ZSV Spectrum-Based Detection of IM Rotor Dissymmetry

Immunity to False Alarms

Abstract. This paper presents a comprehensive study of new tool used to detect rotor asymmetries in induction motors, which operate in different types of operating conditions and different loads. The proposed approach is performed by tracking the amplitude of the most sensitive harmonics in the spectrum of the line neutral voltage (called also the Zero Sequence Voltage (potential difference between the null point of the supply voltage system and the neutral of the star connection of IM stator winding), using a dynamic acquisition rate based on machine frequency supply. To assess detection accuracy under the various severity levels of the faults, two supply conditions are investigated: (i) Motor supplied by network fed and (ii) Motor supplied by inverter fed. Results obtained from experimental tests are presented to validate the study.

Introduction

Induction motors (IM) are used in many industrial processes and are frequently integrated in commercially available equipment. Robustness, cost advantage, high power capabilities, and performance are the major concerns of IM applications. Although IM are reliable, they are subjected to some failures. Therefore, monitoring and diagnosing faults in IMs is a scientific and economic issue which is motivated by objectives for reliability and serviceability in electrical machines drives. There has been a substantial amount of research to provide new condition monitoring techniques for induction motors mostly based on analysing vibration signals, or other signals such as current, and hence several commercial tools are available in this area.

Studies in the area of diagnosis and monitoring of electrical machines have shown that stator and rotor faults are assumed equal. However, the vast majority of articles dealing mainly with rotor fault ([11]) first and then with stator faults and finally bearing faults. [1][2]

Knowing that the topic is so important, this paper deals on rotor fault detection in IMs, this fault that physically result either by short/open circuits or by increasing of the rotor resistance. Among the rotor fault accrued in this type of machines we can cite the broken rotor bars (BRB) in in case of machines with squirrel cage.

There are various methods that have been developed to detect BRB in IMs such us vibration analysis, temperature analysis, acoustic measurement, neuronal and artificial intelligence based methods. However, the most used techniques are based on the monitoring of the stator current spectrum (known by Motor Current Signature Analysis [MCSA]). MCSA is simple and effective in appropriate operating conditions. [3]

Even the advantages that represent this method, this technique has some significant practical limitations such us:

1) Operating conditions can influence the MCSA. In case of rotor asymmetries faults in motors working at a very low load, the main frequency component may hide the fault harmonics because their frequencies are close to the main frequency of the power supply.

2) The diagnosis is difficult if the IM is supplied by a power converter or if the IM operates in a system under time-varying conditions;

3) Recently, the IMs are frequently installed with inverters which provide some advantages but makes the stator current inaccessible to diagnosis.

To overcome some of these limitations, the use of zero sequence voltage (or Line neutral voltage which is the potential difference between the null point of the supply voltage system and the neutral of the star connection of IM stator winding) is proposed and analysed. [4-9]

Because no direct fault detection criterion is provided, the mentioned methods requires the knowledge of the healthy state to take a decision about the rotor. Instead, the proposed harmonic tracking approach is developed using the zero-sequence voltage as electrical indicator to detect of BRBs without the knowledge of a primary state of the motor. This approach is based on standard deviation calculations taken on two frequency ranges, the first standard deviation will be calculated on the first frequency range, this range identifies where the phase jump whose frequency (3−4s)f s.

1) Even the advantages that represent this method, this technique has some significant practical limitations such us:

The second standard deviation represent the picture of measurement noise present between jumps being located at frequencies (3−4s)f s and (3−6s)f s, that is going to be mentioned in this paper as f wr1 and f wr2 respectively. Finally, using this approach, we can generate a decision about the rotor fault which is presented in the end of the proposed method section. It is important to note that the method is valid both for line connected as well as for inverter-fed machines.

Proposed method

The presence of a fault rotor reveals additional components in the spectrum of NV. Indeed, M.E.K. OUMAMMAR demonstrated by a complex analysis, that the appearance of a rotor fault induces additional components in the frequency spectrum of the NV at frequencies given by the relation:

\[ f_{wrm} = \left[ 3h - (3h \pm 1) \right] s \cdot f_s \]

s: slip, fs: supply frequency,  \( h = 1,3,5, \ldots \ldots \)

The information given by the spectrum of the voltage at the third harmonic [10], i.e., nears the spectral line having the frequency 150 Hz can be used for WRIM fault diagnosis.

This section provides an analysis of the tracking harmonics module, the threshold performance and the decision making method.
As already seen in introduction, The proposed method is based on the analysis of the jump \((3-4sf_r)\), which is a function of the motor slip \(s\). This is why it is necessary to calculate the slip of the IM, the easiest way is to use the speed sensor in case of experiment test. In this paper we focus on some harmonics to estimate the slip.

From the equation given the principal RSH found on the spectrum of the line neutral voltage:

\[
f_{i+s} = f_s \left[ \frac{N}{p} (1-s) \pm 1 \pm 2ks \right]
\]

Where: \(\lambda\) is a positive integer; \(p\): Number of pole pairs; and \(N\): Number of rotor bars

We can express the slip as:

\[
s = 1 - \frac{p}{N} \left[ \frac{f_{RSH}}{f_s} \pm 1 \right]
\]

Practically, all IM have a slight asymmetry of construction induced, in the spectrum of Line neutral voltage, the appearance of the frequency component whose frequency equal to \((3-2sf_s)\). Therefore, the slip can be expressed from:

\[
s = \frac{1}{2} \left[ 3 - \frac{f_{RSH}}{f_s} \right]
\]

where: \(f_{RSH}\) is the frequency of rotor slot harmonic.

A searching interval is defined because the frequency of the component \((3-2sf_s)\) changes according to the load motor; their boundaries depend on the max and min values of the slip \(s_{min}\) and \(s_{max}\); these correspond to unloaded machine and full load machine respectively.

Consequently, the searching frequency \(f_{SR}\) belongs to the following interval:

\[
f_{SR} \in \left[ (3-2s_{max})f_s \ldots (3-2s_{min})f_s \right]
\]

In our case, given that we know the fundamental frequency \(f_0\), and as our machine is operating with a nominal speed of 2800 rpm which gives a minimum frequency \(f_{RSH}\) equal to 143.6 Hz, therefore the range selected detection of this jump will be \([140,150]\) Hz.

The next step is to identify the value of the \((3-2sf_s)\) component and its amplitude in the spectrum of the line neutral voltage, the best way to do this is define a frequency range corresponding to the wanted harmonic, this component which has the highest magnitude nearest the 3rd harmonic in the interval defined as:

\[
R = \left[ f_{wr} - i\Delta f ; f_{wr} + j\Delta f \right]
\]

Where: \(f_{wr}\) is target harmonic obtained via the estimated slip, \(\Delta f\) is the frequency resolution (\(\Delta f = f_s/N\)), \(i\) and \(j\) are integers. Once the slip is determined.

Next, the idea is to compare the standard deviation around the \(f_{tar1}\) and \(f_{tar2}\) frequencies. Instead the first standard deviation, noted \(\sigma_1\) will be calculated on the frequency range \((RANGE1)\), this range identifies where is the phase jump whose frequency \((3-4sf_s)\). The second standard deviation, which is noted by \(\sigma_2\) will be calculated on the frequency range \((RANGE2)\).

The mathematical relationship that can calculate the standard deviation is:

\[
\sigma_s = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \frac{N}{N} \sum_{i=1}^{N} x_i)^2}
\]

For an adequate understanding of the principle of calculation of these standard deviations, Fig. 1 shows a representation where the standard deviation \(\sigma_1\) is calculated on the red frequency range while the standard deviation \(\sigma_2\) is calculated on the black frequency range.

In order to make our indicator more robust and to limit false alarms detection, a threshold has been introduced in the criterion that will symbolize with: \(C_{th}\). This threshold compares the variance \(\sigma_1\) with the variance \(\sigma_2\) of \(\varphi(t)\).

Therefore, the authors have defined the following criterion (Table 1):

**Fig. 1. Explication of the proposed method**

**Table 1. Rotor asymmetry decision module**

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Rotor State</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{def} \leq C_{th})</td>
<td>Healthy rotor</td>
</tr>
<tr>
<td>(C_{def} &gt; C_{th})</td>
<td>Defective rotor</td>
</tr>
</tbody>
</table>

Where \(C_{def} = \sigma_1/\sigma_2\), and \(C_{th}\) is the sensitivity degree of our fault detection indicator and it is determined in function of the studied IM. Both, the rotor fault index \(C_{def}\) and the corresponding threshold parameter \(C_{th}\) are determined from experimental results based on the signal detection theory.

The proposed method can be summarized as follows:

- After acquisition, the zero-sequence voltage is sampled, and the slip is measured for each case (to be used just for comparison with the estimated slip).
- The slip estimation module is built using (5) and (6).
- The estimated slip is used to search the frequency component \((3-2sf_s)\) near the 3rd harmonic.
- Once this frequency is estimated, the \(f_{tar1}\) and \(f_{tar2}\) are estimated too, and the standard deviation in the two ranges is calculated to build the criterion and these values can be compared with predefined thresholds to evaluate the machine’s condition.

**Validation of the Proposed Methodology**

To perform a further experimental validation, the proposed method is applied under laboratory conditions to a commercial motor, whose characteristics are explained in the next subsection.

In this section, the proposed method will be illustrated using the case of an IM with rotor asymmetry. Nevertheless, the same procedure can be followed to the treatment of any other type of machine fault or working conditions.

The test bench used is designed to monitor the voltage, current, vibration and speed of IM by using sensor in each measurement. Fig. 2 shows the structure of the laboratory setup. The motor under test is a 3kW, 50Hz, 220V=380V,
The measured signals were analyzed by using Fast Fourier Transform (FFT). For the tested motor, the experiments were performed in the steady state condition to obtain accurate information about the broken rotor bars. For FFT analysis, the Hanning window is used to minimize the frequency leakage.

First, the algorithm is implemented by using a Matlab function. The results of this algorithm are presented in Table 2. The first column in this table corresponds to the measured signals. The rotor state is presented in the second column, the third and fourth column gives the value of the frequencies $f_{tar1}$ and $f_{tar2}$ respectively. The fifth and sixth column gives the calculated and estimated slip. The values of $\sigma_{n}$ and $\sigma_{j}$ calculated on the frequency ranges $\text{RANGE1}$ and $\text{RANGE2}$ are presented in the seventh and eighth columns respectively. And then the module decision is presented in the two last columns.

Fig. 3 shows an example of the application of the frequency tracking module in the S-1bb50 case (Induction motor with one broken rotor bar at 50% of load). In the first plot of this figure, Fig. 3(a), the fault can be observed in the spectrum of the line neutral voltage the target frequencies $f_{tar}$, $f_{tar1}$ and $f_{tar2}$.

In Fig. 3(b), frequency tracking module is shown. It has been built by keeping only the amplitudes of the components of the searched harmonics. For the rest, the same process is done for all tests in table 2.

The method described above (Section III) is applied on the zero-sequence voltage when the machine is directly star-connected to the three-phase network. According to the column giving $\sigma_{n}$ report we note that it is low for a machine operating with a healthy rotor ($\text{S-H100}$ and $\text{S-H50}$), then we perceive that for some healthy functioning we do not detect jump phase ($3-2s)f_{s}$ in this case we consider the rotor in good condition ($\text{S-H0}$).

The appearance of a partial rotor fault does not induce a significant increase of $\sigma_{j}$ relative to $\sigma_{n}$, which does not allow to conclude on such a failure. For an important rotor fault ($\text{S-2bb50}$) we note that this report is greater 10 times that in tests where the machine is healthy. From these results, it can be concluded that the proposed approach is validated, even if $\sigma_{n}$ report in tests $\text{S-2bb25}$ and $\text{S-1bb25}$ is less pronounced as seen in Table 2, but the results are satisfactory.
Table 2. Results of the proposed method.

<table>
<thead>
<tr>
<th>Rotor condition</th>
<th>( f_{ar} )</th>
<th>( f_{art} )</th>
<th>Measured Slip (%)</th>
<th>Estimated Slip (%)</th>
<th>( \sigma_j )</th>
<th>( \sigma_n )</th>
<th>Decision Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-H0</td>
<td>145.23</td>
<td>139.19</td>
<td>4.79</td>
<td>4.77</td>
<td>0.384</td>
<td>0.108</td>
<td>Healthy</td>
</tr>
<tr>
<td>S-H50</td>
<td>144.9</td>
<td>139.23</td>
<td>5.14</td>
<td>5.09</td>
<td>0.105</td>
<td>0.073</td>
<td>1.45 Healthy</td>
</tr>
<tr>
<td>S-1bb0</td>
<td>145.41</td>
<td>140.82</td>
<td>4.63</td>
<td>4.59</td>
<td>0.610</td>
<td>0.067</td>
<td>9.11 Defective</td>
</tr>
<tr>
<td>S-1bb50</td>
<td>144.40</td>
<td>138.81</td>
<td>5.71</td>
<td>5.60</td>
<td>0.015</td>
<td>0.007</td>
<td>4.89 Defective</td>
</tr>
<tr>
<td>S-1bb100</td>
<td>142.33</td>
<td>134.66</td>
<td>3.78</td>
<td>7.67</td>
<td>0.29</td>
<td>0.003</td>
<td>79.30 Defective</td>
</tr>
<tr>
<td>S-2bb0</td>
<td>148.56</td>
<td>147.06</td>
<td>1.47</td>
<td>1.44</td>
<td>0.0316</td>
<td>0.005</td>
<td>6.32 Defective</td>
</tr>
<tr>
<td>S-2bb25</td>
<td>144.37</td>
<td>138.74</td>
<td>5.71</td>
<td>5.63</td>
<td>0.088</td>
<td>0.0082</td>
<td>10.74 Defective</td>
</tr>
<tr>
<td>S-2bb50</td>
<td>143.8</td>
<td>138</td>
<td>6.25</td>
<td>6.2</td>
<td>0.302</td>
<td>0.006</td>
<td>48.01 Defective</td>
</tr>
<tr>
<td>S-2bb100</td>
<td>142.95</td>
<td>137.31</td>
<td>7.11</td>
<td>7.05</td>
<td>0.36</td>
<td>0.006</td>
<td>56.3 Defective</td>
</tr>
<tr>
<td>I-H0</td>
<td>144.9</td>
<td>139.23</td>
<td>5.14</td>
<td>5.09</td>
<td>0.105</td>
<td>0.073</td>
<td>1.45 Healthy</td>
</tr>
<tr>
<td>I-H100</td>
<td>147.40</td>
<td>144.80</td>
<td>2.54</td>
<td>2.61</td>
<td>0.015</td>
<td>0.007</td>
<td>4.89 Defective</td>
</tr>
<tr>
<td>I-1bb0</td>
<td>147.8</td>
<td>144.80</td>
<td>2.54</td>
<td>2.61</td>
<td>0.015</td>
<td>0.007</td>
<td>4.89 Defective</td>
</tr>
<tr>
<td>I-1bb25</td>
<td>144.34</td>
<td>140.68</td>
<td>4.72</td>
<td>4.66</td>
<td>2.218</td>
<td>0.093</td>
<td>23.86 Defective</td>
</tr>
</tbody>
</table>

Conclusion

In this paper, a novel approach to detect rotor fault in IM has been proposed, it is based on the analysis of a new fault indicator that uses both the harmonic tracking and the zero-sequence voltage. The presented indicator allows to have a knowledge about the rotor state, the fault severity, and the corresponding slip for the data acquisition. With the proposed method, the decision making is done, regardless of the motor load or the type of supply. It was shown that the harmonics tracked in this paper are derived to evaluate their immunity to false alarms. The description of the proposed method, its theoretical justification, and the experimental validation under a wide variety of supply types and working conditions have been presented in this paper. As extension of the proposed method, the detection of multiple faults in IMs is currently under development, and will be presented in a future paper.

Authors:

Khalid Dahi, University Mohammed V in Rabat, Ecole Normale Supérieure de l'enseignement Technique, and also a Research Engineer in Ecole Centrale Casablanca Morocco E-mail: khalid.dahi@um5s.net.ma;
Pr. dr Soumia El Hani, University Mohammed V in Rabat, Ecole Normale Supérieure de l'enseignement Technique, Morocco E-mail: s.elhani@um5s.net.ma;
Phd Student, Ilias Ouachtouk, University Mohammed V in Rabat, Ecole Normale Supérieure de l'enseignement Technique, Morocco E-mail: ilias.ouachtouk@gmail.com;

REFERENCES