การศึกษาการใช้วิธีสเปคตรัมแบบต่าง ๆ ของเอฟเอฟที เพื่อการเพิ่มความแม่นยำในการวิเคราะห์การเสียหายของมอเตอร์

จักรพงศ์ ตรีตรง[1]

บทคัดย่อ

ทั่วไปแล้ววิธีสเปกตรัมโดยใช้วิธีของ FFT เป็นที่นิยมใช้ในการวิเคราะห์ความเสียหายของมอเตอร์โดยใช้กระแสไฟฟ้าเป็นข้อมูลหลัก แต่จากการทดลองพบว่า FFT ไม่สามารถให้การปรากฏของฮาร์มอนิกที่เพียงพอสำหรับการวิเคราะห์การเสียหายของมอเตอร์ ที่เป็นเช่นนี้อาจเป็นเพราะได้รับผลกระทบจากการรั่วไหลเชิงสเปกตรัม ดังนั้นบทความวิจัยนี้นำเสนอวิธีใหม่ของการวิเคราะห์การเสียหายของมอเตอร์ โดยจะใช้ FFT รวมกับซีโรเพดดิ้ง (Zero-padding) และวินโด้อิ่ง (Windowing) เป็นวิธีของการประมวลสัญญาณหลักในงานวิจัยนี้ ความคาดหวังของวิธีที่นำเสนอนี้คือสามารถแสดงการปรากฏขนาดของฮาร์โมนิกที่เพียงพอสำหรับการมองเห็นได้ชัดเพื่อการวิเคราะห์การเสียหาย โดยได้ทำการทดสอบวิธีที่นำเสนอนี้กับ 3 ชนิดการเสียหายของมอเตอร์ คือ สภาพดี สภาพที่สเตเตอร์เสีย (ขดลวดซ๊อต) และสภาพที่โรเตอร์เสีย (โรเตอร์บาร์แตก) จากการทดลองพบว่าวิธีที่นำเสนอนี้ สามารถที่แสดงการปรากฏของฮาร์มอนิกที่มองเห็นได้ อาจเป็นเพราะวิธีนี้สามารถขจัดการรั่วไหลเชิงสเปกตรัมและรวมทั้งวิธีนี้ยังช่วยปรับปรุงผลการพล๊อตของ FFT ได้ละเอียดกว่า ดังนั้นวิธีที่นำเสนอสามารถช่วยเพิ่มความแม่นยำในการวิเคราะห์สภาพของมอเตอร์

คำสำคัญ: การประมวลผลสัญญาณ การตรวจสภาพมอเตอร์ มอเตอร์แบบเหนี่ยวนำ เอฟเอฟทีกับวินโด้วิ่งและซีโร่เพดดิ้ง

[1] อาจารย์ ภาควิชาครุศาสตร์เครื่องกล คณะครุศาสตร์อุตสาหกรรม มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าพระนครเหนือ โทรศัพท์ 0-2555-2000 ต่อ 3248 อีเมล: juggrapong@yahoo.com

รับเมื่อ 29 มีนาคม 2555 ตอบรับเมื่อ 19 กรกฎาคม 2555

The Study of Among Different Spectrums Based FFT for the Accuracy Improvement of Electric Motor Fault Analysis

Juggrapong Treetrong[1]

Abstract

The normal FFT (Fast Fourier Transform) is popularly applied in motor fault analysis, in which stator phase currents are used as data sources. However, based on experiments, the method cannot provide sufficient harmonic appearance for motor fault analysis. This is due to the effects of spectral leakages. Hence, this paper proposes a new method for motor fault analysis. Windowed zero-padded FFT was applied as a signal processing method. The method was based on both the windowing and zero-padding of the signal. The expectation was that the method could provide a more visible harmonic amplitude for the purpose of motor fault analysis. The method was tested on 3 different motor conditions: healthy, stator fault, and rotor fault motors at full load condition. The method can provide more visible harmonic amplitudes than other methods because it can eliminate leakages and provide smoother plotting. Thus, it can help improve the accuracy of motor condition classification and the prediction of fault severity levels.

Keywords: Signal Processing, Fault Analysis, Induction Motors, Windowed Zero-padded FFT

[1] Lecturer, Department of Teacher Training in Mechanical Engineering, Faculty of Technical Education, King Mongkut's University of Technology North Bangkok, Tel. 0-2555-2000 Ext.3248, E-mail: juggrapong@yahoo.com

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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. 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 obtained from the technique will be used for maintenance planning so that the remedial action can be done in such planning to reduce downtime and maintain safety.

Motor Current Signature Analysis (MCSA) is one of the most popular techniques for condition monitoring of the motor since decades. The main reason is that the other techniques generally need invasive sensor accessing to the motor and they also need extra equipment/sensors for measuring the required signals. The MCSA is based on frequency analysis or 'spectrum method'. The normal FFT (Fast Fourier Transform)has popularly been applied for ,motor fault analysis by which stator phase currents are used as data sources, it is because of that the faults (stator or rotor faults) can distort the sinusoidal phase current, its main frequency, sideband frequency and other frequencies. Some researchers have applied the spectrum for stator fault [2]-[6] and the rotor fault [7]-[14] by which the principle was generally based on the observation of the side band, its harmonics around the main frequency.

However from the previous research [13] and experiments in the paper, the spectrum method shows the specific harmonic amplitudes unclearly. Hence the normal FFT cannot provide enough information for fault analysis. It may get some effects of measurement noises or may obtain the effects from some other causes. Spectral leakage may be one important cause for unclear fault analysis.

Spectral leakage generally occurs from collecting a discontinuous data signal and then processes them into a spectrum. This causes frequency spectrum of the signal to be spread out. The spreading means that the signal should be concentrated only at one frequency instead of leaking into all the other frequencies. Hence spectral leakage causes some problems to the spectrum by which its component can contain the cause including among noises from the original signal. These cause result to accumulation of noises in the signal and rise to be severe enough to make other smaller signals disappeared at different frequencies. Thus, the spectral leakage can be main causes of unclearly harmonic amplitude appearance which result to make it difficult to analyze the motor faults.

Hence this paper proposes a method of motor fault analysis. The proposed method is based on Windowed-zero-padded FFT. The method includes windowing and zero-padding of the signal. The expectation is that the method can eliminate the problem which has been said above. The method is expected to provide harmonic amplitudes more visible for the purpose of motor fault analysis. Firstly, the paper introduces the concept of the windowed zero-padded FFT. The test rig of this experiment and the results are shown. Finally, the conclusion is briefed.

2. Windowed Zero-padded FFT

Originally, the FFT is adopted from Discrete Fourier Transform (DFT) by which the DFT uses two loops per a time. Hence if a number of time point is N, it takes N^2 of arithmetical operations. The DFT of a time signal x (n) can be calculated from

$$x(e^{j\omega}) = \sum_{n=0}^{N-1} x(n)e^{-j\omega n} \quad n = 0, 1, 2, \ldots, N-1 \qquad (1)$$

The FFT is developed to be faster algorithm by which uses only N*log(N) arithmetical operations. This makes a big difference for very large N. If a time signal function which contains the sequence of N complex numbers x(0), x(1), ..., x(N-1) is transformed into frequency domain which contain the sequence of k complex numbers and $\omega = 2\pi$. Hence the FFT can be expressed by

$$x(k) = \sum_{n=0}^{N-1} x(n)e^{-j2\pi nk/N} \text{ ,k= 0, 1, 2, \ldots, N-1} \qquad (2)$$

where *x(k)* is a signal in frequency domain. j is the imaginary unit, $e^{-j2\pi nk/N}$ is a primitive n^{th} root of unity. x(n) is a signal in time domain and n represents times by which it is between 0 and N-1

2.1 Zero-Padding

Zero-padding is to increase or interpolate the number of data points of the frequency signal *x(k)*. The zero-padding of the frequency signal can be expressed by

$$x_{ZP}(k) = x(k_a) + \left[x(k_b) - x(k_a)\left(\frac{k - k_a}{k_b - k_a}\right) \right] \qquad (3)$$

where $x_{ZB}(k)$ is a frequency signal with the zero-padded FFT. $x(k_a)$ and $x(k_b)$ are the frequency signal points at frequency k_a and k_b respectively. k is a point of frequencies which want to be interpolated. The zero-padding can be used for increasing a higher resolution in the frequency spectrum.

2.2 Windowing

Windowing is to multiply a frequency signal by a rectangular function or window function. There are some rectangular functions which have been applied: Hanning, Hamming, Poisson, Gaussian, Kaiser-Bessel and so on. The Hanning is applied in the paper. Hence the coefficients (w) or a rectangular function of a Hanning window are computed from [15]

$$w(n) = 0.5(1 - \cos(\frac{2\pi n}{N}))\text{, where } 0 \le n \ge N \qquad (4)$$

Thus, a new frequency signal can be calculated by

$$x_W(k) = \sum_{n=0}^{N-1} \left[x(n)e^{-j2\pi nk/N}.w(n) \right] \qquad (5)$$

Where $x_W(k)$ is a frequency signal from the windowed FFT.

2.3 Windowing Zero-Padding

Windowing zero-padding is the combination between the windowing and zero-padding at same time. The purpose is that it can provide both less effects of the spectral leakage and smother spectrum. The FFT with the windowing zero-padding can be expressed by

$$x_W(k) = \sum_{n=0}^{N-1} \left[x(n)e^{-j2\pi nk/N}.w(n) \right] \qquad (6)$$

$$x_{WZB}(k) = x_W(k_a) + \left[x_W(k_b) - x_W(k_a)\left(\frac{k-k_a}{k_b-k_a}\right) \right] \quad (7)$$

where x_{WZB} is a frequency signal from the windowed zero-padded FFT. $x_w(k_a)$ and $x_w(k_b)$ are the frequency signal points at frequency k_a and k_b respectively. k is a point of frequencies which want to be interpolated.

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 levels of the short circuits - 5 turn shot circuit, 10 turn short circuit and 15 turn short circuit and the rotor fault motor is one broken rotor bar.

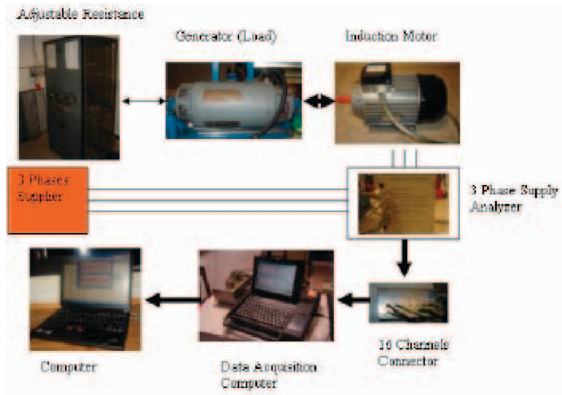

Fig. 1 Schematic of the test rig.

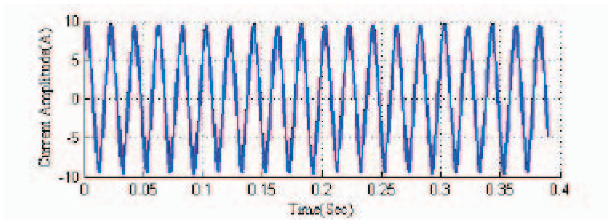

Fig. 2 A typical stator phase current plot.

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 peak 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. The computation time using the Pentium-M PC for the method is less than 10 sec. Hence it is a fault analysis method rather than quick process.

There are four methods which will be applied to analyze the motor faults: normal FFT, zero-padded FFT, windowed FFT and windowed zero-padded FFT.

4.1 Normal FFT

Firstly, the normal FFT (Eq. 2) is applied to analyze the faults by which the stator phase currents from different conditions are used as input data. The spectra of the normal FFT seem to be unable to classify the motor condition clearly (as can be seen in Fig. 3). The highest harmonic amplitude shows the main frequency at 50 Hz. The sideband (25 Hz and 75 Hz) of the main frequency seems to be disappeared by which generally is used to provide information for analyzing the fault in rotor bars. However, the harmonic amplitude at frequency 150 Hz seems to be visible by which generally is used to analyze the fault in stator windings. The measurement of the harmonic amplitudes by the normal FFT can be summarized in Table 1.

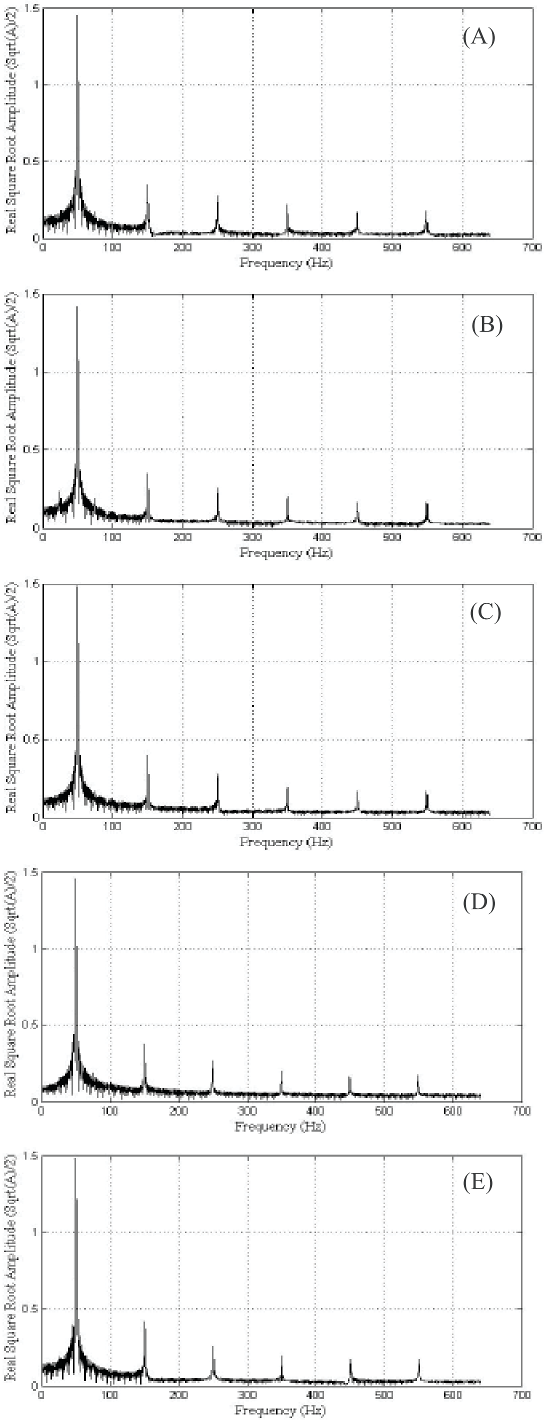

Fig. 3 Normal FFT of the stator phase currents: (A) healthy, (B) broken bars, (C) 5 turn short, (D) 10 turn short, and (E) 15 turn short.

Table 1 Harmonic amplitude measurement of among the FFT

Algorithm/ Conditions	healthy	Broken bars	5 turn short	10 turn short	15 turn short
A11					
Normal FFT	1.441	1.414	1.450	1.456	1.482
Zero-padded FFT	1.467	1.414	1.481	1.474	1.487
Windowed FFT	1.461	1.415	1.482	1.468	1.487
Windowed Zero-padded FFT	1.467	1.415	1.482	1.475	1.489
A12 (A21)					
Normal FFT	0.155	0.230	0.185	0.156	0.187
Zero-padded FFT	0.190	0.240	0.172	0.166	0.187
Windowed FFT	0.123	0.210	0.121	0.140	0.124
Windowed Zero-padded FFT	0.124	0.211	0.121	0.140	0.124
A13					
Normal FFT	0.347	0.350	0.352	0.376	0.417
Zero-padded FFT	0.391	0.355	0.404	0.418	0.429
Windowed FFT	0.374	0.357	0.401	0.403	0.426
Windowed Zero-padded FFT	0.390	0.358	0.406	0.418	0.431

Unit: Square root amplitude divided by two $(\frac{A^{1/2}}{2})$

4.2 Zero-Padded FFT

Secondly, the FFT with zero-padding (Eq.3) is applied to analyze the faults as can be seen in Fig. 4-B. Generally, the zero-padding used to increase the number of data points by the principle of interpolation. Hence the spectrum will be improved with more data after the interpolation which it help spectrum curves

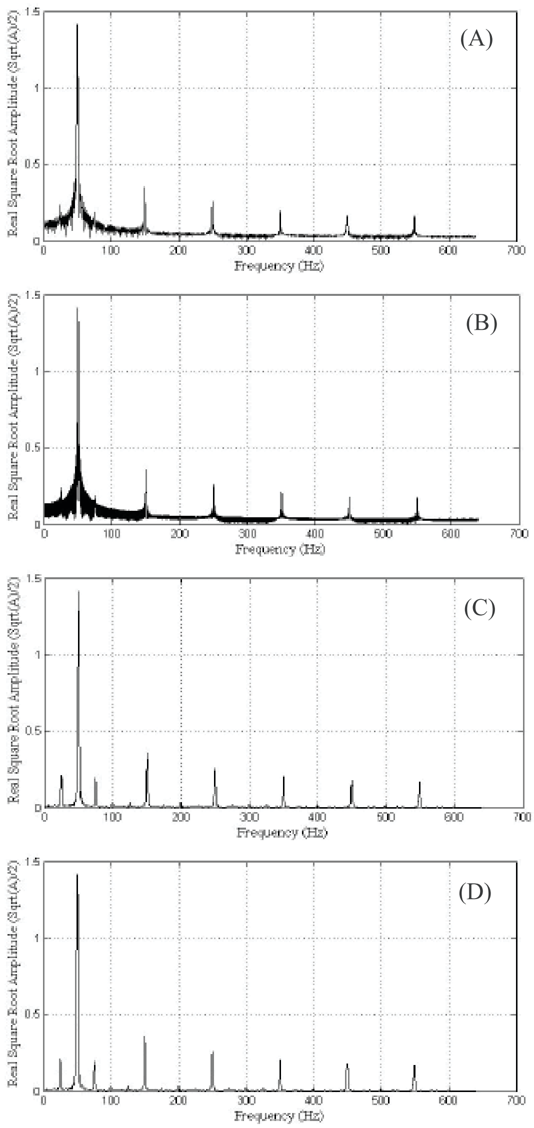

Fig. 4 Among the FFTs of the stator phase currents from broken bar fault: (A) normal FFT, (B) zero-padded FFT, (C) windowed FFT, and (D) windowed zero-padded FFT.

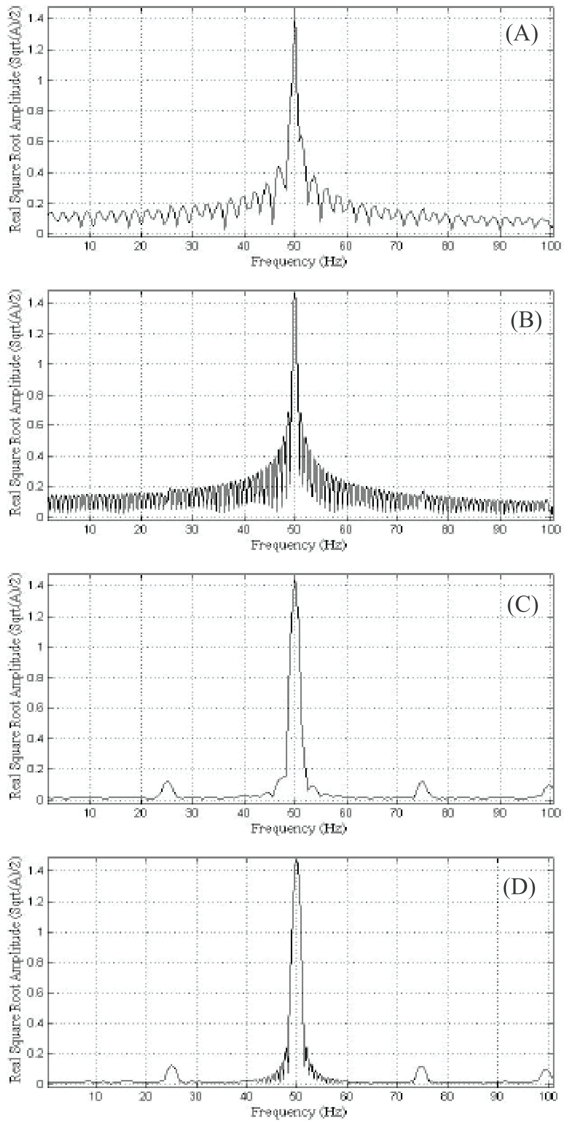

Fig. 5 Zooming plots at main frequency (healthy motor): (A) normal FFT, (B) zero-padded FFT, (C) windowed FFT, and (D) windowed zero-padded FFT.

look smoother (as can be seen in Fig. 5). It can be seen that the spectrum is plotted with more data points. However, the zero-padding cannot help to make small harmonic amplitude more visible. The measurement of the harmonic amplitudes by the FFT with zero-padding can be summarized in Table 1.

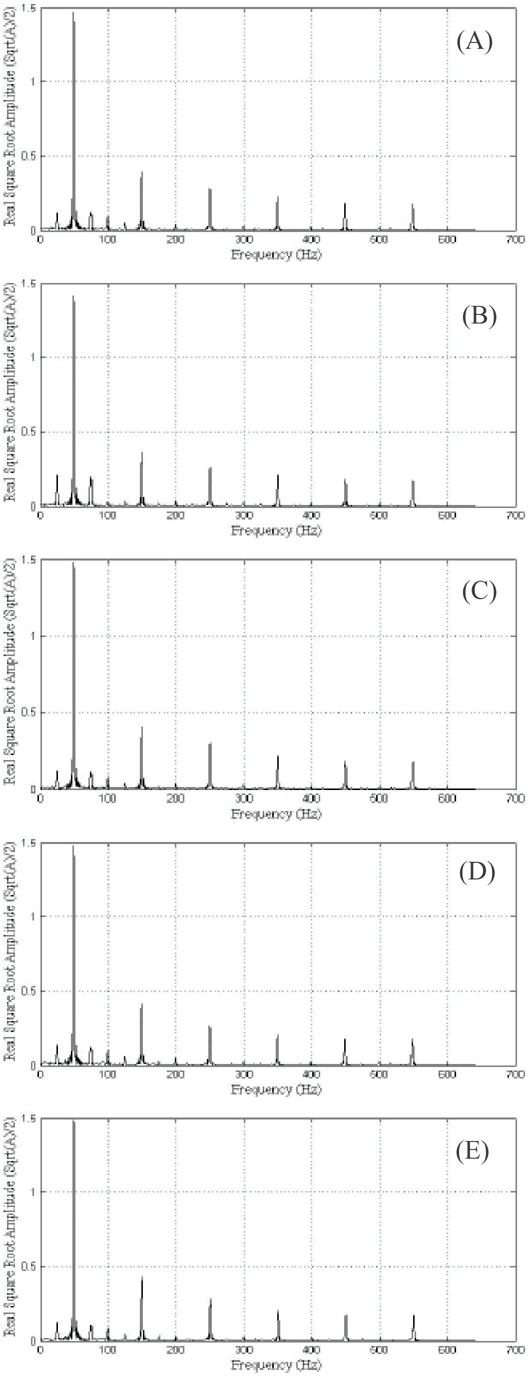

Fig. 6 Windowed zero-padded FFT of the stator phase currents: (A) healthy, (B) broken bars, (C) 5 turn short, (D) 10 turn short, and (E) 15 turn short.

4.3 Windowed FFT

Later, the FFT with windowing (Eq. 5) is applied to apply to analyze the m motor faults as can be seen in Fig. 4-C. It can be seen that the windowing can help the small harmonic amplitudes appear clearly. It is because the spectral leakage which has often made the small amplitude disappeared is eliminated from the spectrum. The sideband and other small ammonic amplitudes can be seen clearly. Hence it can conclude that the windowing is an important tool for getting rid of the spectral leakage. The measurement of the harmonic amplitudes by FFT with windowing can be summarized in Table 1.

4.4 Windowed and Zero-Padded FFT

Finally, the FFT with both zero-padding and windowing (Eq. 6 and Eq. 7) is applied to apply to analyze the motor faults as can be seen in Fig. 4-D for only broken bar conditions and Fig. 6 for all conditions. The method can show among the harmonic amplitude along the frequencies clearly. The method is added with the zero-padding in order to provide the spectrum look better when it is compared to the above method. Fig. 5 is showing the development of spectrum quality: (A) normal FFT, (B) zero-padded FFT, (C) windowed FFT, (D) windowed zero-padded FFT. Based on observation, the FFT with the zero-padding and windowing can provide the most visible spectrum. Hence the windowed zero-padded FFT can be an effective tool for the purpose of motor fault analysis. The measurement of the harmonic amplitudes by the FFT with both the zero-padding and windowing can be summarized in Table 1.

Table 1 is showing the measurement of

the harmonic amplitudes among the different methods. Assuming that A11 is an harmonic at a main frequency 50Hz, A12 and A21 are harmonics at frequencies 25Hz and 75 Hz, A13 is an harmonic at frequencies 150 Hz. Firstly, it is important to notice that the small harmonic amplitudes (such as A12 or A12) from the normal FFT and the zero-padded FFT seem to be higher than the amplitudes from other methods, because it may get the effect of the spectral leakages which is contained in the spectra. This behavior looks similar in all different conditions of the small harmonic amplitudes. Then when the windowing has been applied such as windowed FFT and windowed zero-padded FFT, the small harmonic amplitudes seem to be slightly decreased. It is because the windowing needs to eliminate some effects of the spectral leakages in order to makethe small harmonic amplitude more visible. However in case of big harmonic amplitudes, the spectral leakages do not affect to the height of the amplitudes. Hence the windowing makes the FFT more effective for motor fault analysis. Finally, it is important to notice that, the change in among harmonic amplitudes can be used to classify motor conations. For example, the sideband amplitude of the main frequency at 25 Hz and 50 Hz can be applied for rotor fault diagnosis and a amplitude at frequency 150 Hz can be applied for stator fault diagnosisby which the change of the amplitude at such frequencies can be seen in Table 1.

5. Conclusions

A method of motor fault analysis is proposed. The proposed method is based on windowed zero-padded FFT. Popularly, the normal FFT has been applied for motor fault analysis, but based on experiments, the normal FFT cannot provide enough harmonic appearance for fault analysis. It is because of the spectrum may obtain the effects of spectral leakages. Hence this paper proposes a method for motor fault analysis. The method applies windowed zero-padded FFT in order to get rid of the effect of the spectral leakages. Based on the experiments, the method can provide more visible harmonic amplitudes than other methods, because it can eliminate the leakages and provide smoother spectrum. Thus, it can help to improve an accuracy of motor fault analysis and fault level indication.

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