Inductance evaluation of a squirrel-cage induction machine in presence of eccentricity by MMF and permeance approach
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Abstract- This paper deals with the modelling of an induction machine with dynamic eccentricity fault. The inductances are calculated using the magnetomotive force and the air gap permeance approach and taking into consideration the space harmonics effect. First, the magnitude and the form of the obtained inductances in presence of dynamic eccentricity are discussed and compared to those of the healthy machine. Next, these inductances are introduced in the general induction machine model obtained using the magnetically coupled circuits approach. Simulation results illustrating the induction machine performances for the healthy and the faulty cases are presented. Also, the Fast Fourier Transform FFT of the steady state stator current obtained by simulation is performed to detect any specific components which identify the fault appearance in the machine. The detection of these components is easier when the motor is supplied from a sinusoidal voltage than for a PWM inverter supply.

Keywords- Induction motor; dynamic eccentricity; MMF; air-gap permeance; harmonics.

I. INTRODUCTION

Among electrical machines, induction motors are the most widely used in industry because of their rugged configuration, low cost, and versatility. With their great contributions, induction motors are called the “workhorse of industry”. Because of natural aging processes and other factors related to their operating conditions in industrial applications, induction motors are subject to various faults, such as rotor faults. These faults can be induced by electrical failures such as bar breakage, or mechanical failures such as rotor eccentricity. The first fault occurs from thermal stresses, hot spots, or fatigue stresses during transient operations such as start-up, especially in large motors. A broken bar changes torque significantly and became dangerous to the safety and consistent operation of electric machines [1]. The second type of rotor fault is related to air gap eccentricity. This fault is a common effect related to a range of mechanical problems in induction motors such as load unbalance or shaft misalignment. Long-term load unbalance can damage the bearings and the bearing housing and influence air gap symmetry. Shaft misalignment means horizontal, vertical or radial misalignment between a shaft and its coupled load. With shaft misalignment, the rotor will be displaced from its normal position because of a constant radial force [2-4].

The induction motor modelling with dynamic eccentricity using the winding function approach is examined in many papers [5-8]. The frequency components generated by dynamic eccentricity are explained analytically in [5]. Using the rotating field approach, authors confirm the existence of specific frequency components around the fundamental, caused by the dynamic air gap eccentricity. The interactions between the dynamic eccentricity and the inherent static eccentricity are also illustrated using an adequate mathematical model of the induction machine. For this model, the calculation of inductions is performed by the modified winding function approach.

Authors in [6] use the coupled magnetic circuit approaches for modeling the induction machine under dynamic eccentricity. Different inductions are calculated directly from the geometry and layout of the machine by the turn and winding function approach. Simulation results are also illustrated to show the behaviour of the induction machine under this fault. In [7], authors use the extension of winding function approach to calculate and evaluate machine inductances for a nonuniform air gap. In this approach, the modified winding function is defined as the difference between the turn function for uniform air gap and its average in one period. Using this approach, they confirm that the mutual inductions calculated from the stator or from the rotor are not the same. The modified winding function approach (MWFA) is also used in [8]. Comparing to [7], authors introduce the axial variable ($z$) in addition to the polar variable ($\phi, r$) for inductions calculation.

One can note that the winding function approach is used in all the papers discussed above and the analytical expression of the self and mutual inductions of the induction machine are never presented. For that reason, this paper attempts to introduce the analytical formulation of these inductions using the magnetomotive force (MMF) and the permeance function approach considering time and space harmonics. First, it is important to present the Fourier series decomposition of the stator and the rotor MMF. These MMFs are multiplied by the permeance function and integrated across a surface to produce the flux. Inductances are obtained by dividing the flux linkage by the current. The magnitude and the form of these inductances in presence of dynamic eccentricity are discussed and compared to those of the healthy machine. The calculated inductances are introduced in the general induction machine model obtained using the magnetically coupled circuits approach. Simulation results illustrating the induction machine performances for the healthy the faulty cases are presented. Also, the Fast Fourier Transform FFT of the steady state stator current is performed to detect any specific component which identifies the fault appearance in the machine.
II. INDUCTION MACHINE MODEL WITH THE COUPLED MAGNETIC CIRCUITS APPROACH

The stator of the machine consist on a three windings displaced 120°. The squirrel cage contains \( N_s \) bars which forms \( N_s \) identical loops. Each one consists of two adjacent rotor bars connected by two end ring portions. Therefore, the current distribution can be specified in terms of \( N_s+1 \) independent rotor currents. These currents comprise of the \( N_s \) rotor loop current \( i_j \) (1≤\( j \)≤\( N_s \)) plus a circulating current in one of the end rings \( i_0 \). For the modelling of the induction machine, the following general assumptions are made:

- negligible saturation;
- negligible interbar current;

According to coupled magnetic circuits approach, it is possible to establish voltage equations of stator and rotor loops as [9]

\[
V_i = R_i I_i + \frac{d}{dt} \phi_s \tag{1}
\]

\[
0 = R_j I_j + \frac{d}{dt} \phi_r \tag{2}
\]

\[
\phi_s = L_{ss} I_s + M_{sr} I_r \tag{3}
\]

\[
\phi_r = L_{rs} I_s + M_{rr} I_r \tag{4}
\]

Where \( V_i \) is the stator voltage, \( I_i \) and \( L_i \) are the stator and the rotor currents, \( \phi_s \) and \( \phi_r \) are the stator and the rotor flux linkage, \( R_i \) and \( L_i \) are a 3 by 3 stator resistance and inductance matrix, \( R_r \) and \( L_r \) are a \((N_r+1)\times(N_r+1)\) rotor resistance and inductance matrix. \( M_{sr} \) is a 3 by \( N_s+1 \) matrix consisting of mutual inductances between stator coils and the rotor loops plus the end ring, where \( M_{sr} \) is a \( N_s+1 \) by 3 matrix consisting of mutual inductances between rotor loops and the stator coils.

The mechanical equation of motion depends upon the characteristics of the load. It is assumed here that the torque which opposes that produced by the machine consists of the inertial torque, the friction torque and the external load torque which are explicitly known. In this case the mechanical equation of motion is simply:

\[
\frac{d\omega_r}{dt} = \frac{1}{K_f} \left( C_m - K_f \omega_r - C_L \right) \tag{5}
\]

where \( C_L \) is the load torque, \( K_f \) friction constant. The electromagnetic torque produced by the machine \( C_m \) can be obtained from the magnetic coenergy as [10]:

\[
C_m = \frac{dW_{co}}{d\theta_r} \tag{6}
\]

In a linear magnetic system, the coenergy is equal to the stored magnetic energy as:

\[
W_{co} = \frac{1}{2} \left( L_{ss} I_s^2 + L_{sr} I_s I_r + L_{rr} I_r^2 \right) \tag{7}
\]

III. INDUCTANCES CALCULATION

A. Self and mutual inductances of stator phases

The self inductance \( L_{s_i} \) of any stator phase \( i \) (i=1, 2, 3) can be given by the following equation:

\[
L_{s_i} = \frac{\phi_{s_i}}{I_{s_i}} \tag{8}
\]

where \( \phi_{s_i} \) is the flux linked to this phase generated only by the current \( i_{s_i} \) following the same phase. Due to the high permeability of the stator and the rotor steel and to the short length of the air gap relative to the inside stator diameter, the magnetic field essentially exist only in the air gap and tend to be radial in direction, even with an eccentric rotor [3,4]. At first, let us consider the flux linkages of a single coil of stator winding which is located between \( \phi_{s_i} \) and \( \phi_{s_j} \) in the stator reference frame. In this case, the flux is determined by performing a surface integral over the open surface of the single coil:

\[
\phi_{s_i}(\theta_r) = r.L. \int \frac{F_i(\phi_s) \lambda(\phi_s, \theta_r)}{\phi_{s_i}} d\phi_s \tag{9}
\]

where \( r \) is the average air gap radius, \( L \) is the core length. \( F_i(\phi) \) is the stator phase FMM and \( \lambda(\phi, \theta) \) is the air-gap permeance function, they can be given respectively by:

\[
F_i(\phi_s) = \sum_{n=1}^{N_p} \frac{2N_p - 1}{\pi n_p} K_b(n_p) \cos(n_p \phi_s) \tag{10}
\]

\[
\lambda(\phi_s, \theta) = \lambda_0 (1 + 2 \sum_{n=1}^{N_p} \lambda_n \cos(k(\phi_s - \theta))) \tag{11}
\]

\[
\lambda_0 = \frac{\mu_0}{\varepsilon_0 \delta^2} \left( 1 - \frac{1 - \delta^2}{\delta^2} \right)^n \tag{12}
\]

where \( K_b(n_p) \) is the winding factor of the space harmonic of rank \( n \). It can be given by:

\[
K_b(n_p) = \sin\left( \frac{n_p \pi}{2} \right) \frac{\sin\left( \frac{N_p \pi}{n_p} \right)}{\sin\left( \frac{n_p \pi}{N_p} \right)} \tag{13}
\]

where \( N_p \) is the number of series coils per phase, \( \varepsilon_0 \) is the mean air-gap length, \( \mu_0 \) is the air magnetic permeability and \( \delta \) is the dynamic eccentricity degree. However, the flux linked to the stator phase can be obtained by addition of the flux linked to all the coils which constitute this phase:

\[
\phi_{s_i}(\theta_r) = n_s r L. \sum_{m=0}^{N_p-1} \sum_{n=0}^{m-1} \left( \beta_1 \right)_{i} F_i(\phi_s) \lambda(\phi_s, \theta_r) d\phi_s \tag{14}
\]

where:

\[
\beta_1 = \frac{\tau}{2} - \left( N_{es} - 1 \right) \frac{\pi}{N_s} + m_1 \frac{2\pi}{N_s} + m_2 \frac{2\pi}{p} \tag{15}
\]

\[
\beta_2 = \frac{\tau}{2} - \left( N_{es} - 1 \right) \frac{\pi}{N_s} + m_1 \frac{2\pi}{N_s} + m_2 \frac{2\pi}{p} \tag{15}
\]

Taking into account equation (15) and substituting \( F_i(\phi) \) and \( \lambda(\phi, \theta) \) by their expressions given respectively by (10) and (11), the stator self inductance can be obtained after calculation and simplification by the following relation:
\(L_m)_{de} = (L_m)_{de1} + (L_m)_{de2}\) 

where \((L_m)_{de1}\) and \((L_m)_{de2}\) are given by (17) and (18) respectively.

\[
(L_m)_{de1} = \frac{4.\mu_0.r.L.N_i^2}{\pi.p^2.cos(\frac{\alpha}{2})} \sum_{n=0}^{\infty} \left( \begin{array}{c} K_n(p) \cr n \end{array} \right)^2
\]

\[
(L_m)_{de2} = \frac{L_0}{\sqrt{1-\delta_d^2}} \sum_{n=0}^{\infty} \sum_{k=1}^{\infty} (A_k + B_k) \cos(k \theta_r) \cos(n \phi_{rj})
\]

Similarly, the mutual inductance \(L_{mij}\) between two stator phases \(i\) and \(j\) can be deduced using the same procedure and introducing only the phase angle \(\phi_{mij} = (i-j)\cdot2\pi/3\) between these phases. Therefore, the following expression can be obtained:

\[
(L_{mij})_{de} = (L_{mij})_{de1} + (L_{mij})_{de2}
\]

where \((L_{mij})_{de1}\) and \((L_{mij})_{de2}\) are given by (21) and (22) respectively.

\[
(L_{mij})_{de1} = \frac{L_0}{\sqrt{1-\delta_d^2}} \sum_{n=0}^{\infty} \left( \begin{array}{c} K_n(p) \cr n \end{array} \right)^2 \cos(n \phi_{mij})
\]

\[
(L_{mij})_{de2} = \frac{L_0}{\sqrt{1-\delta_d^2}} \sum_{n=0}^{\infty} \sum_{k=1}^{\infty} (A_k \cos(k \theta_r - n \phi_{mij}) + B_k \cos(k \theta_r + n \phi_{mij}))
\]

One can note from the above expressions that in presence of dynamic eccentricity, the self and mutual inductances of the stator phases are function of the rotor position, and this fact should be taken into account during the calculation of the electromagnetic torque. For a known stator winding configuration it is necessary to calculate expressions (14) and (17) for every rotor position during simulation. Figure 1 shows the variation of the self inductance of the first stator phase and mutual inductance between the first and the second stator phase for \(\delta_d=70\%\) of dynamic eccentricity.

B. Self and mutual inductances of rotor loops

The rotor can be considered equivalent to a \(m\)-phase two layer winding. A turn (loop) is formed by the conductors in the top layer of one slot and the bottom layer of the adjacent slot. The current \(i\), following in the turn is the current in the end ring between the two slots. The number of phases in such a winding would be \(m=N_r/p\) where \(N_r\) expresses the number of rotor bars. The phase shift between the currents in two adjacent turns is \(2 \pi /m = 2\pi.p/Nr\) since the rotor bars are spaced by the angle \(\alpha_r=2.\pi/N_r\) [9]. Using this approach, the FMM \(F_{ij}\) of the \(j^{th}\) loop can be written as:

\[
F_{ij}(\phi_r) = \sum_{n=1}^{\infty} \frac{2 \mu_0 L_0}{\pi.p} \sin\left( \frac{n \alpha_r}{2} \right) \cos(n \phi_r)
\]

So, the self inductance for any rotor loop can be calculated as:

\[
(L_{ij})_{de} = r.L. \frac{\alpha_r}{2} \lambda(\phi_r) d\phi
\]

With exactly the same method and after calculation and simplification, we can obtain the formula providing the self inductance of the rotor loop:

\[
(L_{ij})_{de} = (L_{ij})_{de1} + (L_{ij})_{de2}
\]

where:

\[
(L_{ij})_{de1} = \frac{L_0}{\pi} \sum_{n=1}^{\infty} \sum_{k=1}^{\infty} \sin\left( \frac{n \alpha_r}{2} \right) \sin\left( \frac{(n-k) \alpha_r}{2} \right)
\]

\[
(L_{ij})_{de2} = \frac{2 \pi L_0}{\pi} \sum_{n=1}^{\infty} \sum_{k=1}^{\infty} |A_k| \cos(k \theta_r - n \phi_{rj}) + |B_k| \cos(k \theta_r + n \phi_{rj})
\]

Similarly, the mutual inductance \(L_{mij}\) between any two rotor loops \(i\) and \(j\) can be deduced by introducing only the phase angle \(\phi_{mij} = (i-j)\cdot2\pi/3\). Therefore, we can write:

\[
(L_{mij})_{de} = ((L_{mij})_{de1} + (L_{mij})_{de2}) \cos(n \phi_{mij})
\]

In presence of dynamic eccentricity, self and mutual inductances of rotor loops are independent on the rotor position.
Hence, these inductances should be calculated only once outside of the iterative process of calculation.

### C. Mutual inductances between stator phases and rotor loops

For a machine with uniform air gap, the mutual inductances between stator phases and rotor loops \( L_{rs} \) are the same than the mutual inductances between rotor loops and stator phases \( L_{sr} \). In this section, we will show that, in the case of dynamic eccentricity, the air gap is nonuniform and these mutual inductances will be different. This important result is also confirmed by [6-10]. The mutual inductance between any stator phase \( i \) and any rotor loop \( j \) is the ratio between the flux linked to the rotor loop which is generated by the stator phase and the current following this phase. Hence, the expression of this mutual inductance can be calculated by:

\[
\left( L_{srij} \right)_{de} = rL \int rL \left( \varphi - \varphi_{srij} \right) \lambda(\varphi, \theta_r) \, d\varphi
\]

After calculation of this integral and simplification using trigonometric relations, the mutual inductance between the stator and the rotor can be expressed by:

\[
\left( L_{srij} \right)_{de} = \left( L_{srij} \right)_{de1} + \left( L_{srij} \right)_{de2}
\]

where:

\[
\left( L_{srij} \right)_{de1} = \frac{4 \mu_0 rL N_y}{\pi \mu^2} \sum_{n=1}^{\infty} \left( \frac{K_0(n \alpha_r)}{n^2} \right) \sin \left( \frac{n \alpha_r}{2} \right) \cos \left( k_2 \phi_{srij} \right)
\]

and:

\[
\left( L_{srij} \right)_{de2} = \frac{2N_y rL}{\pi \mu^2} \sum_{n=1}^{\infty} \left( \frac{K_0(n \alpha_r)}{n^2} \right) \sum_{k=1}^{\infty} \sin \left( \frac{(n + k) \alpha_r}{2} \right) \cos \left( k_2 \phi_{srij} \right)
\]

Similarly, the mutual inductance between the rotor loop and the stator phase \( L_{rs} \) is the ratio between the flux linked to the stator phase which is generated by the rotor loop and the current following this loop. So, its expression can be given by:

\[
\left( L_{rsij} \right)_{de} = rL \int F_i(\varphi - \varphi_{rsij}) \lambda(\varphi, \theta_r) \, d\varphi
\]

where \( \beta_1 \) and \( \beta_2 \) are given by (15) and \( \phi_{rsij} = -\phi_{srij} \). After all calculation done, the mutual inductance \( L_{rsij} \) can be given by the flowing relation:

\[
\left( L_{rsij} \right)_{de} = \left( L_{rsij} \right)_{de1} + \left( L_{rsij} \right)_{de2}
\]

where:

\[
\left( L_{rsij} \right)_{de1} = \frac{\left( L_{rsij} \right)_{healthy}}{\sqrt{1 - \delta_d^2}}
\]

and:

\[
\left( L_{rsij} \right)_{de2} = \frac{2rL N_y}{\pi \mu} \sum_{k=1}^{\infty} \left( \frac{E_k(n \alpha_r)}{n} \right) \cos \left( n \varphi_{rsij} \right) \sum_{k=1}^{\infty} \left( A_k + B_k \right)
\]

After calculation of this integral and simplification using trigonometric relations, the mutual inductance between the rotor loop and the stator phase can be calculated by:

\[
\left( L_{rsij} \right)_{de} = \frac{4 \mu_0 rL N_y}{\pi \mu^2} \sum_{n=1}^{\infty} \left( \frac{K_0(n \alpha_r)}{n^2} \right) \sin \left( \frac{n \alpha_r}{2} \right) \cos \left( k_2 \phi_{rsij} \right)
\]
The above expressions show that stator phase–rotor loop mutual inductance and rotor loop–stator phase are dependent on the rotor position. A comparison have been shown in Fig. 2 between the mutual inductance of the first stator phase and the first rotor loop for a healthy machine and for a machine with 50% of dynamic eccentricity. This figure shows also the mutual inductance between the first rotor loop and the first stator phase. It is clear from this figure that the mutual inductances increase in presence of dynamic eccentricity and the mutual inductance between stator phases and rotor loops are different from the mutual inductances between the rotor loops and the stator phases. Figure 3 shows the curves of mutual inductances between stator phases and the rotor loops. It is obvious that the value of the mutual inductance declines with the rise of the air gap length. Mutual inductances between the rotor loops and the stator phases are illustrated in Fig. 4. One can notes that the shapes of these curves are the same as that of the curves for the stator–rotor mutual inductances in a symmetrical machine. Only the magnitude grows with the dynamic eccentricity. The reason for this is that the rotor loop in standard cage rotor induction machine has a quite small pitch, so the rotor loop in one position of the rotor does not experience a significant change in air gap length.

IV. SIMULATION RESULTS

The developed model is used to simulate a 4kW squirrel cage induction machine whose parameters are given in the appendix. For this purpose, a computer script written in MATLAB/SIMULINK has been developed. First it is assumed that the machine is supplied by a three sinusoidal voltages. Figure 5 shows the rotor speed in case of a healthy and a faulty machine. As it is seen, the speed of the healthy machine is 688.5 Hz and that of the faulty one is 687.3 Hz. However, other components exist around the slots harmonics due to the dynamic eccentricity. The frequency of the first component is 588.5 Hz and for the second one, it is 688.5 Hz. However, other components exist around the slots harmonics due to the dynamic eccentricity. The frequency of these harmonics is given by (38) and can be indicated in Fig. 8.

$$f_{sd} = \left( (k_1 N_s \pm n) \frac{f_s}{p} \pm \frac{f_r}{p} \right) f_s$$  (38)

In order to analyse the effect of time harmonic in the spectrum of the stator current, the proposed model is also used to simulate the induction machine with dynamic eccentricity when the supply is a sinusoidal PWM voltage inverter. The output voltage of the inverter contains in addition to the fundamental, other components with frequency $(m_1 k_1 \pm k_2) f_s$ where $m_1$ is the modulation index, $(k_1, k_2)$ are integer and $(k_1 + k_2)$ are an odd integer [14]. Figure 9 shows the stator current spectrum in the interval [500 800Hz] for machine with 40% of dynamic eccentricity operating under 10 N.m load torque. The Principal Slots Harmonics PSH can be located in this spectrum. As it was indicated in the theoretical analysis, the frequency of these components corresponds exactly to this given by:

$$PSH = \left\{ \frac{k N_s L}{p} \left( \frac{l - s}{p} \right) \pm v \right\} f_s$$  (37)

The frequency of the first component is 588.5 Hz and for the second one, it is 688.5 Hz. However, other components exist around the slots harmonics due to the dynamic eccentricity. The frequency of these harmonics is given by (38) and can be indicated in Fig. 8.
The specific fault harmonic, 1997, pp MA2/4.1.60-80 100 800°1, pp. 155-383, Vol. 15, 1999, pp. 383-650 700, 200 Hz. One can note that the specific fault components around the rotor slots harmonics are submerged and it became difficult to distinguish them from these generated by PWM inverter.

Comparing to the spectrum of Fig. 7-c, the spectrum showed by this figure contains in addition to the specific fault harmonics with frequency \( f_s \pm n f_r \), other components with small amplitude due to the PWM harmonics.

Figure 10 shows the stator current spectrum in the interval [500 800 Hz]. One can note that the specific fault components around the rotor slots harmonics are submerged and it became difficult to distinguish them from these generated by PWM inverter.

Analytical expressions of the self and mutual inductances of the induction machine in presence of dynamic eccentricity are presented. These inductances are obtained using the magnetomotive force and the airgap permeance approach and including the space harmonics effect. Compared to a healthy machine, the magnitude of these inductances increases with the dynamic eccentricity degree. In addition of this, the self and mutual inductance of the stator become variable with the rotor position. Concerning the mutual inductances between the stator and the rotor, the results obtained with this approach confirm that the mutual inductances of the stator-rotor loops are different from the mutual inductances of the rotor-stator phases. The developed inductances are introduced in a general model of an induction machine obtained using the magnetically coupled circuits approach. Simulations are performed for two different voltage supplies. The first one is a perfect sinusoidal supply; the second one is a PWM voltage inverter. The MCSA technique is used to detect the specific components of the dynamic eccentricity fault. It has been shown that in case of PWM supply, the identification of these components is more difficult than for a sinusoidal supply.

Appendix

Squirrel cage induction machine parameters

- \( P_s = 5.5 kW; U_s = 380 V; Y \) connection;
- \( I_n = 11.2 A; N_p = 1445 \) rpm;
- \( p = 2; f = 50 Hz; \cos \phi = 0.8; \) Number of rotor bars = 28

REFERENCES


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