Effects of Static Eccentricity on the Temperature Distribution in a Three-Phase Induction Motor

B. R. O. Baptista¹, A. M. S. Mendes², S. M. A. Cruz¹, A. J. M. Cardoso⁴

University of Coimbra / Instituto de Telecomunicações
Department of Electrical and Computer Engineering, Pólo II - Pinhal de Marrocos,
P - 3030-290 Coimbra, Portugal
brunobapt@gmail.com¹, amsmendes@ieee.org², smacruz@ieee.org³, ajmcardoso@ieee.org⁴

Abstract- Motors are vital components in industrial and electrical utilities. In spite of the emergence of new types of electric machines, the squirrel-cage induction motor remains the dominant one. A motor failure can result in large lost revenues. Therefore it becomes convenient to study the consequences of faults in these motors. One of types of faults that can occur in these motors is airgap eccentricity. This paper presents results, based on a Finite Element Analysis, demonstrating the influence of this type of fault in the motor temperature distribution. It is shown that static eccentricity leads to a non-uniform temperature distribution and contributes to the rise of the highest temperature spot in the motor, hence potentially shortening the lifespan of the stator insulation system.

I. INTRODUCTION

Airgap eccentricity is a fault mechanism which can occur in induction motors where the airgap between the stator and rotor is no longer uniform. The reasons for eccentricity include intrinsic shaft tolerance, ball-bearings defects or problems related with the fixing of these motor parts [1]-[2].

Eccentricity is usually classified as static, dynamic and mixed. Static eccentricity is characterized by a displacement of the rotation axis of the rotor with regard to the geometric centre of the stator. Since the rotor is not centered within the stator bore, the field distribution in the airgap is no longer symmetrical. Dynamic eccentricity occurs when the rotation axis of the rotor does not coincide with its geometric centre. In practice, static and dynamic eccentricities tend to coexist. Under these circumstances, it is said that we are in the presence of mixed eccentricity [3], [9]-[13], [15].

In case a motor develops static eccentricity, the field distribution in the airgap is no longer symmetrical. As a result of that, the eccentricity creates additional motor vibrations and unbalanced magnetic pull (UMP), which can be large enough to cause a stator to rotor rub, thus resulting in serious damage to both the stator core and windings. Furthermore, eccentricity causes a non-uniform temperature distribution in the motor, hence leading to additional thermal stresses, which contribute to the appearance of other motor faults [7]-[8], [12], [14].

A critical factor that shortens the motor life is heat. The insulation type used in an electric motor depends on the temperature at which motor will operate.

The relationship between temperature and its effects on the life of the motor’s insulation system has been studied for many years. Montsinger has introduced the concept of the 10º C rule according to which the life of the insulation system is halved for each additional 10º C in the temperature at which it is exposed [3]-[6].

Accordingly to IEC standards, the insulating materials used in electric motors can be classified into four thermal classes, which are presented in Table 1.

Fig 1 shows the life of the insulation system versus the temperature rise [16]. For instance from Fig.1, for a class F insulation material, an increase of 10ºC (from 160º-170º) in temperature will lead to a reduction of about 10000 h in the insulation lifetime.

The research results presented in this paper aim to investigate the temperature distribution in a 4kW, class F induction motor with static eccentricity. This study is developed through a thermal model of the motor, based on a finite element analysis.

Table 1 - Thermal classes of insulating materials (adapted from standards IEC 60085, IEC 60034-1).

<table>
<thead>
<tr>
<th>Temperature class</th>
<th>Hot spot allowance (Cº)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>105</td>
</tr>
<tr>
<td>B</td>
<td>130</td>
</tr>
<tr>
<td>F</td>
<td>155</td>
</tr>
<tr>
<td>H</td>
<td>180</td>
</tr>
</tbody>
</table>

![Fig. 1 - Insulation life versus temperature rise.](image_url)
II. 2D FINITE-ELEMENT MODEL

In order to analyze the motor temperature distribution under the presence of static eccentricity, several simulation tests were performed using a finite element model (FEM) developed for this purpose.

The test motor used in the simulations is a totally enclosed fan cooled (TEFC) three-phase squirrel-cage induction motor of 4 kW, 380 V, 50 Hz, 9.2 A, 1436.25 rpm, 26.6 N.m, \( \cos (\Phi) = 0.8 \), with an airgap of 0.28 mm. The stator windings are star-connected.

Initially, a steady-state magnetic application, coupled with the electric circuit shown in Fig. 3, was taken into consideration, to calculate the nominal motor characteristics. A correct knowledge of the values of all elements of that circuit is essential to obtain accurate results. The mobile part of the motor is shown in the electric circuit with the bars made of conductive material (aluminum), represented by \( M1, M2...M28 \). On the other hand, \( L4, L5...L31 \) represent the leakage inductance of the bars, which is calculated using (1)-(2). Moreover, to model the squirrel cage it is necessary to include the end-rings that short-circuit the rotor bars. Each segment of the end-rings is modeled through a resistance (\( R29...R84 \)) series-connected with a leakage inductance (\( L32...L87 \)), whose values are calculated using (3)-(15) and (16)-(17), respectively. The stator circuits are fed with a balanced voltage supply system consisting in three sinusoidal voltage sources, \( V_R, V_s \) and \( V_T \) with a rms value of 220 V. Each phase has two stranded coils (\( B1, B2, B3, B4, B5, \) and \( B6 \)) in order to represent the going and back side of each coil. The resistances of those stranded coils are calculated by (23) and (24), while the end winding region is represented by \( L1, L2 \) and \( L3 \) and calculated using (18)-(22).

Fig. 2 shows the geometrical mesh model of the induction motor. Table 2 contains some material parameters used in the motor FEM and Table 3 the corresponding solver information. Simulations were performed with a simulated environment temperature of 20ºC.

\[
\lambda_r = \frac{h_r}{3 \cdot b_i} \left( 1 - \frac{\pi \cdot b \cdot h}{8 \cdot S_b} \right)^2 + 0.66 - \frac{h_{or}}{2 \cdot b_i} + 0.3 + 1.12 \cdot h_{or} \cdot \frac{10^3}{l_b} \quad (1)
\]
\[
L_b = \mu_0 \cdot l_b \cdot \lambda_r \quad (2)
\]
\[
R_{ev} = \frac{\rho_{Al} \cdot \pi \cdot p \cdot (D_e - D_i)}{e \cdot h_0} \cdot \frac{(D_i^2)\rho + (D_i^2)\rho}{(D_i^2)\rho - (D_i^2)\rho} \quad (3)
\]
\[
\delta = \sqrt{\frac{4 \pi^2 + f_1}{\rho_{Al} \cdot 10^7}} \quad (4)
\]
\[
\xi = h_b \cdot \delta \quad (5)
\]
\[
K_x = \xi \cdot \frac{\sinh(2\xi) + \sin(2\xi)}{\cosh(2\xi) - \cos(2\xi)} \quad (6)
\]
\[
h_x = h_{bq} - \frac{D_e - D_i}{2} = h_{bq} \quad , \quad D_e = D_i \quad (7)
\]

\[
h_{eq} = \frac{\rho_{Al} \cdot \pi \cdot D_i}{R_w \cdot e + \pi \cdot p_{Al}} \quad (8)
\]
\[
X = \frac{h_{eq}}{h_n} \quad (9)
\]
\[
k = \begin{cases} \frac{0.01X^2 - 0.08X + 1.07}{-0.01X + 0.977} & \text{if } X < 2.36 \\ \text{otherwise} & \end{cases} \quad (10)
\]
\[
h_{bq} = \frac{h_b}{K_x} \quad (11)
\]
\[
e_{eq} = \frac{e \cdot k}{K_x} \quad (12)
\]
\[
D_{eq} = D_{eb} - h_{bq} - h_{or} \cdot 2 \quad (13)
\]
\[
D_{eq} = D_{eb} - h_{eq} \cdot 2 \quad (14)
\]
\[
R_{evs} = \frac{1}{N_r} \cdot \frac{\rho_{Al} \cdot \pi \cdot p \cdot (D_{eq} - D_{eq})}{e \cdot h_{eq}} \cdot \frac{(D_{eq})^p + (D_{eq})^p}{(D_{eq})^p - (D_{eq})^p} \quad (15)
\]
\[
\lambda_i = \frac{2.3 \cdot D_i}{4 \cdot N_r \cdot L \cdot \left( \sin \frac{\pi \cdot D_i}{N_r} \right)^2 \cdot \log \left( \frac{4.7 \cdot D_i}{(e + 2 \cdot h)} \right)} \quad (16)
\]
\[
L_{ei} = 4 \pi \cdot 10^{-7} \cdot L_i \cdot \lambda_i \quad (17)
\]
\[
L_{ew} = \frac{\pi}{2 \cdot p} \cdot (D_{s, int} + 2 \cdot h_{as}) + 2 \cdot h_{ss} \quad (18)
\]
\[
L_{ap} = \frac{\pi}{2 \cdot p} \cdot (D_{s, int} + h_{ss}) \quad (19)
\]
\[
\gamma = 0.67 \cdot L_{eqv} - 0.43 \cdot L_{ap} \quad (20)
\]
\[
L_{cb} = \frac{\mu_0}{18 \cdot p} \cdot \frac{(N_{pp} N_{pp})^2}{N_c} \cdot \gamma \quad (21)
\]
\[
L_f = 2 \cdot L_{cb} \quad (22)
\]
\[
R_{cu} = \rho_{cu} \cdot \frac{l}{S_{cu}} \quad (23)
\]
\[
R_{group} = N_{pp} \cdot R_{cu} \quad (24)
\]

Fig. 2 - Geometrical model and illustration of the finite element mesh.
Table 2 - Material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity: 0.042W/m.°C</th>
<th>Volumetric heat capacity: 1005 J.m⁻³.°C⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.042W/m°C</td>
<td>1005 J.m⁻³.°C⁻¹</td>
</tr>
<tr>
<td>Steel</td>
<td>27W/m°C</td>
<td>3.536E6 J.m⁻³.°C⁻¹</td>
</tr>
<tr>
<td>Copper</td>
<td>K(T)=Ka(1+a(T-T₀))</td>
<td>a=-0.01, Ka=380, T₀=20</td>
</tr>
<tr>
<td>Aluminum</td>
<td>K(T)=Ka(1+a(T-T₀))</td>
<td>a=-3E⁻⁴, Ka=204, T₀=20</td>
</tr>
</tbody>
</table>

Table 3 - Solver information

<table>
<thead>
<tr>
<th>Eccentricity level</th>
<th>Matrix (solver):number of lines</th>
<th>Excellent quality elements (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>110104</td>
<td>94.95</td>
</tr>
<tr>
<td>3/6</td>
<td>117301</td>
<td>91.12</td>
</tr>
<tr>
<td>5/6</td>
<td>115384</td>
<td>88.48</td>
</tr>
</tbody>
</table>

Finally, the procedure followed to introduce static eccentricity in the model is illustrated in Fig. 4. The \( dx \) variable represents the eccentricity deviation, along the \( x \)-axis, with regard to the normal position.

III. SIMULATION RESULTS

The simulation tests were performed for a healthy and eccentric motor, with a load torque of 26.6 N.m. Moreover, different levels of eccentricity were simulated, namely 1/6, 2/6, 3/6, 4/6 and 5/6. Due to the lack of space, this paper only presents results for the case of the motor running in healthy conditions as well as when it has an eccentricity level of 3/6 and 5/6, as summarized in Table 4.

Fig. 5 shows the temperature distribution in the stator of the motor when it is in healthy conditions. As it can be observed, the stator temperature varies in the radial direction and has a symmetric distribution with regard to the center of the rotor, meaning that the points located along a circular radius path centered at point (0,0) have an identical temperature.

Fig. 6 depicts the radial temperature variation. It is important to notice the higher rotor temperature compared to the stator. Moreover the rotor temperature gradient is much smaller. The rotor is one of the major heat sources in the motor. The temperature distribution in the motor, in the presence of eccentricity, is shown in Fig. 7.

Fig. 7a) shows the temperature variation of the points located along a circular path centered at point (0,0). Fig. 7b) shows the temperature distribution in the stator with an eccentricity level of 3/6.

It can be observed that when the motor has eccentricity, the temperature distribution is no longer symmetrical in relation to point (0,0). There is a 4.5 °C variation along the selected path. Note that Fig. 7 b) is rotated 90 degrees clockwise compared to Fig 4.
Finding the highest winding temperature spots is crucial to insulation (and machine) working life. The highest temperature spots in the stator are shown in Table 5. By comparing the case of the healthy motor with the situation of 5/6 eccentricity, it is observed an increase of 6.61 ºC in temperature.

To complement the results presented so forth, Fig. 8 shows the temperature evolution at a point in the stator (red round marker in Fig. 4 at |X|=72 mm and |Y|=0 mm), for the non-eccentric motor (represented by the blue line) and for the motor with two different levels of static eccentricity: 3/6 (represented by the red line) and 5/6 (represented by the green line). As it can be seen, for the same point, three different temperature curves are obtained, hence supporting the conclusion that eccentricity increases the maximum motor temperature.

On the other hand, for the eccentric motor, the field distribution in the airgap is no longer symmetrical. As a consequence of that, it gives rise to an UMP as mentioned before.

Figs. 9 and 10 show the flux density magnitude and radial airgap length along a circular radius path in the airgap, plotted against an angular position measured with regard to the stator, for the non-eccentric and eccentric motor with 5/6 of eccentricity, respectively. As it can be seen from Fig. 10, when the airgap length decreases (blue line), the flux density magnitude increases, in contrast with what is shown in Fig 9.

![Fig. 4 - Airgap flux density versus angular position (healthy motor).](image)

![Fig. 5 - Airgap flux density and radial airgap length versus angular position (5/6 eccentricity level).](image)

### Table 5 - Highest temperature spot in the stator.

<table>
<thead>
<tr>
<th>Eccentricity level</th>
<th>Highest temperature spot in the stator (degree Cº)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>96.68</td>
</tr>
<tr>
<td>3/6</td>
<td>99.87</td>
</tr>
<tr>
<td>5/6</td>
<td>103.29</td>
</tr>
</tbody>
</table>

IV. CONCLUSION

The temperature rise inside the motor can affect several motor components such as the stator windings. These simulation results shown in this paper have demonstrated that motor faults such as eccentricity cause a non-uniform distribution of temperature in the motor, as well as an increase in the highest stator temperature. Since the motor lifespan is directly related to its working temperature, the eccentricity, if present for long periods of time, can shorten the lifetime of the insulation system of the windings, which may eventually lead to a failure in this motor component.

Further studies are to be conducted in order to show the influence of other types of eccentricity in the motor temperature.
V. ACKNOWLEDGEMENT

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VI. REFERENCES


