) (healthy motor). Later the PSD slopes are processed by spectrum method in order to classify the motor faults from Eq. 2. The results of spectrum of the PSD slope can be seen in Fig. 4-(A). Finally, the curves along the amplitudes of PSD slope spectrum are estimated by spline curve which it can be seen in Fig. 4-(B).

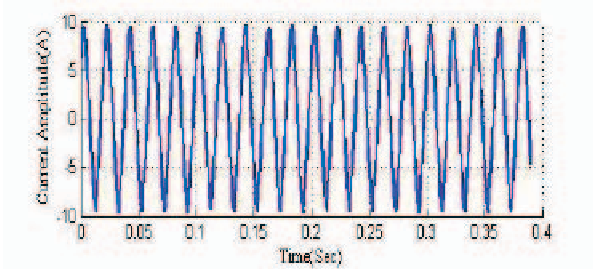

Figure 2 Typical stator phase current plot.

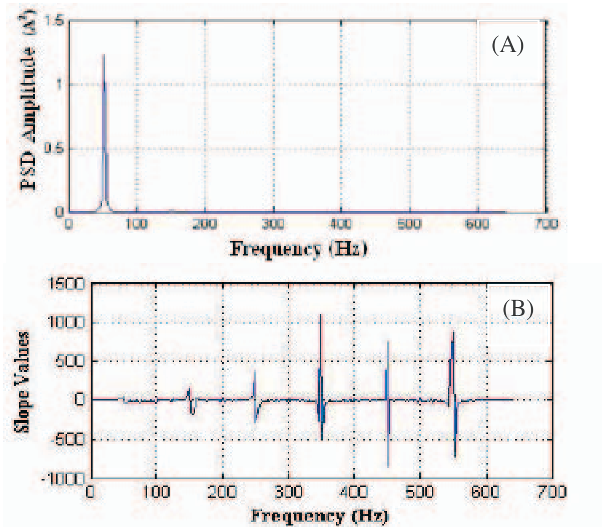

Figure 3 (A) The PSD plotting (healthy motor), (B) The PSD slope (healthy motor).

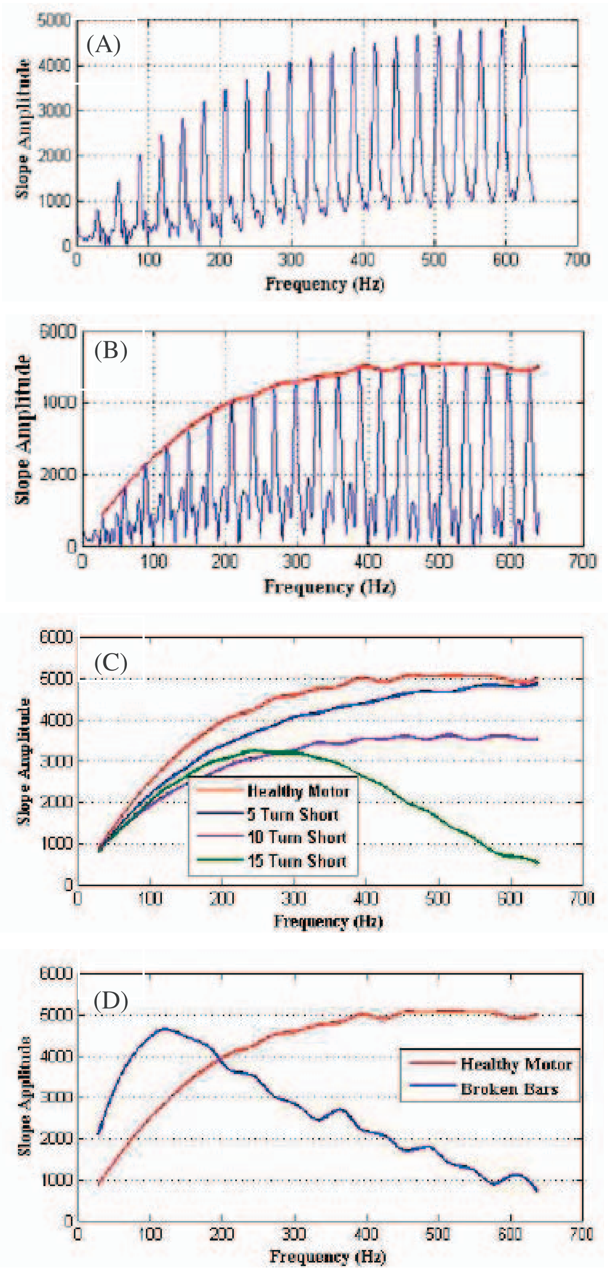

Figure 4 Spectrum of the PSD slope (healthy motor): (A) the PSD slope spectrum, (B) curve estimation of the PSD slope spectrum, (C) estimated curves of healthy and stator short circuits, (D) estimated curves of healthy and broken bar.

Similarly, the stator phase currents from other conditions (stator faults and rotor faults) are processed by the same procedure. Among the estimated curves are used to distinguish the motor faults. The comparison of the estimated curves from different conditions can be seen in Fig. 4-(C) (between healthy and among stator short circuits) and in Fig. 4-(D) (between healthy and broken bars). The computation time using the Pentium-M PC for the method is less than 10 sec. hence it is a method of motor fault detection rather than quick process.

Based on the observation of the experiments, the estimated spline curves provide different shapes among different motor conditions. Thus, the spectrum of the PSD slope can give effective information for motor faults analysis. Additionally, the levels of fault severity can be observed from the change in shape of the estimated spline curves. 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.

4.2 Condition Monitoring Based on Spectrum of Eliminated-Signals

This proposed procedure is the second method of motor condition monitoring by which the eliminated-signals (can be seen in Fig.5-(A)) are applied to analyze the faults. The eliminated-signals are used to be data for spectrum calculation by Eq. 2 which the results can be seen in Fig. 5-(B). Similarly, the eliminated-signals of the stator phase currents from other conditions (stator faults and rotor faults) are processed by the same way. . The comparison of the spectrum from different conditions can be seen in Fig. 5-(C) (between healthy and among stator

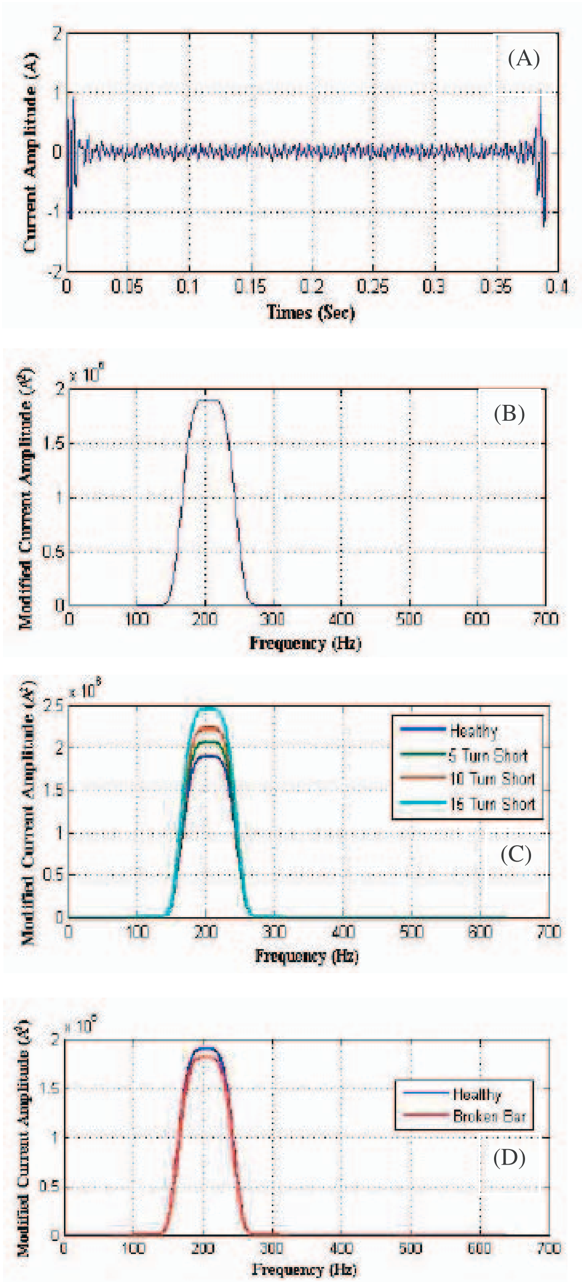

Figure 5 (A) The eliminated signal (healthy), (B) Spectrum of the eliminated signal (healthy), (C) Spectrum of the eliminated signal (healthy, 5 turn short, 10 turn short, 15 turn short), (D) Spectrum of the eliminated signal (healthy, broken bars).

short circuits) and in Fig.5-(D) (between healthy and broken bars). The computation time using the Pentium-M PC for the method is less than 10 sec. Based on the observation of the experiments, the spectrums of the eliminated-signals seem to be able to classify the motor condition. The heights of the spectrum amplitudes have changed when the condition changes. The amplitude heights of each condition can be shown in Table 1. It can be seen that when the numbers of short circuit turns increase, the amplitude height also increases. But when the broken rotor bars happen, the amplitude height decreases. Hence the levels of fault severity can be observed from the change in the amplitude heights of the spectrum.

Table 1 Calculation of modified current amplitude (A^2) from each condition

Conditions	Modified Current Amplitude (A^2)
Healthy Motor	1.82 x106
5 Turns Short Circuit	2.07 x106
10 Turns Short Circuit	2.25 x106
15 Turns Short Circuit	2.47 x106
Broken Rotor Bar	1.76 x106

Unit: Square Ampere (A^2)

Because among the faults happening in the motors can distort the sinusoidal raw currents, hence the eliminated currents which are separated from the raw currents can also contain the distortion. When the eliminated currents are processed by spectrum in order to classify the faults, it can affect the amplitude height. Based on the experiment, the stator and rotor faults can affect the height of the amplitude spectrum. Additionally, the main frequency of the eliminated currents appears at high frequency (200 Hz as seen in Fig. 5-(B), (C) and (D)) but the main frequency of the filtered currents appears at lower frequency (50 Hz as seen in Fig. 3-(A). It is because the raw currents are filtered with high-pass filter. Broadly, the frequency at side-band (25 Hz and 75 Hz) and 150 Hz of the filtered currents is used to reflect rotor faults and stator faults respectively.

From the both proposed procedures, the motor condition can be classified with good accuracy. Additionally, if the both methods are applied simultaneously in each a time of motor fault detection, the accuracy can be improved. However, measurement noises still slightly affect the accuracy of the fault classification.

5. Conclusions

A new procedure of motor fault analysis is proposed. The proposed methods are based on filtered-signals and eliminated-signals. The first proposed procedure is to detect the motor faults by spectrum of PSD slope from the filtered-signals. The second proposed procedure is to detect the motor faults by spectrum of the eliminated-signals. The extended DFT is applied as a key technique for signal processing for both methods. The both methods are tested on 3 different motor conditions: healthy, stator fault, and rotor fault motor at full load condition. Based on the observation of the experiments, the spectrum of the PSD slope can be used to classify some motor faults by observing the change in shape of the estimated spline curves. The spectrums of the eliminated-signals can also be able to differentiate the motor conditions by observing the height of the spectrum amplitude. The both methods can also indicate the level of fault severity. Thus, the both methods can be an effective tool, if they are applied simultaneously for motor fault analysis.

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