Induction motor mechanical fault identification using Park’s vector approach

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Abstract— In this work we have shown that the extended Park’s vector spectrum is rich in harmonics characteristics of mechanical defects (air-gap eccentricity and outer raceway bearing fault). About the use of Park’s Lissajou’s curves to identify mechanical defects, we have demonstrated that this type of index can only detect the occurrence of a fault, but it cannot identify.

Index Terms—fault diagnosis, Park vector, induction motor, eccentricity fault, bearing fault.

I. INTRODUCTION

Today, the induction machines are the powerhouse of the industry. Safety, reliability, efficiency and performance are some of the major concerns and needs for electromechanical applications. Mechanical faults are one of the most common faults in induction motors. The source of the faults is mainly based on bearing faults and the air-gap eccentricities. Therefore, many methods are successfully used for condition monitoring and fault detection in electric motors. Among the noninvasive methods of condition monitoring, vibration monitoring is the most popular method used for mechanical fault [1][2][3].

Recently, some researchers have tried other signature analysis such as stator current and extended Park’s vector approach for induction motors mechanical fault detection. In [4], authors have made use of stator current for the detection of bearing fault. Concari et al. have used stator current to detect and quantify mixed eccentricities faults. Extended Park vector approach and Park’s Lissajou’s curves have presented in [6] in order to detect air-gap eccentricities fault. Silva and Cardoso [7] introduce an approach, based on the spectral analysis of the motor current Park’s Vector modulus, for diagnosing the occurrence of bearing faults in three-phase induction motors. In [8][9][10], authors exploit Park’s Lissajou’s curves in order to detect bearing defect.

Drif and Cardoso [11], have made use of complex apparent power signature analysis for the detection of mixed air gap eccentricity fault. In [12], authors have used instantaneous power and instantaneous power factor to detect the eccentricity related frequency components. The works mentioned above have addressed each mechanical fault (eccentricities or bearing fault) apart. The aim of this investigation was to test the effectiveness of fault signature for both mechanical defects (eccentricities and bearing fault), especially the Park’s vector approach. Initially, we exploit the spectral analysis of Park vector modulus, then, we use Park’s vector Lissajou’s curves.

II. BASIC THEORY

A- Air-gap eccentricity fault

Between the inner stator and outer rotor circumferences, the eccentricity fault causes radial unbalanced magnetic pull (UMP). The direction of the UMP is such that it amplifies the eccentricity. Any eccentricity in the induction motor structure therefore generates extreme fatigue of the ball-bearings. The interaction of the UMP on the stator core also causes abnormal vibration of the stator winding, which could be dangerous. Some consequences of the eccentricity fault in the motor could be [10]:
- Asymmetry and deviation of air-gap flux and line currents.
- Decreasing average torque.
- Increasing losses and decreasing efficiency.
- Rising temperature.

In reality, static and dynamic eccentricities tend to coexist. Ideal centric conditions can never be assured. Therefore, an inherent eccentricity is implied for any real machine, even in newly manufactured ones due to the manufacturing and assembly methods. The combined static and dynamic eccentricities are called mixed eccentricity. In this condition, both rotor and rotation axes are displaced. When mixed eccentricity is present, low frequency components also appear in the spectra of the current space vector modulus (Park vector), which can be given by [6][11][12]:

\[ f_{ecc} = \left| 2f_s \pm k f_r \right| \]  \hspace{1cm} (1)

And

\[ f_{ecc} = k f_r \]  \hspace{1cm} (2)

Where \( f_s \) is the fundamental frequency of the supply, \( f_r \) is the rotor rotation frequency in rps and \( k \) is an arbitrary integer number.

B- Outer raceway gearing fault

Faulty bearings cause the variation of air-gap length when a rotor turns. Since this variation comes from the faulty
structure of a ball bearing, the irregular harmonic frequencies of a ball bearing can be resulting from the bearing model. This fault causes the appearance of characteristic fault frequencies in the spectrum of the measured parameters which are often utilized for fault diagnosis. The characteristic fault frequencies depend on the mechanical dimensions of the bearing, the number \( N_b \) of bearing balls, and the rotational frequency \( f_r \) of the inner raceway for a fixed outer ring. For bearings with between 6 and 12 balls, the fault frequencies for an outer raceway fault \( f_{or} \) can be approximated using, respectively, the following [4]:

\[
f_{or} = 0.4N_b f_r
\]  

(3)

The characteristic fault frequencies are the consequence of the vibration of the machine. The stator current is not affected by the vibration of the machine, but moderately by a relative movement between the stator and rotor (i.e., changes in the air-gap). The characteristic fault frequencies are basically modulated by the electrical supply frequency and are predicted by:

\[
f_{orf} = |f_s \pm k f_{orf}|
\]  

(4)

The frequency components also appear in the spectra of the current space vector modulus (Park vector), which can be given by:

\[
f_{orf} = |2f_s \pm k f_{orf}|
\]  

(5)

And

\[
f_{orf} = k f_{or}
\]  

(6)

C- Park vector approach

In a three-phase induction motor, the sum of stator currents is zero. Therefore, a two dimensional representation can then be used. A suitable representation is based on the current Park's vector. The use of Park's vector as a function of main phase variables \((i_a, i_b, i_c)\), gives the current Park's vector components \((i_d, i_q)\) as

\[
i_d(t) = \sqrt{2/3} i_a(t) - \frac{1}{\sqrt{6}} i_b(t) - \frac{1}{\sqrt{6}} i_c(t)
\]  

(7)

\[
i_q(t) = \frac{1}{\sqrt{2}} i_b(t) - \frac{1}{\sqrt{2}} i_c(t)
\]  

(8)

Its representation (Lissajou's curve \(i_q=f(i_d)\)) has a circular shape, centered at the origin and having a diameter equal to the stator current corresponding to the state of operating of the healthy motor. In the case of faulty motor, the Lissajou's curve changes in shape and in thickness for the reason that the harmonics presence generated by the fault. To calculate the thickness of the elementary Lissajou's curve, the normalized splitting severity factor is used [6]:

\[
(A_p)_N = \frac{(A_p)_{av}}{\rho_{av}}
\]  

(9)

\[
\rho_{av} = \frac{\sum_{k=1}^{N} \sqrt{i^2_{dk} + i^2_{qk}}}{N}
\]  

(10)

\[
(A_p)_{av} = \frac{\sum_{k=1}^{N/2} \left[ \sqrt{i^2_{dk} + i^2_{qk}} - \frac{\sqrt{i^2_{d(k+2)k} + i^2_{q(k+2)k}}}}{N/2}
\]  

(11)

III. TEST BENCH DESCRIPTION AND EXPERIMENTAL RESULTS

A. Test Bench Description

The test motor used in the experimental investigation has been a three-phase 50-Hz, 28 rotor bars, four-pole, 1.1-kW induction machine (Fig.1-a). The induction machine shaft is mounted with a powder brake in order to simulate different level of load torque during the tests (0%, 20%, 40%, 60%, 80% and 100% of full loaded torque).

The studied faults are: air-gap eccentricity and the outer raceway bearing defect.

In order to create an air-gap eccentricity fault in the induction motor, a simple mechanism has been used. Each of the two bearing housings of the rotor has been changed to a pair of eccentric rings placed one into the other (Fig.1-b).

The defective bearings have been installed on the load side of the induction motor. The diagnosis of bearing failures on the load side of the mechanics succeeds as well. The generated artificial faults that have been installed for the following results are shown in Fig.1-c for the outer raceway bearing fault. Eroding the ring of the bearing has resulted in a slot with a width of 2 mm at the outer raceway. The investigated bearing contains 9 balls.

Three phase current sensors are used to monitor the induction machine while working at steady state. Low-pass anti-aliasing filters are implemented in order to set the frequency bandwidth of the analysed signals to a correct range. Then, the outputs of the low-pass filters are directly connected to a data acquisition board (dSpace DS1104 processor board) which contains a Motorola Power PC 603e model and a DSP (TMS320F240 – 20 MHz). The process can be commanded and monitored via the Control Desk software of dSpace. The data sampling is performed using differential channels and a sampling frequency is 10 kHz. The software used is MATLAB™ for the data acquisition and processing.
Fig. 1. Experimental set-up of 1.1 kW to collect healthy and faulty induction machine data in stator current.

B. Experimental Results

The extended Park’s vector is analyzed in the frequency domain using FFT. The Blackman window is chosen because it gives the best compromise between the relative side lobe attenuation and the main lobe width, in order to differentiate the analyzed frequency components used by the tested diagnosis methods.

Any air-gap eccentricity fault introduces two lines in the extended Park’s vector spectrum separated of ±k.fr from the double supply frequency.

The frequencies related at the air-gap eccentricity fault are summarized in Table I. To show the efficiency of the proposed method, some selected spectra are presented. It can be seen that the spectral components coincide with the predicted values (Fig. 2).

For k=1 and f_r=24.3 Hz, there are two harmonic components around 100 Hz (75.7 Hz and 124.2 Hz) in extended Park’s vector spectrum, the magnitude of this two harmonic components can be used as index for eccentricity fault.

Harmonics most notable are those given by 2.8 Hz and 294 Hz obtained respectively by substituting k=-4 and k=8 in equation (1). Note that the harmonics that are multiples of the frequency of rotation are also good indicators for failure of eccentricity, and more particularly: f_r, 2f_r, 3f_r, 4f_r and 8f_r.
The frequencies related at the outer raceway bearing fault are summarized in Table II. To show the efficiency of the proposed method, some selected spectra are presented. It can be seen that the spectral components coincide with the predicted values.

In full loaded case for a faulty motor \( f_r = 24.3\, \text{Hz} \), consequently \( f_{ow} = 86.76\, \text{Hz} \).

The outer raceway ball bearing fault can be observed in the extended Park’s vector spectrum in 88 Hz \( (f_r) \) (Fig.5). In Figures 5, 6, 7 and 8, we can show outer raceway gearing fault frequency components presented in table II. It is clear that the different magnitudes have been affected by the outer raceway bearing fault.

<table>
<thead>
<tr>
<th>Relationship of eccentricity fault frequency components</th>
<th>Theoretical frequency (Hz)</th>
<th>Experimental frequency (Hz)</th>
<th>Magnitude (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2( f_r ) - ( f_r )</td>
<td>75.7</td>
<td>75.7</td>
<td>-72.12</td>
</tr>
<tr>
<td>2( f_r ) - 4( f_r )</td>
<td>2.8</td>
<td>2.7</td>
<td>-63.58</td>
</tr>
<tr>
<td>2( f_r ) + ( f_r )</td>
<td>124.3</td>
<td>124.2</td>
<td>-74.4</td>
</tr>
<tr>
<td>2( f_r ) + 8( f_r )</td>
<td>294.4</td>
<td>294.4</td>
<td>-68.25</td>
</tr>
<tr>
<td>2( f_r ) - 16( f_r )</td>
<td>288.8</td>
<td>289.1</td>
<td>-76.02</td>
</tr>
<tr>
<td>( f_r )</td>
<td>24.3</td>
<td>24.3</td>
<td>-58.66</td>
</tr>
<tr>
<td>2( f_r )</td>
<td>48.6</td>
<td>48.7</td>
<td>-82.6</td>
</tr>
<tr>
<td>3( f_r )</td>
<td>72.9</td>
<td>72.6</td>
<td>-71.8</td>
</tr>
<tr>
<td>4( f_r )</td>
<td>97.2</td>
<td>96.8</td>
<td>-79.49</td>
</tr>
<tr>
<td>12( f_r )</td>
<td>291.6</td>
<td>291.8</td>
<td>-70.16</td>
</tr>
</tbody>
</table>

Fig.5. Spectrum of Park’s vector modulus in the range \([0, 100\, \text{Hz}]\) in the case of: normal condition (blue) and outer raceway bearing fault (red).

Fig.6. Spectrum of Park’s vector modulus in the range \([150, 200\, \text{Hz}]\) in the case of: normal condition (blue) and outer raceway bearing fault (red).

Fig.7. Spectrum of Park’s vector modulus in the range \([250, 300\, \text{Hz}]\) in the case of: normal condition (blue) and outer raceway bearing fault (red).

Fig.8. Spectrum of Park’s vector modulus in the range \([320, 370\, \text{Hz}]\) in the case of: normal condition (blue) and outer raceway bearing fault (red).
TABLE II. FAULT FREQUENCIES COMPONENTS IN THE CASE OF OUTER RACEWAY BEARING FAULT

<table>
<thead>
<tr>
<th>Relationship of outer raceway bearing fault frequency components</th>
<th>Theoretical frequency (Hz)</th>
<th>Experimental frequency (Hz)</th>
<th>Magnitude (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[</td>
<td>2f_o - f_{or}</td>
<td>]</td>
<td>13.24</td>
</tr>
<tr>
<td>[</td>
<td>2f_o - 2f_{or}</td>
<td>]</td>
<td>73.52</td>
</tr>
<tr>
<td>[f_{or}]</td>
<td>86.76</td>
<td>88</td>
<td>-89.11</td>
</tr>
</tbody>
</table>

| \[|2f_o - 3f_{or}|\]                                         | 160.28                      | 159.7                        | -86.65         |
| \[2f_{or}\]                                                | 173.52                      | 173.3                        | -78.81         |
| \[|2f_o + f_{or}|\]                                         | 186.76                      | 187.5                        | -91.65         |

| \[|2f_o + 2f_{or}|\]                                         | 273.52                      | 274.2                        | -70.05         |

| \[|2f_o - 5f_{or}|\]                                         | 333.8                       | 333.5                        | -88.61         |
| \[4f_{or}\]                                                | 347.04                      | 347.1                        | -92.74         |
| \[|2f_o + 3f_{or}|\]                                         | 360.28                      | 360.1                        | -95.17         |

In Figs. 9 and 10, the Park Lissajou’s curves related to the air-gap eccentricity and the outer raceway bearing fault are shown. It is observed that the thicknesses of these curves are clearly increased compared to the healthy conditions. These faults have the same influence on the Park Lissajou’s curve, this may cause a false fault identification, where wrong diagnosis. In this case the Park Lissajou’s curve can only detect a fault occurring, but it did not identify.

In table III and fig.13, the normalized splitting severity factor related to the thickness of the Lissajous curves in the case of healthy condition, air-gap eccentricity and outer raceway bearing fault, are presented for different load levels (Figs. 11 and 12).
TABLE III: NORMALIZED SPLITTING SEVERITY FACTOR

<table>
<thead>
<tr>
<th>Load levels</th>
<th>20%</th>
<th>40%</th>
<th>60%</th>
<th>80%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy motor</td>
<td>0.38</td>
<td>0.42</td>
<td>0.61</td>
<td>0.95</td>
<td>1.34</td>
</tr>
<tr>
<td>Air-gap eccentricity</td>
<td>0.82</td>
<td>0.57</td>
<td>0.76</td>
<td>1.1</td>
<td>1.64</td>
</tr>
<tr>
<td>Bearing fault</td>
<td>0.53</td>
<td>0.61</td>
<td>0.77</td>
<td>1.22</td>
<td>1.88</td>
</tr>
</tbody>
</table>

Fig.13. Normalized splitting severity factor for mechanical faults

IV. CONCLUSIONS

From this study we can conclude that the extended Park’s vector spectrum is rich in harmonics characteristics of mechanical defects (air-gap eccentricity and outer raceway bearing fault). Experimental investigation showed the existence of other harmonics than those presented in [6] for the case of default of eccentricity, and in [9] for the case of bearing fault. Note that the bearing studied in [9] is the same used in our test bench.

About the use of Park’s Lissajou’s curves to identify mechanical defects, we have shown that this type of index can only detect the occurrence of a fault, but it cannot identify.

REFERENCES


