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Modelling of Squirrel -Cage Induction Machines dedicated to monitoring fault conditions

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Abstract

Recently, in many industrial processes research has picked up a fervent place and a particular importance in the area of fault diagnosis of electrical machines, in fact, a fault prognosis has become almost indispensable. The need of a mathematical model of three-phase induction machine, suitable for the simulation of machines behaviour under fault conditions, has received considerable attention. This paper addresses an accurate model for three-phase squirrel cage induction motors, based on coupled magnetic circuit theory, capable to take into account any conditions of the machine like stator and/or rotor faulty conditions. The exactitude of the model is due to the use of the real geometry of the machine together with the physical layout of all windings. Moreover, the detailed depiction of the machine permits to determine new accurate formulas of inductances, such as, the self-inductances of the rotor loops, stator coils, as well as the mutual inductances between the stator coils and rotor loops. To demonstrate the effectiveness of the model, the case of broken rotor bars as a source of rotor electrical asymmetry was studied. Experimental results show that the proposed model predicts the induction machine behaviour with a good accuracy.

KEYWORDS: induction machines; line neutral voltage; an accurate model; frequency harmonics; voltage dissymmetry.

NOMENCLATURE

f	frequency	N_t	number of stator turns
h	order of harmonic	n_b	number of rotor bars
K_{dh}	distribution coefficient	r	mean radius of the airgap
K_{rh}	shortning coefficient	μ_0	permeability of free space
K_{bh}	winding coefficient	ω_r	rotor angular velocity
N_s	number of stator slots	Q	number of slot per pitch turn
N_c	number of conductor per stator slot	θ_r	rotor position
N_e	number of slots per pole and per phase	g	airgap length
		L	machine length

P	number of pole pairs		
L_b, L_e	rotor bar and end ring leakage inductance	L_{mr}	self magnetizing inductance
R_b, R_e	rotor bar and end ring leakage resistance	$L_{ri\ rj}$	mutual inductance between rotor i_{th} loop and j_{th} loop
M_{ie}	mutual inductance between stator phase winding and rotor end ring		
$M_{aj}^{sr}, M_{bj}^{sr}, M_{cj}^{sr}$	mutual inductance between stator a, b, c-phase winding and rotor j_{th} loop		

I.

1. INTRODUCTION

Recently, the cage induction motor provides the most common form of electromechanical drive for industrial, commercial and domestic applications. The diagnosis of failures of the industrial systems, if it is carried out with effectiveness or if it makes possible to detect in early way degradation, represents one of the means to contribute to gain points of productivity. However, the basis of any reliable diagnostic method is an understanding of the electric, magnetic and mechanical behaviour of the machine in healthy-state and under fault conditions. It becomes important to know with some degree of accuracy the behaviour of the machine in these working conditions in order to be able to develop adequate and effective diagnostic techniques. The utility of models for fault diagnosis is restricted because it is even theoretically impossible to include all nonidealities that exist in a real machine. It is well known also that model accuracy and computation time represent two opposite criteria. A series of models are used to evaluate the sensitivity and reliability of the stator and rotor feature [1...9]. However, the majority of these models are based on the simple idealist machine without taking into account the physical layout of the stator and rotor windings. In this paper, an alternative way for formulating the suitable model, capable of predicting the performance of induction motor is suggested. The main objective is to offer a correct and general mathematical formula of the self-inductances of the rotor loops, stator coils, as well as the mutual inductances between the stator coils and rotor loops to be used during any faulty comportment of the motor. In order to avoid the highly time consuming calculation of inductances we have decomposed those latter into Fourier series without any kind of reference frame transformation. The paper also demonstrates the importance of line neutral voltage consideration. One can notice that the generation of voltage dissymmetry presented by the line neutral voltage of the machine did not receive much attention in the literature [10,11,12]. It has been found that some new components are generated in the line voltage and these new components have a direct impact on the line current harmonic generations. To demonstrate the effectiveness of the proposed model, certain high frequency harmonics that can be predicted theoretically, are shown to be present in the line neutral voltage of the simulated machine. Experimental results also confirm the presence of these harmonics.

2. SYSTEM EQUATIONS

When the space harmonics are taken into account, we cannot consider the neutral voltage equal to zero.

2.1. Multi-loop model with consideration of line neutral voltage

Suppose that stator three-phase windings are Y connected. Neglected line neutral voltage produces other new harmonics in the motor. These harmonic components appear to compensate the sources of MMF harmonics provided by the line neutral voltage itself. Consequently, for an accurate diagnostic the line neutral voltage must be considered. The primary equations of the induction machine can be written in vector-matrix form. When we consider the line neutral voltage, we have:

$$[V_{3s}] = [R_s] \cdot [i_{3s}] + \frac{d}{dt}[\psi_{3s}] + [V_n] \quad (1)$$

$$\begin{bmatrix} [V_r] \\ [V_e] \end{bmatrix} = [0] = \begin{bmatrix} [R_r] & R_e/n \\ & M \\ R_e/n \Lambda & R_e \end{bmatrix} \cdot \begin{bmatrix} [i_m] \\ [i_e] \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_m \\ \psi_e \end{bmatrix} \quad (2)$$

As usual, $[v]$ is the voltage vector, $[i]$ is the current vector. $[R_s]$ and $[R_r]$ are the stator and rotor resistance matrices respectively. Because of the asymmetry of the machine, it is impossible to evaluate the line neutral voltage. For that, it is necessary to put the equations of the model in the line to line voltage waveform.

$$\begin{pmatrix} V_{sab} \\ V_{sbc} \end{pmatrix} = \begin{pmatrix} R_s & -R_s \\ -R_s & 2R_s \end{pmatrix} \cdot \begin{pmatrix} i_{sa} \\ i_{sb} \end{pmatrix} + \frac{d}{dt} \begin{pmatrix} \psi_{sab} \\ \psi_{sbc} \end{pmatrix} \quad (3)$$

where:

$$V_{sxy} = V_{sx} - V_{sy}, \quad \psi_{sxy} = \psi_{sx} - \psi_{sy}$$

The stator current spectrum contains not only the components produced by space harmonics, but also other components such as characteristic harmonics that exist because of line neutral voltage neglect. The theoretical formula of the neutral voltage is [14]:

$$\begin{aligned} v_n = & - \sum_{h=1}^{\infty} \sum_{k=0}^{N_r-1} \frac{s\omega_s}{2} M_{srh} I_{rk} \{ \cos((3h - (3hs + 1))\omega_s t + \psi_{1h}) - \cos((3h - (3hs - 1))\omega_s t + \psi_{2h}) \} - \\ & + \frac{d\theta}{dt} \sum_{h=1}^{\infty} \sum_{k=0}^{N_r-1} \frac{3h}{2} M_{srh} I_{rk} \{ \sin((3h - (3hs + 1))\omega_s t + \psi_{1h}) + \sin((3h - (3hs - 1))\omega_s t + 3h\phi_h + \psi_{2h}) \} \end{aligned} \quad (4)$$

2.2. Mechanical equations

It follows that the electromagnetic torque can be expressed by:

$$\Gamma_e = \sqrt{\frac{3}{2}} P \sum_{h=1}^{\infty} \left[h \cdot M_{srh} \left\{ i_{AN} \sum_{k=1}^{N_r} I_{rk} \cdot \sin \left(h(\theta + \phi_h + (k-1) \cdot a) \right) + i_{BN} \sum_{k=0}^{N_r-1} I_{rk} \sin \left(h(\theta + \phi_h + k \cdot a) - \frac{2\xi_h \pi}{3} \right) \right\} + i_{CN} \sum_{k=0}^{N_r-1} I_{rk} \sin \left(h(\theta + \phi_h + k \cdot a) + \frac{2\xi_h \pi}{3} \right) \right] \quad (5)$$

3. CALCULATION OF INDUCTANCES

Generally, inductance can be characterized as the property of a circuit element by which energy is capable of being stored in a magnetic field. In order to distinguish the different definitions of inductances, to have an accurate and optimal diagnosis it is necessary to present the detail of all mathematical development of the different inductances. The winding function approach takes advantage to define inductances of a machine. The calculation of all relevant inductances for the induction machine is based on the winding functions theory. A closed area counting the stator core, airgap and rotor core can be found and its boundary AOB. In general, the distribution of air gap magnetic motive force (MMF) generated by the current i_A circulating in the winding A can be expressed as:

$$F_A(\varphi, \theta_r) = N_A(\varphi, \theta_r) i \quad (6)$$

Consequently, the flux for a winding B due to the current i_A can be easily written in the following way:

$$\Psi_{BA} = \mu_0 r L \int_0^{2\pi} n_B(\varphi, \theta_r) F_A(\varphi, \theta_r) g^{-1}(\varphi, \theta_r) d\varphi \quad (7)$$

Using a relation (18), the mutual inductance between any two windings "i" and "j" in any electric machine can be computed by:

$$L_{BA} = \frac{\Psi_{BA}}{i_A} = \mu_0 r L \int_0^{2\pi} n_B(\varphi, \theta_r) N_A(\varphi, \theta_r) g^{-1}(\varphi, \theta_r) d\varphi \quad (8)$$

Similarly, the expression for the self inductances of the electrical machine of stator winding and rotor loop is given as:

$$L_{AA} = \mu_0 r L \int_0^{2\pi} n_A(\varphi, \theta_r) N_A(\varphi, \theta_r) g^{-1}(\varphi, \theta_r) d\varphi \quad (9)$$

where φ is the angular position of the rotor with respect to the stator frame, θ is a particular angular position along the stator inner surface, $g^{-1}(\varphi, \theta)$ is termed the inverse air-gap function which becomes $1/g$ due to the assumption of uniform air-gap. The quantity L is the length of stack and r is the average radius of the air gap. The term $N_i(\varphi, \theta)$ and $N_j(\varphi, \theta)$ are called the winding function and represent, in effect, the MMF distribution along the air gap for a unit current flowing in winding i and j respectively.

3.1. Self- and mutual inductances of stator phases

The self-inductance of a winding is the ratio of the total flux linked with the winding and the current circulating in it with all other winding currents made equal to zero. For the winding self-inductance calculation, consider the flux linkages of a single turn which is located at an angle θ . The flux is derived by performing a sum over the open surface of the single turn.

In a Fourier series the winding function of coil b in the phase q is given by:

$$N_q(\theta) = \frac{2N_t}{p\pi} \sum_{n=1}^{\infty} \frac{K_{bn}}{h} \cos[h.p(\theta - \theta_0 - q \cdot \frac{2\pi}{3p})] \quad \text{with: } \theta_0 = (Ne - 1 + Q) \frac{\pi}{N_s} \quad (10)$$

Fig.4 shows the turns function and the winding function of the induction motor with a single layer winding arrangement (see machine parameters in Table 1).

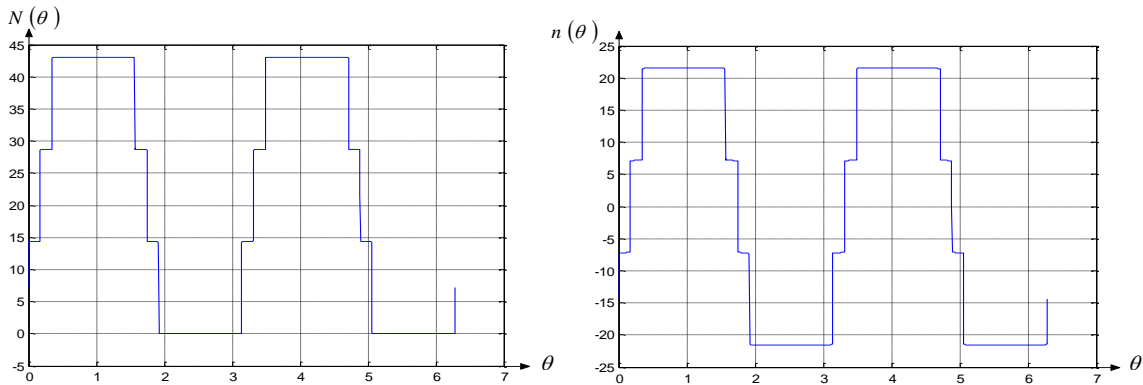


Figure 4: turns function (left) and winding function (right) of a coil placed in the stator of the motor obtained from simulation.

- Self magnetizing inductance of the « q » stator phase:

Given the dimensions of the induction motor, the self magnetizing inductance of any stator phase can be determined by the following equation:

$$L_{mq} = \frac{4\mu_0 rL}{g} \frac{N_t^2}{p^2 \pi} \sum_{n=1}^{\infty} \frac{K_{bh}^2}{h^2} \quad (11)$$

- Mutual inductances between two phases:

The total mutual inductance between any two stator phases is given by:

$$M_s = L_{ab} = L_{ba} = L_{bc} = L_{cb} = L_{ca} = L_{ac} = \frac{4\mu_0 rL}{g} \frac{N_t^2}{p^2 \pi} \sum_{n=1}^{\infty} \frac{K_{bh}^2}{h^2} \cos\left(h \frac{2\pi}{3}\right) \quad (12)$$

3.2. Self- and mutual inductances of rotor loops

For the calculation of self magnetizing inductances of rotor loops and the mutual inductances between any two rotor loops we introduce Fourier series development in equation 9. The winding function of each rotor loop is decomposed into two functions, the positive part for calculating the self inductances and the negative part for calculating the mutual inductances respectively. After calculation we have for the positive part:

$$N_{1k}(\theta') = \left(\frac{\alpha_r}{2}\right)\left(1 - \frac{\alpha_r}{2\pi}\right) + \left(\frac{2}{\pi}\right)\left(1 - \frac{\alpha_r}{2\pi}\right) \times \sum_{m=1}^{\infty} \frac{1}{m} \sin\left(m \frac{\alpha_r}{2}\right) \cos\left[m\left(\theta' - \left(k - \frac{1}{2}\right)\alpha_r\right)\right] \quad (13)$$

For the negative part:

$$N_{2k}(\theta') = \left(-\frac{\alpha_r}{2\pi}\right)\left(1 - \frac{\alpha_r}{2\pi}\right) + \left(\frac{2}{\pi}\right)\left(\frac{\alpha_r}{2\pi}\right) \times \sum_{m=1}^{\infty} \frac{1}{m} \sin\left(m \frac{\alpha_r}{2}\right) \cos\left[m\left(\theta' - \left(k - \frac{1}{2}\right)\alpha_r\right)\right] \quad (14)$$

- Self magnetizing inductance of the « k » rotor loop:

The inductance of a rotor mesh j is defined as the summation of the self magnetizing inductance, the self leakage inductance of the rotor bar and the self leakage inductance of the rotor end ring gives by the following expression:

$$L_{mj} = \frac{\mu_0 rL}{g} \left[\left(\frac{\alpha_r^2}{2\pi} \right) \left(1 - \frac{\alpha_r}{2\pi} \right) + \left(\frac{4}{\pi} \right) \left(1 - \frac{\alpha_r}{2\pi} \right) \sum_{m=1}^{\infty} \left(\frac{\sin(m \frac{\alpha_r}{2})}{m} \right)^2 \right] \quad (15)$$

- Mutual inductances between rotor loops:

To consider that the rotor meshes are magnetically coupled by the intermediary of the rotor flux flow in air-gap, we obtain:

$$L_{m(j+1)j} = \frac{\mu_0 rL}{g} \left(- \left(\frac{\alpha_r^2}{2\pi} \right) \left(1 - \frac{\alpha_r}{2\pi} \right) + \left(\frac{4}{\pi} \right) \left(\frac{\alpha_r}{2\pi} \right) \times \sum_{m=1}^{\infty} \left(\frac{\sin(m \frac{\alpha_r}{2})}{m} \right)^2 \cos(m \alpha_r) \right) - L_{b(j+1)} \quad (16)$$

$$L_{m(j-1)j} = \frac{\mu_0 rL}{g} \left(- \left(\frac{\alpha_r^2}{2\pi} \right) \left(1 - \frac{\alpha_r}{2\pi} \right) + \left(\frac{4}{\pi} \right) \left(\frac{\alpha_r}{2\pi} \right) \times \sum_{m=1}^{\infty} \left(\frac{\sin(m \frac{\alpha_r}{2})}{m} \right)^2 \cos(m \alpha_r) \right) - L_{bj}$$

(17)

The mutual inductance between any no adjacent Meshes is calculated by the general expression:

$$L_{mj-k} = \frac{\mu_0 rL}{g} \left(- \left(\frac{\alpha_r^2}{2\pi} \right) \left(1 - \frac{\alpha_r}{2\pi} \right) + \left(\frac{4}{\pi} \right) \left(\frac{\alpha_r}{2\pi} \right) \times \sum_{m=1}^{\infty} \left(\frac{\sin(m \frac{\alpha_r}{2})}{m} \right)^2 \cos[m(j-k) \alpha_r] \right) \quad (18)$$

3.3. Mutual inductances between stator winding and a rotor loop

The mutual inductance between stator winding and rotor loop is:

$$M_h^{sr} = \sum_{n=1}^{\infty} M_h \cos \left[hp \left(\theta_r - \theta_0 + \left(j - \frac{1}{2} \right) \alpha_r - q \frac{2\pi}{3p} \right) \right] \quad (19)$$

with:

$$M_h = \frac{4\mu_0 rl}{g} \frac{N_t}{P^2 \pi} \frac{K_{bh}}{h^2} \sin\left(\frac{hp \alpha_r}{2} \right)$$

Fig. 6 shows the mutual inductance between the first rotor loop and stator phases.

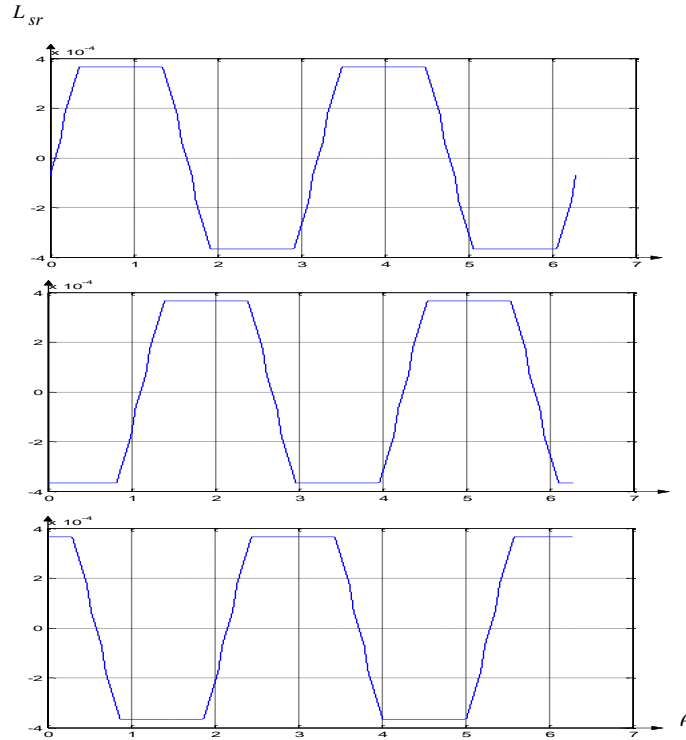


Figure 6. Plot of mutual inductance between the first rotor loop and stator phases

4. INTEGRATION OF THE DIAGNOSTIC APPLICATIONS

4.1. Diagnosis of rotor faults

In order to show the effectiveness of the mathematical model, with integration of all inductances development, we have simulated the induction machine with broken rotor bars. In order to simulate that, we have to force the bar currents to fall to zero. This is achieved by increasing the rotor bar resistance. It has been recognized for years that the main effect of a rotor fault in an induction motor is the appearance of some additional components in the motor supply current at frequencies given by [15]:

$$f_{rf} = (1 \pm 2k g) f_s \quad (20)$$

where: f_s fundamental supply frequency (Hz), g rotor slip, $k = 1, 2, 3, \dots$

The main indicator about the presence of this type of fault corresponds to the two current spectral components at frequencies given by (20) when $k=1$. Under rotor fault conditions the maximum values of the rotor loop currents

are not equal ($I_{rmi} \neq I_{rmj} \Big|_{i \neq j}$) and the neutral voltage is different of zero ($v_n \neq 0$). In this case, additional harmonic components are induced with their related frequencies f_h specified by:

$$f_h = [3h - (3h \pm 1)s]f_s \quad (21)$$

where f_s supply frequency and $h = 1, 3, 5, 7, \dots$

5. SIMULATION RESULTS AND EXPERIMENTAL VERIFICATION

The differential equations derived above can be solved by fourth-order Runge-Kutta method. The simulation and experimental studies were conducted using a machine of 3 phases, 50 Hz, 36 stator slots, 28 rotor bars and 2 pairs of poles. The experimental setup is shown in Fig. 7. The induction motor is star-connected with the neutral accessible at the terminals. The voltage inverter is monitored by a digital signal processor (DSP) TMS320F240. The stator neutral voltage is measured with a data acquisition card powered by GaGe (CS 1602). After the acquisition time, the data are sent to the supervising personal computer (PC) via serial communication link, and MATLAB will be used for frequency-domain analysis.

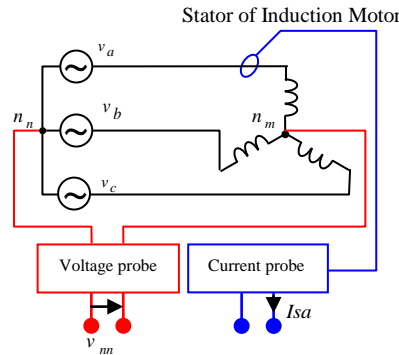


Figure 7. Experimental set-up

The simulation waveform of the line neutral voltage for a healthy induction motor with and without space harmonics in the proposed model under symmetrical conditions are depicted in Fig. 8. Pay attention that neglected line neutral voltage tends to disguise the presence of new harmonic components. To support this statement, another interesting simulation was performed. The corresponding FFT spectrum of the current under steady state condition is plotted in Fig 9. In this Figure, we clearly remark the appearance of other faulty frequencies than real space harmonics due to neglected line neutral voltage. Figs.10 demonstrates around the third harmonic, one finds the specific harmonics related to broken rotor bars fault.

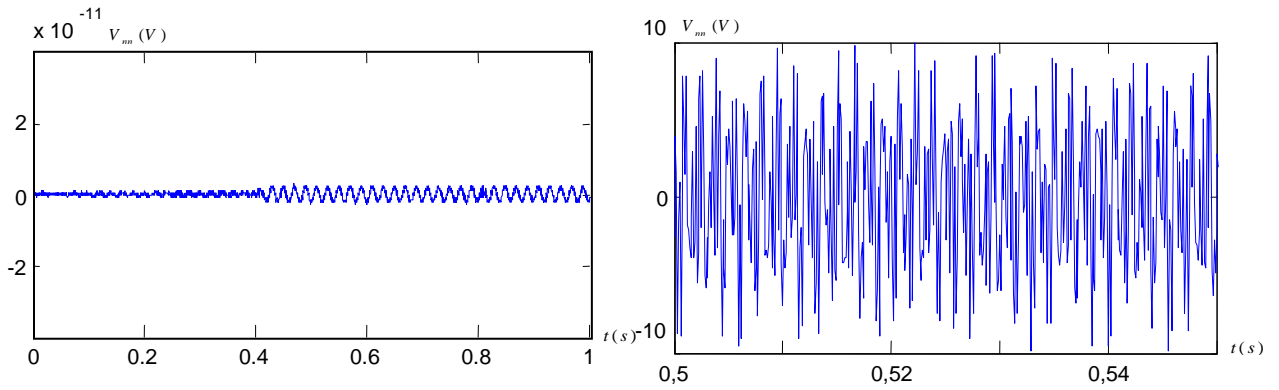


Figure 8. Neutral voltage under healthy condition, without considering the space harmonics (Left) and with considering the space harmonics (Right).

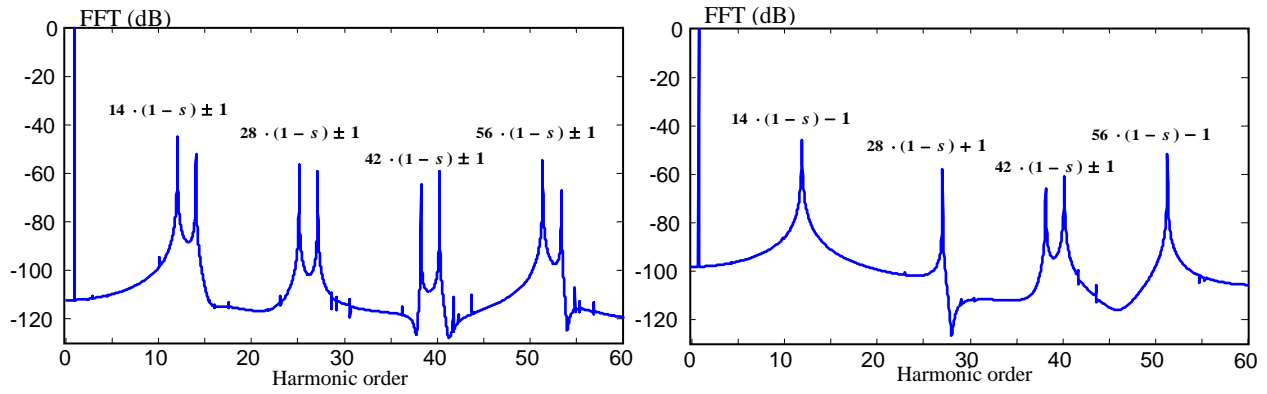


Figure 9. Normalized FFT of the stator line current under healthy condition without considering the neutral line voltage (Left) and with considering the line neutral voltage (Right).

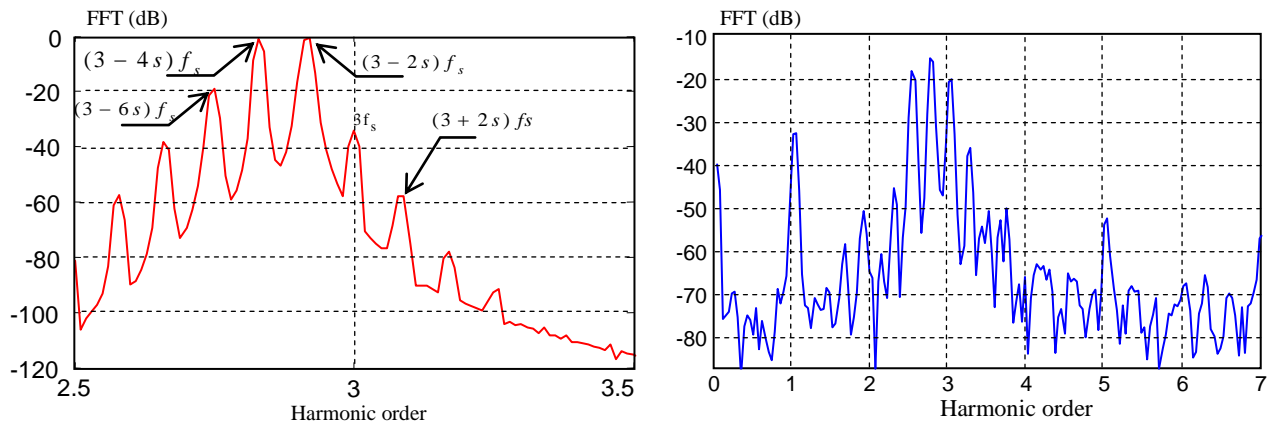


Figure 10: Spectrum of voltage supply around the third harmonic of machine with three broken bars simulation (Left) and experimental (Right).

6. CONCLUSION

Literature review suggests that modelling of induction machines to be completely adequate for the purpose of fault diagnosis has received considerable attention. Most of these models are often inaccurate in predicting the effect of space harmonics in the line neutral voltage and in the line current of the machine, particularly when the machine is considered under symmetrical conditions. One can easily remark that the accuracy of the coupled magnetic circuit based modeling method depends greatly on the accuracy of the inductances calculation as well as on the accuracy of their derivation. In order to improve the performance of the large existing diagnosis methods a detail of inductances calculation is needed and this is the main objective of this paper. The accuracy of the inductance profiles used for the simulation has been verified through the experimental results. The proposed model accounts not only for the effect of flux space harmonic components travelling in the air gap but also, clarifies the error introduced in the simulation results when the line neutral voltage is not considered. Finally, it should be mentioned that although the mathematical development of the inductances has been used to diagnose broken rotor bar fault successfully, it can also be used, to a high degree of accuracy, in order to avoid the mis-diagnosis and increases its reliability to detect any other fault in the stator or the rotor frame.

TABLE I
Specifications of the induction motor

Rated power	3kW
Rated voltage	380 V
L	0.12m
R	50 e-3m
Supply frequency	50 Hz
Number of stator slots	36
Number of poles	4
Number of winding turns per phase group	86
Number of rotor bars	28
Self leakage inductance of the stator phase	0.0129 H
Self leakage inductance of the rotor bar	6.03 e-7 H
Self leakage inductance of the rotor end ring	6.06 e-9 H
Stator phase resistance	1.9 Ω
Rotor bar resistance	65.9 e-9 Ω
Rotor end ring resistance	1.23 e-6 Ω
Inertia momentum	0.052 Kg.m ²
Air gap	0.5 mm

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