Abstract— Early detection of incipient fault is highly necessary for condition assessment, predictive maintenance and reliability operation of induction motors. For this task, motor current signature analysis based on frequency characteristic is well-utilized to detect indicators of permanently short circuit condition. This paper characterizes the current behavior of induction motor under temporary short circuit located in stator winding using wavelet transform. The non periodic, very short duration and high impedance short circuit currents in induction motor can be effectively identified using magnitude and energy of high frequency signal based wavelet transform.

Index Terms— early detection, induction motor, temporary fault, wavelet transform.

I. INTRODUCTION

INDUCTION motors are widely used in industrial processes because of their mechanical robustness, reliability, cost efficiency and safety. They are the workhorse components in many industrial processes. As their heavy duties increase, they are often exposed to hostile environments that lead to early deterioration in motor failure. Therefore, maintenance strategy is needed to avoid higher loss of industrial production caused by motor breakdown. During the last decade, there have been many interests in early fault detection and diagnosis techniques using condition-based maintenance (CBM). CBM program replaces or extends the periods of predictive maintenance (PM) which are regularly scheduled off-line test and replaced based on previous record or estimated machine failure. CBM provides better utilization of equipment and components that promote to considerable reduction of downtime and maintenance costs [1]. However, this conventional method is supposed to be on-line, reliable and suitable to detect symptom of faults.

Approximately 30% of all motor faults are caused by failure of motor winding due to insulation problems. The majority of induction motor winding failure is gradually from lower short circuit current to higher level and finally broken. The short circuit current is characterized starting from very short duration, low intensity and non periodical. Under such conditions, motor is still probably running in nominal speed and torque. If the problem persists, short circuit current level become longer, high, frequently and even permanently. At this time, motor temperature will increase drastically until the motor stop running.

On line fault detection and monitoring of induction motor is widely known. The most common method for characterization of fault is using motor current called motor current signature analysis (MCSA). In this method, frequency base analysis is utilized. Also, the rms values of normalized harmonics current by wavelet transform is used as detection variables. This method is able to accurately detect inter-turn winding short circuit within 2 seconds duration [1]. On the other hand, the variant of MCSA denoted bispectrum which represents both amplitude and phase number of harmonics current signal analysis is used to detect the faults. This method is effectively used to detect some faults phenomena that cannot be detected by conventional MCSA [2]. Another method is the induction motor fault detection based on time analysis. In this method, vibration signal of induction motor is processed by wavelet transform. Then, energy of signal extracted from wavelet transform is used as identification variable. Several fault cases located in gear-set platform can be detected using this method [3]. The most recent identification method is the combination of several wavelets types with pattern classification technique of support vector machine (SVM), called Haar wavelet [4]. This method had already been implemented and distinctively known as the best performance of induction motor fault detection. Some laboratory experiments were performed to simulate the temporary fault in stator winding using Haar wavelet transform. The result shows that the method is effective and able to detect the fault [5].

In this research, the temporary short circuit condition in stator winding of induction motor is investigated. The problems are characterized as follows:

1) They have short time transient period, current spike includes the starting and ending points of short circuit.
2) They are not permanent which means that the short circuit condition occur in short time then disappear.
3) They are not periodic which indicates the short circuit does not always occur at fix time period.
4) They have high impedance which suggests the short circuit current level less than 300% of rated motor.

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These fault specifications are necessary to define in order to represent the initial condition of induction motor winding failure. Based on these characteristics, the wavelet transform is applied for the identification process. Finally, this method is then compared with the fast Fourier transform (FFT) method based fault identification.

II. METHODOLOGY

In recent years, there are many significant proposed methods dealt with induction motor fault identification method. However, only few researchers have investigated the temporary fault detection [1], [5]. For temporary fault detection, it is necessary to have information, such as the timing when the fault starts, the level or magnitude of the fault current and the fault duration. The information are beneficially considered when examining the induction motor design related to environmental installation, operating time, guarantee and lifetime. In this paper, several cases of temporary fault are performed by laboratory experiment. For this purpose, the current characteristics of induction motor are divided into four types as follows:

- type-1 : normal current
- type-2 : short time temporary fault
- type-3 : starting point of temporary fault
- type-4 : ending point of temporary fault

All these temporary fault characteristics can be represented in one single type. This is the advantage of wavelet transform as the signal processing method because it has the ability to quantify different types of non-stationary signal. FFT analysis only gives a global representation of frequency of the signal, while wavelet transform can provide both frequency and time representation [6]. Therefore, the exact time during faults can be recorded using wavelet method. In case of induction motor fault detection, the standard methods based on FFT techniques are failed to detect motor failures or damages under either variable load or variable speed because the frequencies around the base frequency are not very clear [7].

In this case, the magnitude and energy of high frequency signal extracted from wavelet transform is used to distinguish the fault phenomena. Haar wavelet is selected for this task because it has simpler calculation, easier implementation and better performance than other wavelet types [4].

III. DISCRETE WAVELET TRANSFORM

The discrete wavelet transform (DWT) is a technique for analyzing signals. It was developed as an alternative method to the short time Fourier transform (STFT) for solving problems related to frequency and time resolution properties. Unlike the STFT that provides uniform time resolution for all frequencies, the DWT provides high time resolution and low frequency resolution for high frequencies and high frequency resolution and low time resolution under low frequencies. Wavelet transform acts basically similar to high pass filter and low pass filter in producing high and low frequency signals. The wavelet transform calculation of signal \(x(k)\) is defined as follows:

\[
W(j, k) = \sum_{j} \sum_{k} x(k)2^{-j/2} \psi(2^{-j} n - k)
\]

(1)

where \(\psi(t)\) is the time function with finite energy and fast decay, called the mother wavelet with scale and sifted by \(j\) and \(k\) respectively. The DWT analysis can be performed using a fast, pyramidal algorithm related to multi rate filter banks.

As a multi rate filter bank the DWT can be viewed as a constant filter bank with octave spacing between the centers of the filters. Each sub band contains half the samples of the neighboring higher frequency sub band. In the pyramidal algorithm, the signal is analyzed at different frequency bands with different resolution by decomposing the signal into a coarse approximation and detail information. The coarse approximation is then further decomposed using the same wavelet decomposition step. The process is achieved by successive high pass and low pass filtering of the time domain signal and is defined by the following equations:

\[
y_{\text{high}}[k] = \sum_{n=1}^{n=k} x[n]g[2k - n]
\]

(2)

\[
y_{\text{low}}[k] = \sum_{n=1}^{n=k} x[n]h[2k - n]
\]

(3)

where \(y_{\text{high}}[k], y_{\text{low}}[k]\) are the outputs of the high pass \((g)\) and low pass \((h)\) filters, respectively after sub sampling by 2.

Because of the down sampling the number of resulting wavelet coefficients is exactly the same as the number of input points [8].

In this paper, the magnitude of high frequency signal is obtained from the absolute value in (2). Meanwhile, the energy of high frequency signal is calculated as follows:

\[
e = \sum_{n=1}^{n=k} \left| y_{\text{high}}[n]\right|^2
\]

(4)

![Fig.1. Experimental set up](image-url)
a. Current signal type-1; normal operation

b. Current signal type-2; very short duration, short circuit at 25% winding, impedance 37 Ohm

c. Current signal type-3; starting point, short circuit 75% winding, impedance 37 Ohm

d. Current signal type-4; end point of short circuit, 75% winding, impedance 24 Ohm

e. High frequency signal type-1

f. High frequency signal type-2

g. High frequency signal type-3

h. High frequency signal type-4

Fig. 2: Current signal characterization where the dashed line indicates the normal current.
Fig. 3: FFT spectrum of current signal.

IV. EXPERIMENTAL SETUP

The experimental setup as shown in Fig. 1 includes a 0.25 hp, 1400 rpm, 220 volt, 50 Hz induction motor. Short circuit is performed by connecting input terminal (reference point) to 25%, 50%, 75% and 100% of total winding. The approaches are to simulate the short circuit condition in stator winding. Variable resistor which is series connected to short circuit switch represent short circuit impedance. Combinations of location and impedance are considered as the short circuit scenarios. For each scenario, the motor current is captured by a monitoring system which has 50kHz sampling frequency.

V. EXPERIMENTAL RESULTS

Several cases of temporary short circuit are performed to investigate the current signal patterns. The type results of motor current are shown in Fig. 2. Again, the motor current patterns are classified into four types. Type-1 is the normal operation; type-2 is the pattern of very short duration of short circuit, called spike. Type-3 is the starting time of short circuit. In this type, the trend of current signal is similar to normal condition, then start changing when the short circuit begins. The last one is the type-4 which represents the ending of short circuit. In this case, the signal pattern is opposite to the pattern of type-3. At the ending point of short circuit, the signal pattern starts to follow the normal operation. Different type cases are summarized in Table I.

VI. ANALYSIS AND DISCUSSION

This part provides measurement implications under several testing scenarios. Under normal operation, designated as type-1, the current signal is ideally sinusoid. The high frequency signal of wavelet transform is calculated in (3). The results show that the signal magnitudes reach less than 0.055 and the energy is relatively constant between 0.101 and 0.144. On the other hand, type-2, -3 and -4 are the motor current patterns under short circuit condition. Under these condition, the value of current is changed in short duration and there is rapid change of current signal contributes to increasing high frequency magnitude of wavelet transform. The characteristic is totally different compared with motor under load changing where the progress of current changes is slow [9].

Type-2 of motor current is characterized as spike. In this case, the current increases to certain point then decreases rapidly which results in high values of high frequency signal. Fig. 2f shows that when temporary fault occurs, the high frequency signal is much higher than that of non-fault period. The energy of the signal is linear to number of higher values and calculated in (4). For example, in the cases no. 13 and 14 as shown in Table I, they have similar energy values but not their magnitudes. On the other hand, the case no. 9 has more spikes even it has higher magnitude value than the case no. 8.

480
<table>
<thead>
<tr>
<th>Case Number</th>
<th>Current Pattern Type</th>
<th>Operation Condition</th>
<th>Fault Resistance (Ω)</th>
<th>Magnitude (Ampere)</th>
<th>Energy</th>
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<td>Normal</td>
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<tr>
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<td>-</td>
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<td>0.101</td>
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<td>-</td>
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<tr>
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<td>Normal</td>
<td>-</td>
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<tr>
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<td>-</td>
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<td>0.134</td>
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<td>7</td>
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<tr>
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<td>2.928</td>
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<tr>
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<tr>
<td>14</td>
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<tr>
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<tr>
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<td>31</td>
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<td>3</td>
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<td>0.083</td>
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<td>0.122</td>
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<tr>
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<td>0.055</td>
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</tbody>
</table>

Similar behaviors are shown in type-3 and -4 patterns. Transient phenomena is detected using high frequency signal analysis when short circuit is just starting or ending. As shown in Fig. 2e, the highest value of high frequency is achieved at the beginning of short circuit and the condition of highly dense values of fault transient. A similar case also occurs in type-4. Sharp transient phenomena means shorter time to reach highest value which results higher value of high frequency magnitude. Conversely, the shorter time of transient phenomena, it reduces the magnitude of high frequency values which suggests the decreasing in energy of high frequency signal. In case type-3 and 4, the transient phenomenon is occur in one side; starting or ending point of short circuit. This condition is totally different from type-2 that occur both sides. As a result, the energy measurement of type-2 is relatively higher than the type-3 and 4.

Current analysis using FFT is provided in Fig.3. It is shown that frequency contents between type-1 and type-2 in Fig. 3a and Fig.3b are equal, although the magnitude of spike fault is greater than normal. Meanwhile, for type-3 and 4 in Fig. 3c and 3d, the side band frequency is sight out at band frequency between 0-25Hz and 80-110Hz. These results imply that spike fault is not well detected because the frequency content is pretty similar to the normal one. The FFT method can detect the starting or ending fault if the observation is focused on side band frequency. For these reasons, the wavelet analysis is more clearly than FFT to identify the spike and is simply able to provide the timing information of fault occurrence.
The only thing that needs be concerned in using wavelet method is to more closely observe the magnitude and energy of type-3 and -4. The zooming results from Table I are presented in Fig. 4. Plot of magnitude and energy level of these fault condition is almost similar to the normal condition (see Fig. 4e). However, basically it is only few cases in this respect and the possibility this occurrence is small. Nevertheless, this trend will be investigated more detail in the future study.

VII. CONCLUSION

This paper has characterized the temporary short circuit in induction motor using discrete wavelet transform. Laboratory experiment is performed to simulate several cases of temporary short circuit. Four type motor currents related to temporary short circuits are defined as normal, very short time, short circuit at the starting point and the ending point. Wavelet transform is utilized to obtain the high frequency signal current. The characteristic of each type is measured by the values of magnitude and energy of the signal. From theses values, it is easy to distinguish between normal operation and fault condition. The temporary fault itself is divided into two characteristics as spike and border of short circuit. Spike short circuit is identified within very short duration of short circuit, while the border of short circuit includes the starting point and ending point of short circuit. The duration of latest type is longer than the previous one. However, their magnitude and energy values are relatively lower. The relative term in this study means that there are 3 of 33 inconsistence cases against the common trends. This might be affected from the transient duration, magnitude and sampling time. Further study is intensively needed to investigate this kind of inconsistency.

REFERENCES