An Unbalance Component Technique for Induction Motor Fault Detection

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Abstract— Although many fault detection techniques have been proposed in literature for induction motor (IM) condition monitoring, reliable IM fault detection still remains a challenging task especially in real industrial applications. An unbalance component analysis (UCA) technique is developed in this paper to extract representative features from line currents for fault detection in IMs. The UCA is composed of two processing procedures: closed loop current analysis and spectrum aggregation. A closed loop current analysis approach is proposed to reduce balanced components in each phase, and reveal the fault features due to unbalance. A spectrum aggregation method is suggested to integrate the fault features among three phases for broken rotor bars and bearing fault detection. The effectiveness of the developed UCA technique is verified by experiments corresponding to IMs with broken rotor bars and the bearing defect.

Index Term— Induction motors, fault detection, rolling element bearings, broken rotor bars, symmetrical component analysis.

I. INTRODUCTION

INDUCTION motors (IMs) are extensively used in various industrial applications such as manufacturing, transportation and mining. A reliable condition monitoring system is very useful in industries to detect IM fault at its earliest stage to improve operation efficiency and reduce maintenance cost for both IMs and the driven machines. R&D activities have been directed, for decades, for IM fault detection, and many techniques have been proposed in literature in this field. Nevertheless each of these techniques has its own strength and limitations, and could be used for specific monitoring applications only [1]. Reliable condition monitoring still remains a challenging task to improve the performance and efficiency of IMs [2].

IM fault detection can be undertaken based on the analysis of information in the form of temperature, acoustic signal, vibration, and current. Although the local or bulk temperature could be used to diagnose some of IM defects [3], the heat accumulation and progression are usually slow, which may not be suitable for incipient fault detection. The acoustic noise could indicate some IM faults [4], such as severe and distributed defects; however the acoustic signal is prone to contamination by background noise, which results in low signal-to-noise ratio. Although vibration signals have relatively high signal-to-noise ratio [5,6], accelerometers have high installation requirements, which are difficult to reach in IM structures; in addition, it is difficult to use vibration signals to detect IM electrical defects such as broken rotor bars. The alternative is to use the line current signal for analysis, which is non-invasive to the IM structure [7], and could be used to detect both mechanical and electrical IM faults. Thus this research will focus on IM fault diagnosis using current signals.

The spectral analysis could be the most extensively used approach for IM fault detection [8,9]. For example, Ayhan et al. undertook spectral analysis for broken rotor bars with low sampling rate [10]. Liu et al. conducted spectrum analysis of instantaneous power for broken rotor bars and eccentricity fault detection [11]. Eltabach et al. compared the external and internal spectral analysis for broken rotor bar fault detection [12]. Benbouzid et al. [13] and Devaney et al. [14] developed bearing fault model using spectrum analysis for IM defect detection. Zhou et al. presented a noise cancellation based spectral analysis method for bearing fault detection [15]. The authors in [16] also presented a spectrum synch technique for broken rotor bars and bearing fault detection. On the other hand, although some time-frequency methods have been proposed for IM defect detection, by the use of short-time Fourier transform [17], wavelet transform [18], and the wavelet packet decomposition [19], IM fault detection is still based on spectral analysis of the processed signals. One drawback of the spectral analysis is that the leakage of supply frequency harmonics may bury the fault characteristic frequency components, especially with low slip or in light load conditions [11].

To tackle the aforementioned problem, a new unbalance component analysis (UCA) technique is proposed in this work to extract characteristic features from the unbalance line current signals for more accurate IM fault detection. The proposed UCA has the following novel aspects: (1) the unbalance information of each phase current is examined using the closed loop current to reveal the fault characteristic spectral components; (2) a spectrum aggregation method is suggested to process characteristic features among three phases for IM fault detection.

The remainder of this paper is organized as follows. The proposed UCA technique is discussed in Section II. The effectiveness of the UCA is demonstrated in Section III via experimental tests corresponding to different IM conditions. Some concluding remarks are summarized in Section IV.

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II. THE UNBALANCE COMPONENT ANALYSIS

IM fault characteristic spectral components are usually masked by some balanced frequency components such as supply frequency harmonics. The proposed UCA technique will mitigate the balanced spectral components to reveal the unbalance features. A spectrum aggregation method is suggested to enhance the fault features among three phases.

A. Symmetrical Component Analysis

IMs normally operate in a balanced three phase sinusoidal steady-state [20]. The line currents could be represented by phasors. As illustrated in Figure 1, Phasor B is 120° lag to phasor A and phasor C is 120° lag to phasor B. IM faults will cause unbalanced operations. In symmetric component analysis, unbalance currents can be resolved into balanced currents as positive, negative and zero sequence components. Given the factor $\alpha = \angle 120^\circ$, $\alpha^2 = \angle 240^\circ$ and three phase currents $I_A$, $I_B$ and $I_C$, the symmetrical components can be calculated as

$$
\begin{bmatrix}
I_- \\
I_-
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
1 & \alpha & \alpha^2 \\
1 & \alpha^2 & \alpha
\end{bmatrix} \begin{bmatrix}
I_A \\
I_B \\
I_C
\end{bmatrix}
$$

where $I_-$, $I_-$ and $I_0$ represent the respective positive, negative and zero sequence currents. The negative sequence current has been used for motor fault detection [21,22]. Figure 2(a) shows reverse rotating three phase currents that may be caused by IM defects. As illustrated in Figure 2(b), the negative sequence current should be zero for balanced three phase currents. The fault features could introduce reverse rotating currents, while the negative sequence current will become nonzero.

![Fig. 1. Three phase current phasors.](image)

![Fig. 2. (a) Reverse rotating three phase current phasors; (b) the negative sequence current phasor.](image)

B. Closed Loop Current Analysis

The symmetrical component analysis examines the relationship among three phases [23]; however the relationship between the unbalance of each line current and the corresponding IM defect has not been explored in the literature. The ideal line currents are sinusoidal waves but an IM defect will cause distortion to the sinusoidal waves with some specific pattern. Figure 3(a) illustrates a closed loop vector path with two symmetric vectors (second order loop) in terms of phase A. Given $\beta = \angle 180^\circ$, the closed loop currents (CLCs) of three phases can be computed by

$$
\hat{I}_A = \frac{1}{2}(I_A + \beta I_A) \\
\hat{I}_B = \frac{1}{2}(I_B + \beta I_B) \\
\hat{I}_C = \frac{1}{2}(I_C + \beta I_C)
$$

where $\hat{I}_A$, $\hat{I}_B$ and $\hat{I}_C$ will be zero for an ideal sinusoidal wave. The disturbances caused by IM defects will distort the sinusoidal wave. In the CLC, the sinusoidal waves such as supply frequency harmonics will be mitigated, so as to highlight defect related features.

In a closed loop vector path with three symmetric vectors (third order loop) as illustrated in Figure 3(b), the CLCs of three phases can be computed by

$$
\hat{I}_A = \frac{1}{3}(I_A + \alpha I_A + \alpha^2 I_A) \\
\hat{I}_B = \frac{1}{3}(I_B + \alpha I_B + \alpha^2 I_B) \\
\hat{I}_C = \frac{1}{3}(I_C + \alpha I_C + \alpha^2 I_C)
$$

The unbalance features related to the third order loop will be explored by examining the derived CLCs in Equations (5)-(7).

![Fig. 3. (a) Phasor A with 0° and 180° lags, respectively; (b) phasor A with 0°, 120° and 240° lags, respectively.](image)

C. Spectrum Aggregation

The phasor rotation method as discussed in Section II(B) can be used to analyze the unbalance in each phase current. Some fault features will be more prominent in one phase or two phases. The maxima of three phase CLC spectra will be used to enhance fault features. Given CLCs of $\hat{I}_A(i)$, $\hat{I}_B(i)$ and $\hat{I}_C(i)$, $i = 1, 2, ..., N$, and $N$ is the length of CLCs, the aggregated spectrum will be determined by

$$
U(i) = \text{sup}_j S(\hat{I}_j(i))
$$

where $j = A, B$ and $C$; $S(I)$ is the power spectral density (PSD) of the current $I$. 

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D. Smoothing

The flowchart of the proposed UCA technique is illustrated in Figure 4. Firstly, current signals are collected using appropriate current sensors. Then the CLC analysis is used to extract unbalance information in each phase. The PSD is computed and aggregated to extract features in three phases. The derived spectrum is smoothed to facilitate feature extraction:

\[
V(i) = \frac{1}{2r+1} \left( \sum_{i=1}^{2r+1} U(i) + \sum_{i=N-2r}^{N-r} U(i) + \sum_{i=r}^{N} U(i) \right) \quad i \leq r + 1 \\
V(i) = \frac{1}{2r+1} \left( \sum_{i=1}^{2r+1} U(i) + \sum_{i=N-2r}^{N-r} U(i) + \sum_{i=r}^{N} U(i) \right) \quad i > N - r \\
\]

where \( r = 1, 2, 3, \ldots \) is the half width of the smoothing window.

![Flowchart of the proposed UCA technique.](image)

E. Fault Characteristic Frequencies

Investigations have revealed that most IM defects are related to rolling element bearings (up to 75%) and rotor bars (more than 10%) [24]. Correspondingly, the proposed UCA technique will be mainly applied to detect these IM defects.

In general, the fault detection of IM broken rotor bars is based on spectral analysis by inspecting sideband characteristic spectral components:

\[
f_{bl} = (1 - 2ks)f_p \quad (10) \\
\]

\[
f_{br} = (1 + 2ks)f_p \quad (11)
\]

where \( f_{bl} \) and \( f_{br} \) are the left sideband and right sideband of the IM broken rotor bar characteristic frequencies, respectively, \( k = 1, 2, \ldots \); \( f_p \) is the power supply frequency in Hz; \( s = \frac{n_s - n_a}{n_a} \times 100\% \) is the slip of the IM. \( n_s \) and \( n_a \) (in rpm or Hz) are the speed of rotating magnetic field and the shaft, respectively.

In IM bearing fault detection, initial bearing defect (e.g., pitting and fatigue cracks) usually occurs on the fixed ring race (i.e., the outer race in general) firstly, since the fixed race material is subjected to more dynamic loading; thus this work will focus on outer race defect detection of IM bearings.

The bearing outer race characteristic vibration frequency \( f_v \) depends on bearing geometry and shaft speed such that

\[
f_v = \frac{N_b}{2} \left( 1 - \frac{d \cos(\theta)}{D} \right) f_r \quad (12)
\]

where \( N_b \) is the number of rolling elements in the bearing, \( f_r \) is the rotor speed, \( d \) is the diameter of rolling elements; \( D \) is the bearing pitch diameter; \( \theta \) is the contact angle.

The corresponding current characteristic frequency \( f_c \) will be calculated by

\[
f_c = \left| f_p \pm mf_v \right| \quad (13)
\]

where \( m \) is a positive integer \((m = 1, 2, 3, \ldots)\).

III. PERFORMANCE EVALUATION AND IM FAULT DETECTION

A. Experiment Setup

Figure 5 shows the experiment setup employed in the current work to evaluate the effectiveness of the proposed UCA technique. The speed of the tested IM is controlled by a VFD-B AC speed controller (from Delta Electronics) with output frequency 0.1~400Hz. A magnetic particle clutch (PHC-50 from Placid Industries) is used as a dynamometer for external loading. Its torque range is from 1 to 30 lb·ft (1.5 - 40 N·m). The motor used for this research is made by Marathon Electric, and its specifications are summarized in Table I. The gearbox is used to adjust the speed ratio of the dynamometer. The current sensors (102-1052-ND) are used to measure line currents. A rotary encoder (NSN-1024) is used to measure the shaft speed with the resolution of 1024 pulses per revolution. Stator current signals are collected using a Quanser Q4 data acquisition board, which are then fed to a computer for further processing. The supply frequency is 50 Hz and the sampling frequency is set at \( f_s = 20 \) kHz.

![The motor experiment setup: (1) the tested IM, (2) the speed controller, (3) the gearbox, (4) the load system, (5) current sensors, (6) the data acquisition system, (7) the computer.](image)

<p>| TABLE I. MOTOR SPECIFICATIONS. |
|---------------------------|---------------------|</p>
<table>
<thead>
<tr>
<th>Phase</th>
<th>Connection</th>
<th>RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Y</td>
<td>2850</td>
</tr>
<tr>
<td>2</td>
<td>1/3</td>
<td>Rotor Bars</td>
</tr>
<tr>
<td>50</td>
<td>Stator Slots</td>
<td>24</td>
</tr>
</tbody>
</table>

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To evaluate the performance of the proposed UCA technique, the PSD of phase A line current and PSD of the negative sequence current will be used to diagnose IM broken rotor bar fault and the bearing defect. The smoothing window width \( r = 5 \) is used in the tests.

**B. Broken Rotor Bar Fault Detection**

Figure 6 shows the PSDs of the phase A current, negative sequence current and the third order CLC with respect to a healthy IM and an IM with one broken rotor bar at 50% load level. It is seen from Figure 6(a) that there are no fault characteristic frequency components due to the masking effect of the 50Hz supply frequency. Figure 6(b) shows the spectrum of negative sequence current, in which fault frequencies cannot be recognized due to the ineffective feature extraction of the symmetrical component analysis. It is also observed that the magnitude of the supply frequency is about 240dB in Figure 6(a) and 150dB in Figure 6(b), respectively. In Figure 6(c), the magnitude of the supply frequency magnitude is mitigated to 65dB and other frequencies are protruded. The green rectangles mark the broken rotor characteristic frequencies of 43.93Hz and 56.27Hz.

Figures 7, 8 and 9 show the PSDs of CLCs in three different load conditions for IMs with one broken rotor bar, two broken rotor bars and three broken rotor bars, respectively. In these three figures, the fault frequencies marked by green rectangles deviate from 50Hz supply frequency further as the load increases. In 50% and 2% load conditions, the fault characteristic frequency components (green rectangles) are prominent and provide clear fault diagnosis. Although the fault characteristic frequencies (i.e., 39.02Hz and 61.59Hz) in 100% load level in Figure 7(a) are not prominent, the higher order fault frequencies, for example at 33.4Hz, are more prominent for IM fault detection.

![Fig. 6. PSDs of (a) Phase A current; (b) negative sequence current; and (c) CLC, in 50% load condition. The blue solid line represents the healthy state and the red dotted line denotes the state of IM with one broken rotor bar.](image-url)

![Fig. 7. The PSDs of CLC with respect to (a) 100% load; (b) 50% load; and (c) 2% load. The blue solid line represents the healthy state and the red dotted line denotes the state of IM with one broken rotor bar.](image-url)
C. IM Bearing Fault Diagnosis

Figure 10 shows the PSDs of the phase A current, negative sequence current and the third order CLC corresponding to a healthy IM and an IM with the bearing defect at 2% load level. It is seen in Figure 10(a) that fault characteristic frequencies could not be observed from the spectrum of the line current. The fault characteristic frequency at 100.1Hz, however, could be recognized at both Figure 10(b) and Figure 10(c). Figure 11 illustrates the PSDs of the phase A current, negative sequence current and the third order CLC corresponding to a healthy IM and an IM with the bearing defect at 70% load level. It is seen in Figure 11(b) that fault characteristic frequencies could not be observed from the spectrum of the negative sequence current. The fault characteristic frequency at 98.43Hz, however, could be recognized at both Figure 11(a) and Figure 11(c). Therefore, the PSD of the third order CLC can reveal fault characteristic frequency in both cases and is supervisor to the PSDs of both the line current and the negative sequence current.

Figure 12 shows the PSDs of CLCs in the band [298Hz 304Hz] at five different load levels: 2%, 20%, 50%, 70% and 100%. It is seen that the left fault characteristic frequency deviates from the 301Hz supply harmonic as the load increases, which can be used for initial bearing fault detection. Figure 13 illustrates the PSDs of CLCs in the band [97Hz 104Hz] at five different load levels: 2%, 20%, 50%, 70% and 100%. It is clear that the left fault characteristic frequency component is located further away from the 100.3Hz supply frequency harmonic as the load increases, which can provide clear indication of IM health conditions (initial bearing damage in this case).
Fig. 10. The PSDs of (a) Phase A current; (b) negative sequence current; and (c) CLC, in 2% load condition. The blue solid line represents the healthy state and the red dotted line denotes the state of IM with the bearing defect.

Fig. 11. The PSDs of (a) Phase A current; (b) negative sequence current; and (c) CLC, in 70% load condition. The blue solid line represents the healthy state and the red dotted line denotes the state of IM with the bearing defect.

Fig. 12. The PSDs of CLC with respect to (a) 100% load; (b) 70% load; (c) 50% load; (d) 20%; and (e) 2% load in the band [298Hz 304Hz]. The blue solid line represents the healthy state and the red dotted line denotes the state of IM with the outer race faulted bearing.
IV. CONCLUSION

An unbalance component analysis technique, UCA, has been proposed in this work to detect IM defects. The unbalance current information in each line is extracted by the suggested closed loop current analysis. The three phase information is recognized by spectrum aggregation. The derived spectrum is smoothed for feature extraction and fault characteristic frequency components can be highlighted in the resulting spectrum. The effectiveness of the UCA technique has been verified by experimental tests corresponding to the common IM faults (i.e., broken rotor bars and the bearing defect) under different load conditions (i.e., 2%, 20% 50%, 70%, and 100% load levels). The test results have demonstrated that the proposed UCA technique can provide more accurate diagnosis of IM health conditions, which has a potential to be implemented for real world IM condition monitoring.

REFERENCES


