Effects of the Short-Circuit Faults in the Stator Winding of Induction Motors and Fault Detection through the Magnetic Field Harmonics

Alexandru-Ionel CONSTANTIN¹, Virgiliu FIRETEANU¹, Vincent LECONTE²

¹POLITEHNICA University of Bucharest, EPM_NM Laboratory, 313 Splaiul Independentei, Bucharest, ROMANIA
²CEDRAT SA, 15 Ch. de Malacher Inovallée, 38246 Meylan Cedex, FRANCE
constantin.alex.ionel@gmail.com, virgiliu.fireteanu@upb.ro, vincent.leconte@cedrat.com

Abstract- Based on the finite element analysis of the electromagnetic field in time domain, this paper studies effects of the short-circuit faults in the stator winding of an induction motor and the influence of this fault on the magnetic field outside the motor. The detection of the short-circuit fault through the magnetic field is based on the comparison of harmonics of the output voltage of coil sensors for the healthy and faulty motor states. The influence of the magnetic saturation of the motor on the fault diagnose efficiency is studied.

Keywords: Induction machine, stator winding short-circuit, fault detection, finite element analysis

I. INTRODUCTION

The interest for the finite element investigation of the electromagnetic field in electrical machines increases. The numerical simulation of the healthy and faulty operation states, respectively the study and detection of different faults based on the finite element models, offers a deeper understanding of the associated phenomena [1 – 10].

This paper studies short-circuit faults in the stator winding [10] based on Flux2D finite element models [11]. The effects of faults on the time variation of the current, of the electromagnetic torque and of the unbalanced force acting on the rotor are studied. The magnetic field outside the motor is investigated through the time variation of the output voltage of coil sensors in case of healthy and faulty motor states, for no load and for loaded motor operation.

II. FINITE ELEMENT MODEL AND THE TIME DOMAIN ANALYSIS OF THE ELECTROMAGNETIC FIELD FOR THE INVESTIGATION OF THE SHORT-CIRCUIT FAULTS

The geometry and mesh of the electromagnetic field 2D computation domain in Fig. 1 (a), (b) and the circuit model, Fig. 1 (c), correspond to a four poles squirrel cage induction motor of 11 kW, rated supplied 3 x 380 V; \( f_n = 50 \) Hz, delta winding connection. The computation domain contains the stator and the rotor cores that are magnetic and nonconductive regions, 48 stator slots - nonconductive, nonmagnetic and source regions, the 32 bars of the rotor squirrel cage aluminum made, the motor frame (8 mm thickness, 0.045 \( \mu \)Ωm) and the motor shaft, which are regions of solid conductor type, the motor airgap and the infinitely extended air region outside the motor. In order to investigate the magnetic field in this last region, the computation domain includes two coil sensors around a magnetic core, Sensor\( \text{Ox} \), whose sides in Fig. 1 (b) is blue colored, and Sensor\( \text{Oy} \) in red color, located in near proximity of the motor.

Fig. 1. Geometry (a) and mesh (b) of the electromagnetic field computation domain and the circuit model (c)
The Phase B and the Phase C of the stator winding are represented in the circuit model, Fig. 1 (c), by four coil components that reflects the four groups representing each the four go- and the four return sides of the elementary coils. Each elementary coil occupies two stator slots and four elementary coils series connected represent one stator pole. The three inductance components in Fig. 1 (c) correspond to the stator winding outside the stator core.

It is the Phase A, Fig. 1 (c), of the stator winding where the short-circuit faults are considered. The part of this winding representing one stator pole, which regroups four elementary coils, is represented in the circuit model, Fig. 1 (c), through eight coil components. These are the go- and the return sides of the four elementary coils. Through the four resistors in the circuit model, Fig. 1 (c), it is possible to simulate the short-circuit of one, of two, of three or of four elementary coils of of the Phase A.

For each of the two sensors, the circuit model, Fig. 1 (c), includes two coil components and a resistor of high resistance for the evaluation of sensors output voltage.

The state variable of the electromagnetic field - the magnetic vector potential \( \mathbf{A}(x,y,z,t) \), satisfies the following differential equations:

\[
\text{curl}\left[\frac{1}{\mu} \text{curl} \mathbf{A}\right] + \left(\frac{\partial \mathbf{A}}{\partial t}\right)/\rho = \mathbf{J}_s(x,y,z,t); \text{div} \mathbf{A} = 0 \quad (1)
\]

where \( \mu \) is the magnetic permeability, \( \rho \) is the resistivity and \( \mathbf{J}_s \) is the current density in the stator slots. The term \((\partial \mathbf{A}/\partial t)/\rho\) reflects the density of the induced current in the regions of solid conductor type.

In the 2D field model considered in this paper the source current density has the structure \( \mathbf{J} = 0, \mathbf{J}_s(x,y,t) \). As consequence, the vector potential \( \mathbf{A} = 0, \mathbf{A}_s(x,y,t) \) is oriented along the \( \mathbf{Oz} \) axis and does not depends on the coordinate \( z \). The second equation (1) is implicitly satisfied.

The investigation of the electromagnetic field inside and outside the motor uses the transient magnetic model of the induction motor [6] with imposed constant speed 1450 rpm for the rated load motor operation and the synchronous speed 1500 rpm for ideal no load motor operation. The value \( \Delta t = 0.05 \text{ ms} \) of the time step is considered in the time domain analysis of the electromagnetic field. Thus, the harmonic variations with the frequency equal or less than 1000 Hz are evaluated in at least 20 steps on a period.

The results in this paper concern the steady state of the electromagnetic field, in which the amplitudes of all electric and field quantities are time independent. Since the steady state of the transient solution is reached in about 0.5 s from the computation start \( t = 0 \), the time interval \((0.52...0.6) \text{ s}\) is considered for the results analysis.

III. EFFECTS OF THE STATOR SHORT-CIRCUIT FAULTS ON THE MOTOR OPERATION PARAMETERS

Taking into account small values of the resistance for the first, respectively for the last short-circuit resistors in the Phase A of the motor, Fig. 1 (c), the short-circuits of one elementary coil, respectively of four elementary coils series connected are simulated. The time variation of the Phase A current for the loaded motor is different for the healthy state, Fig. 2 (a), for the faulty states with one elementary coil in short-circuit, Fig. 2 (b) and with four coils in short-circuit, Fig. 2 (c). The corresponding rms values of the Phase A current are 12.88 A, 13.83 A and 28.29 A respectively.

The figures 3 and 4 show amplitudes of the harmonics of the Phase A current for the healthy (cyan) and faulty motors (red) in the cases one coil short-circuit, respectively four coils short-circuit. If in the first case the amplitude of the main harmonic of 50 Hz has only a slight increase, in the second case this harmonic increases 2.2 times.
In comparison with the healthy state, Fig. 5 (a), the electromagnetic torque time variation is slightly different for one coil in short-circuit, Fig. 5 (b). The difference is important for four coils in short-circuit, Fig. 5 (c). The corresponding mean values of the electromagnetic torque are 76.78 Nm, 76.26 Nm and 73.01 Nm, respectively.

The increase of the number of harmonics under 2500 Hz of the electromagnetic torque is evident when pass from the healthy, Fig. 6 (a), to one coil short-circuit fault, Fig. 6 (b), and to four coils short-circuit, Fig. 6 (c). The amplitude of the 100 Hz harmonic increases 963.8 times from the case (a) to case (b) and 4052.8 times from (a) to (c).

The most important effect of the stator short-circuit faults concerns the unbalanced electromagnetic force on the rotor.
IV. THE SHORT-CIRCUIT FAULTS AND THE OUTPUT VOLTAGE OF COIL SENSORS

This section analyses results related the time dependence of the output voltage of SensorOx and SensorOy coil sensors and the amplitude of this voltage harmonics in the ranges [0 … 1000] Hz and [500 … 1000] Hz when pass from the healthy state to one of the faulty states. The main interest is to choose an efficient solution for the detection of faulty states through the magnetic field outside the motor. The loaded motor with the speed 1450 rpm is considered in the first part and the ideal no load operation with 1500 rpm after.

**Loaded motor:** The rms value of the SensorOx voltage with time variations in Fig. 9 is as follows: 1148.0 mV for the healthy motor (a), 1154.9 mV for the one coil short-circuit (b) and 1708.0 mV for the four coils short-circuit (c).

The amplitudes of different harmonics for the healthy and the one coil short-circuit states, Fig. 10, are not so different. Figure 11 shows four coil short-circuit an important increase in of the 50 Hz harmonic and of an important number of harmonics in the range [500 ... 1000] Hz. The most important, the 925 Hz harmonic, increases roughly two times. The 550 Hz, 650 Hz, 850 Hz and 950 Hz harmonics increases more than two times in the faulty state.

![Fig. 9. Time variation of SensorOx voltage for the healthy motor (a), one coil short-circuit fault (b) and four coils short-circuit fault (c).](image)

![Fig. 10. Amplitude of harmonics of SensorOx voltage. Comparison healthy motor - one coil short-circuit fault.](image)

![Fig. 11. Amplitude of harmonics of SensorOx voltage. Comparison healthy motor – motor with four coils short-circuit fault.](image)

Similar results for SensorOy related the time variation of the output voltage are presented in Figs. 12 and 13. The rms value of the SensorOy output voltage are 1448.5 mV for the healthy motor (a), 1396.5 mV in case of one coil short-circuit (b) and 870.4 mV in case of four coils short-circuit (c).

![Fig. 12. Time variation of SensorOy voltage for the healthy motor (a), one coil short-circuit fault (b) and four coils short-circuit fault (c).](image)

![Fig. 13. Amplitude of harmonics of SensorOy voltage. Comparison healthy motor – motor with one coil short-circuit fault.](image)
The amplitude of different harmonics for the healthy state and the two faulty states, Figs. 13 and 14, is different from those corresponding to SensorOx. The amplitude of an important number of harmonics generated by the short-circuit fault decreases.

![Image of harmonic frequency plot]

**Fig. 14. Amplitude of harmonics of SensorOy voltage. Comparison healthy motor – motor with four coils short-circuit fault.**

No load motor operation. The rms value of the SensorOx voltage with the time variation in Fig. 15, is 1620.2 mV for the healthy motor (a) and 1570.6 mV for one coil short-circuit (b). Harmonics in the range [500 ... 1000] Hz, Fig. 16, increase when pass from the healthy state to the faulty state.

![Image of time variation plot]

**Fig. 15. Time variation of SensorOx voltage for the healthy motor (a) and for the motor with one coil short-circuit fault (b). No load motor operation.**

The rms value of the SensorOy voltage with the time variations in Fig. 17 is 1682.5 mV for the healthy motor (a) and 1504.3 mV for one coil short-circuit (b). Similarly with SensorOx, harmonics in the range [500 ... 1000] Hz, Fig. 18, have a very important increase when pass from the healthy to the faulty state.

![Image of harmonic frequency plot]

**Fig. 16. Amplitude of harmonics of SensorOx voltage. Comparison healthy motor – motor with one coil short-circuit fault. No load motor operation.**

**Fig. 17. Time variation of SensorOy voltage for the healthy motor (a) and motor with one coil short-circuit fault (b). No load motor operation.**

**Fig. 18. Amplitude of harmonics of SensorOy voltage. Comparison healthy motor – motor with one coil short-circuit fault. No load motor operation.**

The comparison of the results for the cases Loded motor and No load motor operation shows that the last one must be the choice for the short-circuit fault detection based on harmonics of the magnetic field outside the motor. The 650 Hz is the frequency of the most appropriate harmonics for the fault detection with both sensors.

V. MAGNETIC SATURATION AND THE EFFICIENCY OF THE SHORT-CIRCUIT FAULTS DETECTION

The motor without frame is considered for the study of the influence of the magnetic saturation. The one coil short-circuit fault is considered.

All simulations whose results were previously analyzed correspond to the rated value 380 V of the rms voltage of the three voltage sources in Fig. 1 (c). The corresponding maps of the magnetic flux density, Fig. 19 (a), and of the relative magnetic permeability, Fig. 20 (a), emphasize an important level of the saturation of the motor magnetic cores.

If the supply voltage decreases from 380 V to 220 V, the saturation decreases and the mean value of the magnetic permeability, Fig. 20 (b), increases. The time variation of
the magnetic field outside the motor will be less influenced by the magnetic nonlinearity of the motor laminations.

**Loaded motor:** The most important harmonic of the coil sensors output voltage for motor operation at 1450 rpm has the frequency 525 Hz. The results in Table 1 show the decrease of the amplitude of this harmonic when the short-circuit fault appears, SensorOy being more sensitive. The decrease of the amplitude of the 525 Hz harmonic when pass from the healthy state to the faulty state is more important when the level of the magnetic saturation decreases, respectively when the 380 V supply is replaced by 220 V.

**No load motor operation:** In case of 1500 rpm motor speed, two harmonics were considered in Tables 2 and 3. The increase of the amplitude when the fault appears is much more important for the 650 Hz than for 550 Hz. This increase is much more important for the 550 Hz harmonic when pass from the 380 V supply to 220 V. Consequently, the no load motor operation with supply voltage lower than the rated value it is a better solution to detect the appearance of a short-circuit in the stator winding through harmonics of the magnetic field outside the motor with frequency in the range [500 ... 1000] Hz.

<table>
<thead>
<tr>
<th>Supply [V]</th>
<th>380</th>
<th>220</th>
<th>380</th>
<th>220</th>
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<tr>
<td>Healthy</td>
<td>553.6</td>
<td>8.232</td>
<td>622.6</td>
<td>11.78</td>
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<tr>
<td>Faulty</td>
<td>519.8</td>
<td>6.913</td>
<td>266.7</td>
<td>3.473</td>
</tr>
<tr>
<td>Faulty / Healthy</td>
<td>0.84</td>
<td>0.84</td>
<td>0.43</td>
<td>0.295</td>
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</tbody>
</table>

Table 1. Amplitude of SensorOx and SensorOy 525 Hz harmonic in [mV]

<table>
<thead>
<tr>
<th>Supply [V]</th>
<th>380</th>
<th>220</th>
<th>380</th>
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<tbody>
<tr>
<td>Healthy</td>
<td>64.4</td>
<td>0.199</td>
<td>31.1</td>
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<td>76.7</td>
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<tr>
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<td>1.19</td>
<td>24.43</td>
<td>4.19</td>
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</table>

Table 2. Amplitude of SensorOx and SensorOy 550 Hz harmonic in [mV]

VI. CONCLUSIONS

The short-circuit fault in the stator winding is reflected in the rms values and the spectrum of stator currents harmonics and in the harmonics spectrum of the electromagnetic torque. But the most important effect of this fault related the motor operation concerns the unbalanced electromagnetic force on the rotor armature. The detection of the short-circuit fault in the stator winding based on the evaluation of the harmonic s in the range [500 ... 1000] Hz of the magnetic field outside the motor represents a simple and very efficient solution. It was proved that the change of the amplitude of some harmonics of the output voltage of coil sensors placed near the motor when the short-circuit appears is more important in case of motor no-load operation than in case of loaded motor. A better efficiency of the fault detection is obtained if the magnetic core of the motor is characterized by a lower magnetic saturation.

It rest to verify in perspective if similar conclusions are valid for motors with another number of poles or with other numbers of stator and rotor slots.

REFERENCES


