

Modelling and Detection of Inter-Turn Short Circuits in Stator Windings of Induction Motor

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Abstract—This paper is devoted to the development of a mathematical model of the induction motor operating under stator inter-turns short-circuits. The model is based on the multiplied coupled circuit approach. The inductances calculation is performed thanks to an extension in 2-D of the modified winding function approach (eMWFA), which is able to take into account the space harmonics in addition to the effects of rotor bar skewing and to the linear rise of MMF across the slots. One have to note that an appropriate extension of this model can consider the stator winding faults in presence of broken rotor bars or static, dynamic or axial eccentricity. It is shown that the inter-turn short circuit gives rise to some spectral components witch appear in the current line spectrum. Some experimental tests validate these results and confirm the presence of other components due to several phenomenons cited in previous works.

Index Terms—Diagnosis, stator faults, inter-turns short-circuit, induction machines, stator current.

I. INTRODUCTION

The squirrel cage, 3-phase AC induction motors are the most common prime machines in industrial processes. This is chiefly due to their low cost, reasonable size, ruggedness and low maintenance. In industrialized nation, they can typically consume between 40 to 50% of all the generated capacity of these countries [3]. Usually, the induction motors work under many stresses from various nature (thermal, electric, mechanical and of environment) which can affect their lifespan by involving the occurrence of stator and/or rotor faults [1], [2]. The need for on-line condition monitoring of large induction motors has increased because a sudden failure of critical motor can cause great economical losses. Therefore, the main goal of the operator of electrical drives is to reduce the maintenance costs and to prevent unscheduled downtime of these machines.

Failure surveys [6] have reported that 40% of the motor failures were caused by bearing related failures, 38% by stator winding failures, 10% by rotor related failures and 12% by mixed failures which affect other parts of the machine. It is now obvious that the stator winding breakdown is one frequent fault in induction motors. Also, it should be noted that the majority of stator winding failures result from crash of turn-to-turn insulation (Fig. 1). These failures are usually due to an electrical, thermal, mechanical and environmental stress.

Early detection of inter-turn short circuit during motor operation would eliminate some subsequent damage to adjacent coils and stator core, reducing repair cost and motor

outage time. As exposed in several preceding works, many techniques studied the detection of turn-to-turn faults.

Penman and al [12] have used the axial leakage flux monitoring as a method for detecting the occurrence of an inter-turn short circuit by means of a large coil fixed concentrically around of the shaft of the machine, whilst the motor was operating. Also, they state that the fault position could be located by monitoring four coils placed symmetrically in the four quadrant of the motor at a radius of about half the distance from the shaft to the stator end winding. In [3], Thomson and al proved through a lot of experimental results on industrial motors that we can diagnose accurately shorted turns in low voltage stator windings of induction motors by using the motor current signature analysis (MCSA) based on the monitoring of the frequency components expressed by:

$$f_{sc} = f_s \left\{ \frac{n}{p} (1-s) \pm k \right\} \quad (1)$$

where f_{sc} is the spectral component indicating of turn-to-turn faults, f_s is the supply frequency, $n = 1, 2, 3, \dots$, $k = 1, 3, 5, \dots$, p is the number of pole pairs and s is the slip.

Also, it was shown in [3] that these components are less sensitive to the load changes which are not the case in the axial leakage flux monitoring. In [13], techniques based on the measurements of negative-sequence impedance or negative-sequence current were presented. However, negative sequence can also be caused by voltage unbalance, machine saturation etc. In [14], Nandi and al. proposed a novel method based on the monitoring of certain rotor-slots-related harmonics at the terminal voltage of the machine, once it is switched off. Unlike negative sequence current or impedance measurement, this technique is insensitive to supply voltage unbalance. In [10], it was reported that the observation of the air-gap torque could be used as a method to diagnose some faults both on stator or rotor side. The Extended Park's Vector Approach (EPVA) has also been successfully applied in the diagnosis of inter-turn stator winding faults in three-phase induction motors by monitoring the behaviour of a spectral component at twice the fundamental supply frequency [15]. It was shown that the amplitude of this spectral component is directly related to the degree of asymmetry of the motor winding.

In order to monitor precisely the squirrel cage induction motors, we have to elaborate an accurate model which enables us to predict the performances and to extract faults signatures

on electromagnetic torque, stator current, axial flux, etc. However, it should be taking into consideration two opposite criteria: the performance of the model and the computation time. Several modelling and simulation studies have been published, related to the analysis of the presence of internal faults in the stator winding induction motors. In [11], Tallam and al. presented a transient model using reference frame transformation theory. The dynamic equations presented in state space form which are suitable for digital simulation. This model has limitations because it was based on restrictive assumptions. In [16], Bachir presented a novel model which takes into account the effects of shorting of one or more circuits of stator phase winding by introduction of the short-circuit elements in the conventional Park's model. Then, the application of parameter estimation technique allows the detection and the localization of faults in the three phase stator winding.

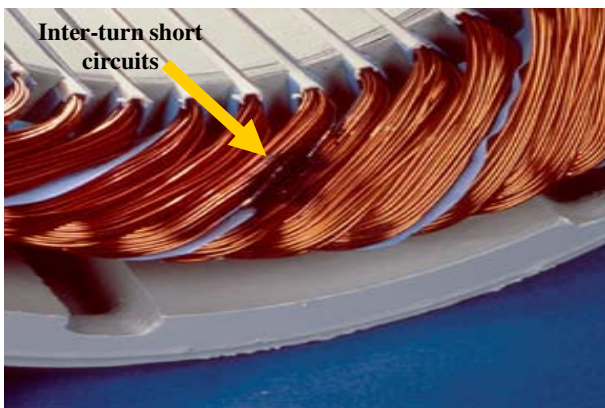


Fig. 1. Consequences of inter-turn short-circuit.

In this work, an accurate transient model of squirrel cage induction motors under stator faults is presented. The study of the stator failures made by [4] will be completed by taking into account the effects of the skewing rotor bars and opening slots thank to eMWFA [17], [18]. The expressions of inductances resulting from this technique are less complicated to be implemented into algorithm than those obtained starting from the expression of inductance per unit of length given in [5]. The data obtained with this model can provide useful informations about the electric behaviour of the motors under stator winding faults conditions. This is our main goal.

II. SYSTEM EQUATIONS

Let us suppose that the rotor cage is a whole of meshes connected between them electrically and coupled magnetically, one can lead to the following voltage equations:

$$[U_s] = [R_s][I_s] + \frac{d[\psi_s]}{dt}, \quad (2)$$

$$[0] = [R_r][I_r] + \frac{d[\psi_r]}{dt}, \quad (3)$$

$$[\psi_s] = [L_{ss}][I_s] + [L_{sr}][I_r], \quad (4)$$

$$[\psi_r] = [L_{rs}][I_s] + [L_{rr}][I_r]. \quad (5)$$

where $[U_s]$ is the vector of stator voltages, $[I_s]$ and $[I_r]$ are the stator and rotor current vectors, m is the number of stator phases, N_b is the number of rotor bars, $[R_s]$ is $(m \times m)$ stator resistance matrix, $[L_{ss}]$ is $(m \times m)$ stator inductance matrix, $[L_{sr}]$ is mutual inductance $m \times (N_b + 1)$ matrix, $[R_r]$ and $[L_{rr}]$ are $(N_b + 1) \times (N_b + 1)$ matrixes from the rotor resistance and inductance respectively.

The equations describing the mechanical parts of the system are:

$$C_e - C_r = J_r \frac{d\omega_r}{dt} \quad (6)$$

with

$$C_e = \left(\frac{dW_{co}}{d\theta_r} \right)_{(I_s, I_r = \text{constant})} \quad (7)$$

and

$$W_{co} = \frac{1}{2} ([I_s]^T [L_{ss}] [I_s] + [I_s]^T [L_{sr}] [I_r] + [I_r]^T [L_{rr}] [I_r] + [I_r]^T [L_{rs}] [I_s]), \quad (8)$$

where W_{co} is the co energy, C_e is the electromagnetic torque, C_r is the load torque, J_r the rotor load inertia and ω_r is the mechanical speed.

III. CALCULATION OF INDUCTANCES

A. General Case

It is very important to know that the accuracy of the calculation of the magnetisation and mutual inductances is the key point to a successful simulation of the induction motors. All inductances of the system are calculated using the eMWFA. Let us suppose that we have two windings A and B composed of A_i and B_j coils (where $i=1, 2, \dots, q$ and $j=1, 2, \dots, p$). Each coil is composed of w turns. Thus, in case of a uniform air-gap, the inductance between any two coils A_i and B_j (the permeability of magnetic circuit is supposed infinite) can be evaluated by the following expression:

$$L_{B_j A_i}(x_r) = \frac{\mu_0}{g_0} \int_0^{2\pi r l} N_{A_i}(x, z, x_r) n_{B_j}(x, z, x_r) dz dx \quad (9)$$

Where: l is the effective length, r is the average radius of the air-gap and g_0 is the average length of the air-gap. Note that like describing in [7], $N_{A_i}(x, z, x_r)$ is the spatial winding function of the coil A_i and $n_{B_j}(x, z, x_r)$ is the spatial turns distribution of B_j . According to the manner of the coils connections, this inductance is obtained by summing all mutual inductances between the q and p coils of windings A and B respectively, such as:

$$L_{BA}(x_r) = \sum_{i=1}^q \sum_{j=1}^p \pm L_{B_j A_i}(x_r) \quad (10)$$

B. Introduction of the Skewing Rotor Bars

Considering the axial asymmetry due to skew, and according to Fig. 2, the mutual inductance between coil A_i and the rotor loop r_j is given by the following expression:

$$L_{A_i r_j}(x_r) = \frac{\mu_0}{g_0} \int_{x_{1j}}^{x_{2j}} \int_{z_{1j}(x)}^{z_{2j}(x)} N_{A_i}(x, z, x_r) n_{r_j}(x, z, x_r) i_{A_i} dz dx. \quad (11)$$

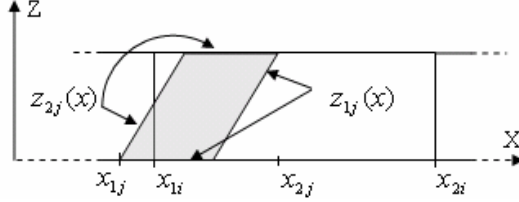


Fig. 2. Illustration of the skewing bars

The bars skewing is presented by the definition of the terminals of integration z_{1j} and z_{2j} which will be deduced while referring to fig 2, these considerations make it possible to define the function of the spatial winding distribution in the following way:

$$n_{ij}(x, z, x_r) = \begin{cases} 1 & x_{1j} < x < x_{2j}, z_{1j}(x) < z(x) < z_{2j}(x) \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

One can take notice that the stator inductances and those of the rotor are not affected by the effect of the bars skewing [5], [18].

IV. MODELLING OF INTER-TURN SHORT CIRCUIT

In the first instance, we consider a simple elementary example (Fig. 3), where the coil A - X' has six turns occupy two slots. When a short-circuit appears between the contact points $c1$ and $c2$, five coils in series are obtained. Moreover, an additional independent shorted-circuited turns is magnetically coupled with the other circuits.

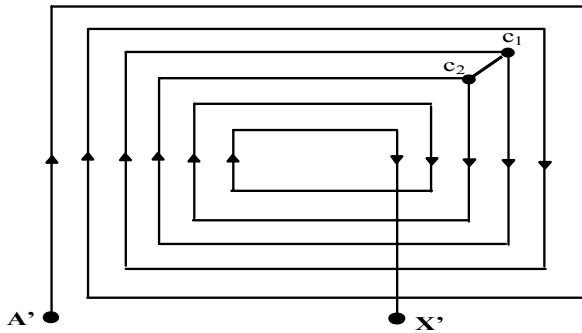


Fig. 3. Elementary representation of an inter-turn short-circuits.

Turn-to-turn short circuits in a three phase induction motor can be analysed in a similar manner. So the development of another equivalent circuit, representing the stator phases in the presence of turn-to-turn faults are imperative. Fig. 4 represents

the system equivalent circuit without stator winding coupling and with two additional branches. shc relates to the turns short-circuited and $c1c2$ relates to the short-circuit branch. R_{shc} represents the effective resistance of the short-circuited turns, which is generally small. However, the R_{c1c2} (the resistance of the short-circuit branch) is very large in case of healthy state. The simulation of a sudden short-circuit can be made by the decreasing value of the resistance R_{c1c2} .

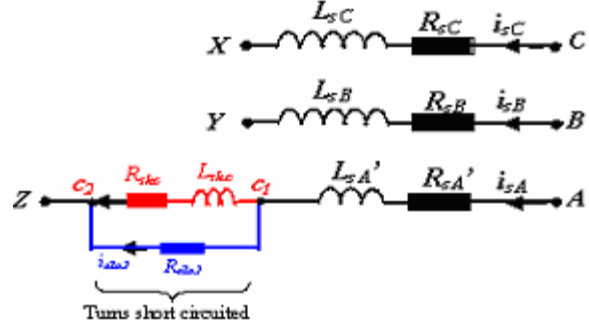


Fig. 4. Equivalent circuit of the stator phases with inter-turn short-circuit.

It is to be reminded that as resulting of inter-turn short-circuit, the winding function of the injured phase changes. As a consequence, the resistance, the self inductance of this phase and its mutual inductances with all the other circuits change also. No coupling will be considered with the $c1c2$ branch because of its non-inductive nature.

Hence, the model given by equations (2) and (3) does not undergo great changes, but we must extend the voltages currents vectors, such as:

$$[U_s] = [u'_{sA} \ u_{sB} \ u_{sC} \ u_{shc}]^T \quad (13)$$

$$[I_s] = [i'_{sA} \ i_{sB} \ i_{sC} \ i_{shc}]^T \quad (14)$$

Consequently, the initialisation of the inductances and resistances matrices by taking into account of the introduced branches is necessary. We note that all new inductances are calculated by the eMWFA.

V. SIMULATION RESULTS

The simulation analysis was performed on an 11kW, 4 poles three-phase induction motor. The stator winding arrangement of this motor and its parameters are shown in the appendix. The mathematical model obtained and all inductances expressions (in both cases: with and without skewing rotor bars and opening slots) were implemented under MATLAB environment. In order to well observe the effects of the skewing bars and the slots opening on the stator/rotor mutual inductances, we showed the L_{r1A} inductance and its derivative dL_{r1A} relating to a healthy state in the same graph, without and with skewing bars and slots opening (Fig. 5 and Fig. 6). The plot of dL_{r1A} enables us to have an idea on the quality of the passage of the rotor loop under the stator winding field. One can note that this passage becomes soft in presence of the skew and with the consideration of the linear rise of MMF across the slots. This one reduces some influences such as the

oscillating torque [17].

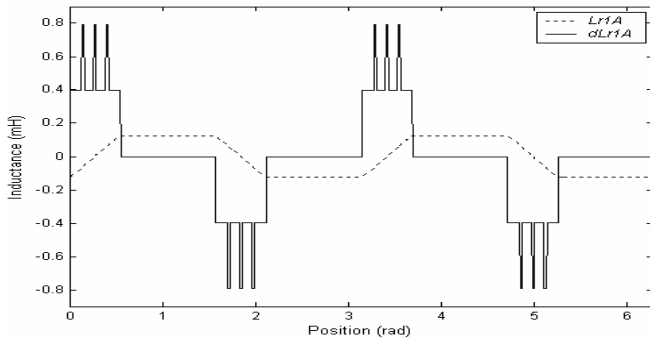


Fig. 5. Mutual inductance between the stator phase A and the rotor loop $r1$ and its derivative, without skewing rotor bars and slots opening.

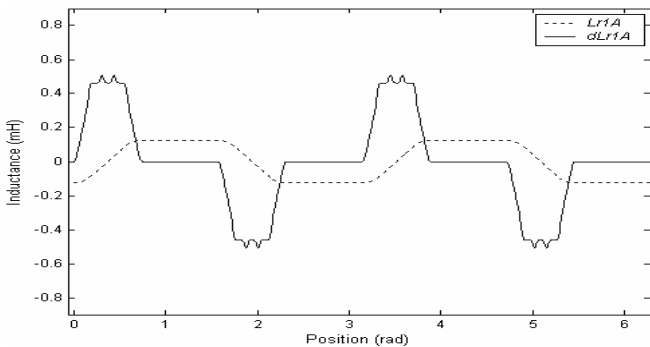


Fig. 6. Mutual inductance between the stator phase A and the rotor loop $r1$ and its derivative, with skewing rotor bars and slots opening.

Fig. 7 shows the mutual inductances between the three stator phases and the first rotor loop for healthy winding.

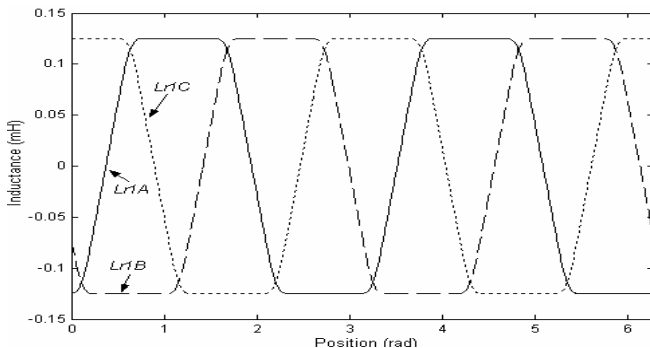


Fig. 7. Mutual inductances between stator windings and rotor loop r_1 (healthy motor).

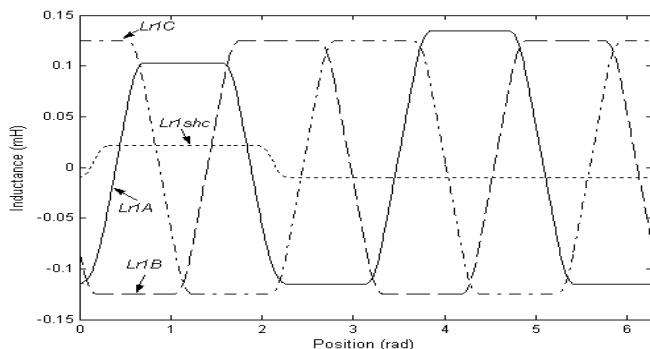


Fig. 8. Mutual inductances between stator phases and rotor loop $r1$ (motor with 14 turns short circuited).

Now, considering the case of a short-circuit which touch 50% of the turns of the first coil of phase A , that is to say 14 turns of the coil placed in slots 1 and 12 respectively (it means that approximately 6.25% of the turns of phase A are short circuited). The resistance R_{shc} of the turns short-circuited will be, in this case $R_s/16$, and the new resistance of phase A becomes $15.R_s/16$. Fig. 8 shows the new mutual inductances between the stator phases and the rotor loop $r1$. It is obvious that the inter-turn short-circuit affects only the inductances of the injured phase.

Fig. 9 depicts the currents i_{sA} and i_{shc} of the motor for a loaded machine. Before the occurrence of the stator faults, both of these currents are equal and have the same phase. At the moment $t_{cc}=0.8s$, we decrease the resistance R_{c1c2} in order to simulate an inter-turn short-circuit failure; this operation will reduce the resistance of the phase A which becomes 1.64Ω while the resistance of the short-circuited turns is 0.11Ω . Consequently, the current i_{sA} increase lightly accompanied by a sudden and great increase in current i_{shc} . This one becomes in opposition of phase compared to i_{sA} . The high current i_{shc} involves an excessive rise in the heat what destroys quickly the stator winding. For this reason, that it is interesting to detect an incipient turn-to-turn fault before it leads to a total failure of the machine.

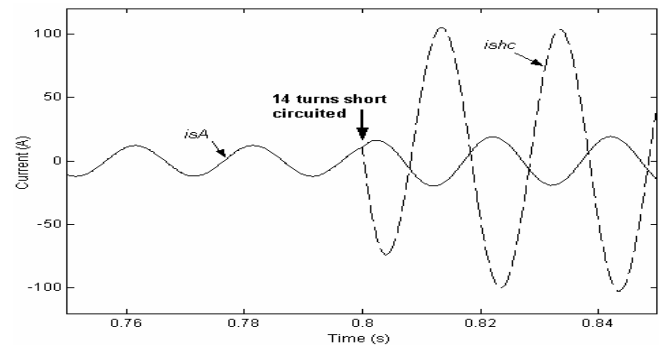


Fig. 9. Phase current i_{sA} and current in short circuited turns.

Inter-turn short circuits have a cumulative effect in decreasing MMF in the vicinity of the short circuited turns. Firstly, when a short circuit occurs, the injured phase winding has less turns and therefore less MMF. Secondly, the turns short-circuited will create their own FMM but in opposition of phase with that of the injured phase.

Among the great consequences of an inter-turn short-circuit; we situate the appearance of a negative sequence of the current in the stator windings [14]. The interaction of the latter with the rotor currents produces pulsations in the torque at twice the line frequency [10]. These pulsations create consequently speed ripples like exposed in fig. 10. The stator windings show these oscillations as a variation in the principal flux. Consequently, a spectral component at 150 Hz appeared in the stator currents, as well as an increasing value of the principal slots harmonics amplitude (Fig. 11 and Fig.12) given by

$$f_{sh} = f_s \left\{ \frac{N_b}{p} (1-s) \pm k \right\}, \quad (15)$$

when replacing k by 1.

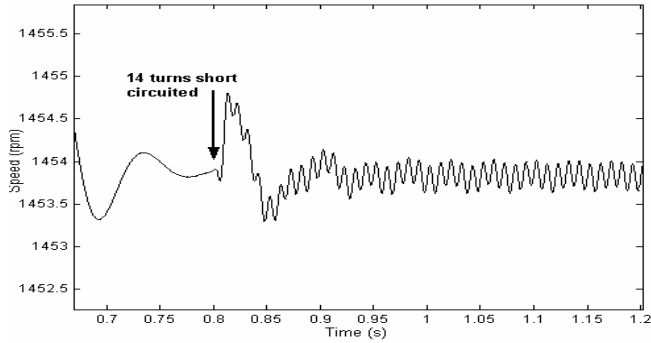


Fig. 10. The mechanical speed of the motor with inter-turn short-circuit

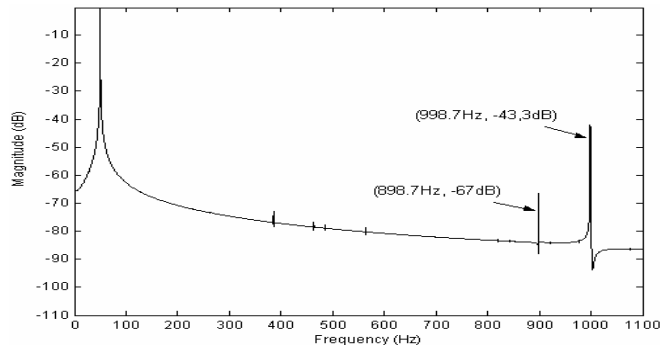


Fig. 11. Simulation spectrum of stator current of phase A , for a healthy motor (rated load).

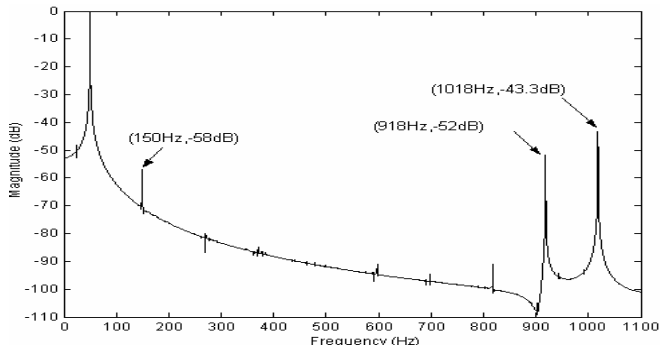


Fig. 12. Simulation spectrum of stator current of phase A , for a motor with inter-turn short-circuits (rated load).

VI. EXPERIMENTAL RESULTS

In order to validate the simulation results, a special test model was used. It is a 1.1kW 220/380V 50Hz four pole induction motor whose stator windings were modified in order to have accessible several tapping. That can be used to introduce inter-turn short circuits with different number of turns. This test bench is available at the LAII in Poitiers, France. A shorting resistor was used to limit the value of the short circuit current in order to protect the motor winding from complete/total failure.

Fig. 13 shows the spectra of the line current for a loaded motor ($s = 0.05$) when it runs in healthy conditions. Some frequency components (150Hz, 250Hz, etc.) exist which are a result of the saturation of magnetic material. The lower rotor slot harmonic is visible at 615Hz.

We consider now the case of eighteen turns of phase A are shorted (3.88 % of all turns of phase A). The amplitude of the

third line harmonic increases (Fig. 14). This is in good agreement with the simulation results. On an other hand, the components corresponding to $k=5$ (415Hz) and 11 (115Hz) in equation (15), are increasing by 18,3dB and 11dB factor respectively in comparison to the third and the lower rotor slot harmonic.

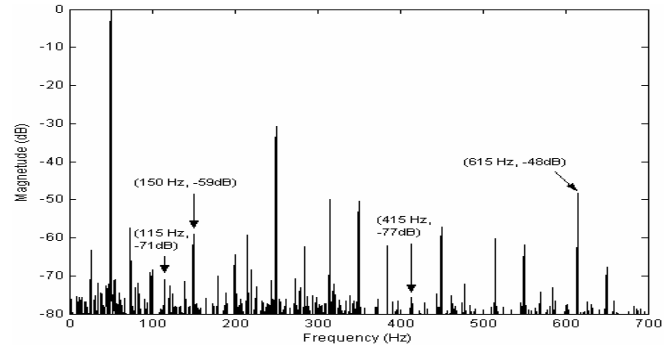


Fig. 13. Experimental spectrum of stator current of phase A , for a healthy motor (rated load).

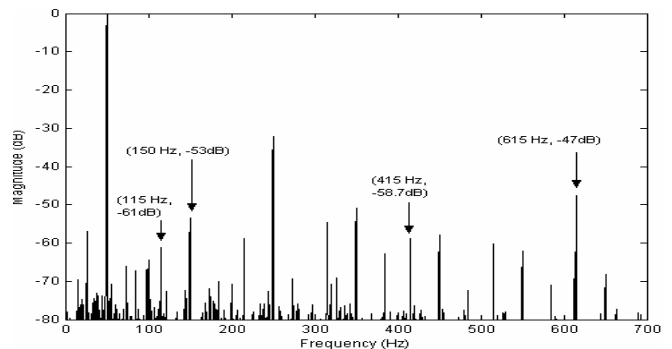


Fig. 14. Experimental spectrum of stator current of phase A , for a motor with eighteen shorted turns (rated load).

VII. CONCLUSION

In this work, a mathematical model of the squirrel cage induction motors was presented. It allows the simulation of the stator defects such as the inter-turn short-circuits. This model is established by taking into account all the space harmonics as well as the skewing rotor bars and the slots opening. We showed that the calculation of inductances, for healthy or faulty motor, can be made by the eMWFA. The expressions of inductances resulting from this technique are less complicated to be implemented into algorithm than those obtained starting from the expression of inductance per unit of length. Tests of simulation on a motor of 11kW have highlight the dangerous consequences of the inter-turn short-circuits. We showed that the appearance of an inter-turn short-circuits generate a spectral component at 150Hz and increase the amplitude of the principal slots harmonics. The experimental tests validate these results. It is well known that the third harmonic exist in the line current spectrum of a healthy machines as a result of saturation of the magnetic material. Moreover, it is more sensitive to the unbalanced voltage supply. Further, the principal rotor slots harmonics are sensitive to other faults such as static or dynamic eccentricity. We have found also that other slots harmonics (like harmonics corresponding to $k=5$ and $k=11$ in (15)) increased in amplitude in presence of an

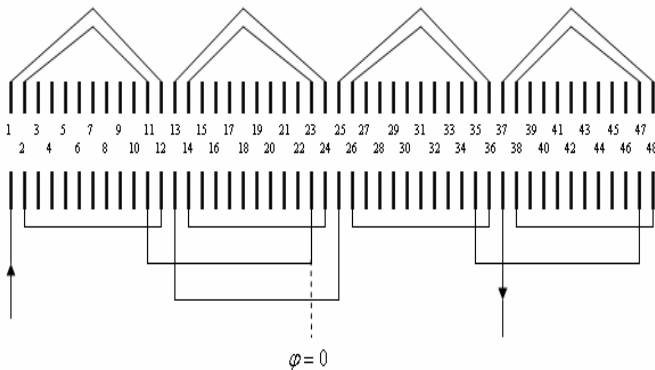
inter-turn short circuit. Nonetheless, a lot of experimental tests on several power motor ranges are advisable in order to clearly identify the line components in the current signature pattern that are only a function of shorted turns and are not due to any other problem.

ACKNOWLEDGMENT

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APPENDIX

- The stator winding distribution of the simulated motor.



- Parameters of the simulated motor.

Rating power	$P = 11 \text{ kW}$
Rated frequency	$f = 50 \text{ Hz}$
Number of pole pairs	$p = 2$
Air gap length	$g_0 = 0.0008 \text{ m}$
Average radius	$r = 0.082 \text{ m}$
Length of stator stack	$l = 0.11 \text{ m}$
Turns per coil	$w = 28$
Number of stator slots	$N_s = 48$
Number of rotor bars	$N_b = 40$
Phase resistance	$R_s = 1.75 \ \Omega$
Rotor end ring leakage inductance	$L_e = 18 \text{ nH}$
Rotor bar leakage inductance	$L_b = 95 \text{ nH}$
Rotor bar resistance	$R_b = 31 \ \mu\Omega$
Rotor end ring resistance	$R_e = 2.2 \ \mu\Omega$
Rotor inertia	$J_T = 0.0754 \text{ kgm}^2$
Angle between two rotor bars	$\gamma = \pi/20 \text{ rad}$
Stator slot opening	$\beta = \pi/86 \text{ rad}$

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