Multiple Coupled Circuit modeling of Induction Machines under Rotor Bar Fault

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***Abstract*— An accurate and simpler approach for modeling and simulating the dynamic behavior of induction machines under rotor fault is presented here. This method is based on the coupled magnetic circuit theory. The system of differential equations describing the induction machine in presence of rotor broken bar faults is given. The machine inductances are calculated by means of the magnetic energy stored in the air-gap. The proposed model allows a precise study of several machine faults signature in various machine main quantities. Finally, some simulation results illustrate the proposed global in the case of broken rotor bars fault.**

Keywords—Faults detection, Induction Machine (IM); Fault diagnosis; broken bars

I. INTRODUCTION

Induction motors are critical components in many industrial processes. In spite of their robustness they do occasionally fail and their resulting unplanned downtime can prove very costly. There for, condition monitoring of electrical machines has received considerable attention in recent years [1] and [2].There are many ways to detect mechanical and problems in induction motors, either directly or indirectly. There are several different types of faults that manifest themselves in an induction motor. Faults are often classified according to where they occur in the motor [3]. The most common faults are: Stator faults resulting in the opening of the phase winding, Rotor faults due to broken rotor bars or broken end-rings, static or dynamic air-gap irregularities (eccentricity faults) and bearing failures[11, 12].These mechanical faults have varying effect on the electrical signatures of the motor. These faults produce one or more of the symptoms: unbalanced air-gap voltage and line current, increased torque pulsations, decreased average torque, increased losses and reduction in efficiency.Many researches have focused their attention on incipient fault detection and preventive maintenance. In recent years intensive research efforts have been focused on the technique of monitoring and diagnosis of electrical machines [4], and [5]. Different

Methods same time frequency domain analysis of induced voltages in search coils placed internally around stator tooth tip and yoke ,time domain analysis of electromagnetic torque and flux pharos, motor current signature analysis (MCSA) [6], and harmonic analysis of torque and speed have been used to motor fault detection.

The availability of simulation model in the case of faulty machine becomes attractive. The aim of this paper is to develop an accurate model that is capable to predicting the performance of inductance machines under rotor faults. The proposed model is based on a coupled magnetic circuit approach and the differential equations governing on inductance machine behavior are given.

II. ORIGINAL PHASE AXES MODEL OF AN ASYNHRONOUS MACHINES

A. Modeling of IM in healthy state

The stator of the machine consists of three sinusoidal distributed winding displayed by 120 .The mesh model is based on a coupled magnetic circuits approach and by making the following assumptions: The state of operation remains far from magnetic saturation, the magnetic permeability of iron is considered infinite and the air gap is very small and smooth, space magnetic motive force (MMF) and flux profiles are considered to be sinusoidal distribution and higher harmonics are negligible.

The external model three –phase current is obtained through the expressions of electric equations with the stator and the rotor which is magnetic coupled through mutual inductances.

$$[u] = \begin{bmatrix} u^s \\ u^r \end{bmatrix} = \begin{pmatrix} [R_{SS}]_{3\times3} & [0] \\ [0] & [R_{RR}]_{3\times3} \end{pmatrix} \begin{bmatrix} I^s \\ I^r \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi^s \\ \varphi^r \end{bmatrix} \quad (1)$$

$$[\varphi] = \begin{bmatrix} \varphi^s \\ \varphi^r \end{bmatrix} = \begin{pmatrix} [L_{SS}] & [M_{SR}(\theta)] \\ [M_{RS}(\theta)] & [L_{RR}] \end{pmatrix} \begin{bmatrix} I^s \\ I^r \end{bmatrix} \quad (2)$$

Where the elementary vector voltage and current are defined such as (3)-(4)-(5)-(6)

$$[u^s] = [u_a^s \quad u_b^s \quad u_c^s] \quad (3)$$

$$[u^r] = [u_a^r \quad u_b^r \quad u_c^r] \quad (4)$$

$$[I^s] = [I_a^s \quad I_b^s \quad I_c^s] \quad (5)$$

$$[I^r] = [I_A^s \quad I_B^r \quad I_C^r] \quad (6)$$

The matrices resistance, self-inductance of the stator and the rotor windings, and their mutual inductances matrix are respectively as (7):

$$[R_{SS}]_{3\times3} = \begin{pmatrix} R_a^s & 0 & 0 \\ 0 & R_b^s & 0 \\ 0 & 0 & R_c^s \end{pmatrix} \quad (7)$$

$$[R_{RR}]_{3\times3} = \begin{pmatrix} R_A^r & 0 & 0 \\ 0 & R_B^r & 0 \\ 0 & 0 & R_C^r \end{pmatrix} \quad (8)$$

$$[L_{SS}]_{3\times3} = \begin{pmatrix} L_a^s & M_{a,b}^s & M_{a,c}^s \\ M_{b,a}^s & L_b^s & M_{b,c}^s \\ M_{c,a}^s & M_{c,b}^s & L_c^s \end{pmatrix} \quad (9)$$

$$[L_{RR}]_{3\times3} = \begin{pmatrix} L_A^r & M_{A,B}^r & M_{A,C}^r \\ M_{B,A}^r & L_B^r & M_{B,C}^r \\ M_{C,A}^r & M_{C,B}^r & L_C^r \end{pmatrix} \quad (10)$$

$$[M_{SR}(\theta)]_{3\times3} = m_{sr} \begin{pmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) \\ \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta) \end{pmatrix} \quad (11)$$

To the set of (1) (2) equations, one must add the mechanical equation of the shaft:

$$J\frac{d\Omega}{dt} + f.\Omega = C_{elm} - C_L \quad (12)$$

$$\frac{d\theta}{dt} = \Omega \quad (13)$$

Ω is the rotor angular speed, J is the drive inertia,f is the drive viscous friction coefficient, C_L is the load torque and C_{elm} is the electromagnetic torque expressed as:

$$C_{elm} = \frac{1}{2}[I]^T\left\{\frac{d}{d\theta}[L]\right\}.[I] \quad (14)$$

Whereθ is the rotor position.

Now incorporating equation (14) in (12),it can be written the system of differential equations which governs on the induction machine behavior

$$\begin{cases} \frac{d}{dt}[I] = -[L]^{-1}\left([R] + \Omega.\frac{d[L]}{d\theta}\right)[I] + [L]^{-1}.[u] \\ \frac{d\Omega}{dt} = \frac{1}{2J}[I]^t\left\{\frac{d[L]}{d\theta}\right\}[I] - \frac{f}{J}.\Omega - \frac{1}{J}C_L \\ \frac{d\theta}{dt} = \Omega \end{cases} \quad (15)$$

Equations (1) (2) and (12) can be written as a differential algebraic state system which governs the induction machines.

$$\begin{pmatrix} \begin{pmatrix} u^s \\ u^r \end{pmatrix} \\ -C_{load} \\ 0 \end{pmatrix} = \begin{pmatrix} [R_{SS}] & \Omega_r.\frac{d[M_{SR}(\theta)]}{d\theta} & [0] & [0] \\ \Omega_r.\frac{d[M_{RS}]}{d\theta} & [R_{RR}] & [0] & [0] \\ [C^s] & [C^r] & f & 0 \\ [0] & [0] & -1 & 0 \end{pmatrix} . \begin{pmatrix} I^s \\ I^r \\ \Omega_r \\ \theta \end{pmatrix} + \begin{pmatrix} [L_{SS}] & [M_{SR}(\theta)] & [0] & [0] \\ [M_{RS}(\theta)] & [L_{RR}] & [0] & [0] \\ [0] & [0] & J & 0 \\ [0] & [0] & 0 & -1 \end{pmatrix} . \begin{pmatrix} I^S \\ I^r \\ \Omega_r \\ \theta \end{pmatrix} \quad (16)$$

$$[M_{SR}(\theta)] = m_{sr}.\begin{bmatrix} f_1^s & f_2^s & f_3^s \\ f_3^s & f_1^s & f_2^s \\ f_2^s & f_3^s & f_1^s \end{bmatrix} \quad (17)$$

$$f_i^s = \cos\left(p\theta + (i-1)\frac{2\pi}{3}\right) \quad i=1,\,2,\,3 \quad (18)$$

The derivate angular of the previous mutual inductance is expressed as:

$$\Omega_r.\frac{d[M_{SR}]}{d\theta} = m_{sr}.\begin{bmatrix} g_1^s & g_2^s & g_3^s \\ g_3^s & g_1^s & g_2^s \\ g_2^s & g_3^s & g_1^s \end{bmatrix} \quad (19)$$

Where $g_i^s = \Omega_r.\mathrm{p}.\sin(p\theta + (i-1) - \frac{2\pi}{3})$; And the related mechanical elements$[C^s]$ and $[C^r]$ are calculated as (20)-(21):

$$[C^s] = 0.5.m_{sr}[H].[I^r] \quad (20)$$

$$[C^r] = 0.5.m_{sr}[H].[I^s] \quad (21)$$

$$[H] = m_{sr}.\begin{bmatrix} h_1^s & h_2^s & h_3^s \\ h_3^s & h_1^s & h_2^s \\ h_2^s & h_3^s & h_1^s \end{bmatrix} \quad (22)$$

III. SQUIRREL CAGE INDUCTION MOTORS

The differential equations system of the induction machine in the healthy case, and the broken rotor bars have been introduced in this part.

A. Case of delta connected stator phases

This model follows the coupled magnetic approach by treating the current in each rotor bar as an independent variable. The analysis is based on the following assumptions. 1) Symmetric machine 2) uniform air-gap, 3) negligible saturation and insulated rotor bar. The stator comprises of three phase concentric winding. Each of these winding is treated as a separate coil [4], and [8]. The cage rotor consists of Nr+1 bar can be described as a Nr identical and equally spaced rotor loop. As shown in figure 1, each loop is formed by two adjacent rotor bars and the connecting portions of the end-rings between them. Hence, the rotor circuit has Nr+1 independent current as variables. The Nr rotor loop currents are coupled to each other and to the stator winding through mutual inductances. The end ring loop does not couple with the stator winding; it however couples the rotor currents only through the end leakage inductance and the end ring resistance.

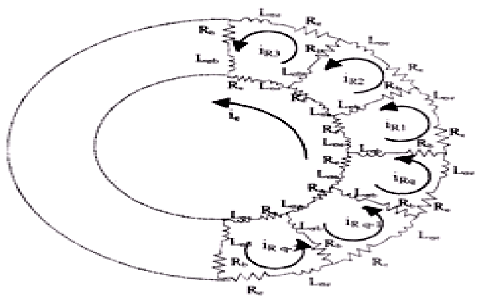

Fig .1 Rotor cage equivalent circuit

$$\begin{pmatrix} \begin{bmatrix} V^s \\ V^r \end{bmatrix} \\ -C_r \\ 0 \end{pmatrix} = \begin{bmatrix} [L_{SS}] & [M_{SR}] & [S_o] & [S_o] \\ [M_{RS}] & [L_{RR}] & [S_o] & [S_o] \\ [S_o]^T & [S_o]^T & J_t & 0 \\ [S_o]^T & [S_o]^T & 0 & 1 \end{bmatrix} . \begin{pmatrix} \begin{bmatrix} I^s \\ I^r \end{bmatrix} \\ \Omega_r \\ \theta \end{pmatrix} + \quad (23)$$

$$\begin{bmatrix} [R_S] & \left[\Omega_r . \frac{dM_{SR}}{d\theta}\right] & [So]^T & [So]^T \\ \left[\Omega_r . \frac{dM_{SR}}{d\theta}\right] & [R_R] & [S_o]^T & [S_o]^T \\ C_{stator} & C_{rotor} & f_v & 0 \\ [S_0] & [S_0] & -1 & 0 \end{bmatrix} . \begin{pmatrix} \begin{bmatrix} \dot{I}^s \\ \dot{I}^r \end{bmatrix} \\ \dot{\Omega}_r \\ \dot{\theta} \end{pmatrix}$$

Where

$[V^r] = [V_1^r\ V_2^r\ V_3^r \ldots\ldots\ldots V_{N_r}^r\ V_e^r]$,

$[I^r] = [I_1^r\ I_2^r\ I_3^r \ldots\ldots\ldots I_{N_r}^r\ I_e^r]$,

$[S_0] = [0\,0\,0\,0\ldots\ldots]$ and $[R_S]$, $[L_{SS}]$

The matrix $[R_R]$ is n by n symmetric where, $R_{b(k-1)}$ resistance of the bar number k and R_e is the end ring segment resistance.

$$[R_R] = \begin{bmatrix} R_{b0} + R_{b(N_R-1)} + 2\frac{R_e}{N_R} \cdots & 0 & 0 & 0 \cdots\ \text{-}\ R_e \\ \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots R_{b(k-1)} & R_{bk} + R_{b(k-1)} + 2\frac{R_e}{N_R} & -R_{bk} \cdots\ \text{-}\ R_e \\ \vdots & \vdots & \vdots & \vdots \\ -R_{b(N_R-1)} \cdots\cdots & 0 & 0 & 0 \cdots\ \text{-}\ N_r.R_e \end{bmatrix} \quad (24)$$

The mutual inductance between the stator coils and the rotor loops is $3 \times (N_r + 1)$ matrix; which is function of θ, the spatial position of the rotor

$$[H] = M_{sr} \begin{bmatrix} \cos(\theta) & \cos(p\theta + a) & \cdots & \cos(\theta + (N_r + 1)) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \cos\left(p\theta + \frac{2\pi}{3} + a\right) & \cdots & \cos\left(\theta + (N_r + 1).a + \frac{2\pi}{3}\right) \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(p\theta - \frac{2\pi}{3} + a\right) & \cdots & \cos\left(\theta + (N_r + 1) - \frac{2\pi}{3}\right) \end{bmatrix} \quad (25)$$

M_{sr} is the maximal value of the standard rotor mutual inductance given by(26):

$$M_{sr} = \frac{4}{\pi} . \frac{\mu_0}{e.p^2} . N_s . L . R \sin\left(p . \frac{\pi}{n}\right) \quad (26)$$

The $[L_{RR}]$ is n by n symmetrical matrix where L_b is the rotor leakage inductance, L_e the rotor end ring leakage inductance and M_{RR} is the mutual inductance between two rotor loops.

$$M_{RR} = -\frac{1}{N_r^2} . \frac{\mu_0}{e} . 2\pi . L . R \quad (27)$$

The principal inductance of the rotor mesh is given by (28) and (29):

$$L_{Rp} = \frac{N_r - 1}{N_r^2} . \frac{\mu_0}{e} . 2\pi . L . R \quad (28)$$

$$L_{Rp} = \begin{bmatrix} L_{RP} + 2L_b + 2\frac{L_e}{N_R} & M_{RR} - L_b & M_{RR} & M_{RR} & \cdots & M_{RR} \\ M_{RR} - L_b & L_{RP} + 2L_b + 2\frac{L_e}{N_R} & M_{RR} - L_b & M_{RR} & M_{RR} & \cdots \\ M_{RR} & M_{RR} - L_b & L_{RP} + 2L_b + 2\frac{L_e}{N} & M_{RR} - L_b & M_{RR} & \cdots \\ M_{RR} & \vdots & \ddots & \ddots & \ddots & \ddots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots \\ M_{RR} - L_b & M_R & M_{RR} & \cdots & M_{RR} - L_b & L_{Rp} + 2L_b + 2\frac{L_e}{N_R} \end{bmatrix} \quad (29)$$

The mutual inductance derivate in this case is defined as (30):

$$\left[\Omega_r.\frac{dM_{SR}}{dt}\right]=\begin{bmatrix} \Omega_r.p\sin(\theta) & \Omega_r.p\sin(p\theta+a) & \cdots & \Omega_r.p\sin(\theta+(N_r+1)) \\ \Omega_r.p\sin\left(\theta+\frac{2\pi}{3}\right) & \Omega_r.p\sin\left(p\theta+\frac{2\pi}{3}+a\right) & \cdots & \Omega_r.p\sin\left(\theta+(N_r+1).a+\frac{2\pi}{3}\right) \\ \Omega_r.p\sin\left(\theta-\frac{2\pi}{3}\right) & \Omega_r.p\sin\left(p\theta-\frac{2\pi}{3}+a\right) & \cdots & \Omega_r.p\sin\left(\theta+(N_r+1)-\frac{2\pi}{3}\right) \end{bmatrix} \quad (30)$$

$$C_{rotor}=0.5.p.[I_s][H] \quad (31)$$

$$C_{stator}=0.5.p.[I_R][H]^T \quad (32)$$

Where

$$[H]=\begin{bmatrix} sin(\theta) & sin(p\theta+a) & \cdots & sin(\theta+(N_r+1)) \\ sin\left(\theta+\frac{2\pi}{3}\right) & sin\left(p\theta+\frac{2\pi}{3}+a\right) & \cdots & sin\left(\theta+(N_r+1).a+\frac{2\pi}{3}\right) \\ sin\left(\theta-\frac{2\pi}{3}\right) & sin\left(p\theta-\frac{2\pi}{3}+a\right) & \cdots & sin\left(\theta+(N_r+1)-\frac{2\pi}{3}\right) \end{bmatrix} \quad (33)$$

B. *Analytical modelling of IM in faulty state: under broken bar fault*

This section discusses the broken bars and rings faults. To simulate a broken rotor bar, we increase its resistance by a coefficient such as the current in the bar is closest to zero [9] and [10]. The fault is considered in the kth bar. In this case, we change only the resistance matrix $[R_r]$ in the equation (24) by (34):

$$[R_{RT}]=[R_R]+[R_F] \quad (34)$$

$$[R_F]=\begin{bmatrix} 0 & \cdots & 0 & \cdots & \cdots & 0 \\ \vdots & \cdots & \vdots & \vdots & \cdots & \vdots \\ \vdots & \cdots & 0 & 0 & \cdots & 0 \\ 0 & 0 & R_{bF_k} & -R_{bF_k} & 0 & 0 \\ 0 & 0 & -R_{bF_k} & R_{bF_k} & 0 & 0 \\ \vdots & \vdots & 0 & 0 & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix} \quad (35)$$

IV. INDUCTANCE CALCULATION IN PROPOSED ANALYTICAL MODEL

The inductances are calculated by means of a winding function. According to this theory and for a constant air-gap, the mutual inductance between any two windings i and j is given by (36):

$$M_{ij}=\frac{\mu_0 lr}{g}\int_0^{2\pi} N_i(\theta_r,\varphi).N_j(\theta_r,\varphi)d\varphi \quad (36)$$

$N_r(\theta_r,\varphi)$ and $N_j(\theta_r,\varphi)$ are the winding function of the I and j coil, respectively. They represent the spatial distribution of the MMF along the air gap for a unit current circulating in the winding. This function depends on the spatial position of any point along the air gap defined by φ and rotor angular position compared to given reference defined by θ_r.

Considered the stator winding disposition shown by Fig 1, taking as a reference, the magnetic axis of the first phase, the normalized stator winding function for this phase is as (37),

$$N_s=\frac{N_s}{2}.cos\varphi \quad (37)$$

Substituting (37) into (36), one can deduce the magnetizing inductance for each stator coil as (38):

$$L_{ms}=\frac{\mu_0 l.r.N_s^2\,\pi}{4g} \quad (38)$$

The total inductance of the stator coil is the sum of magnetizing inductance L_{ms} and the leaking inductanceL_{sf}.However, one can write for a symmetric stator winding that:

$$L_{sa}=L_{sb}=L_{sc}=L_{sf}+L_{ms} \quad (39)$$

Where l is the stack length, r is the average radius of the air gap, gis the radial air-gap length and N_s is the number of turns of the stator coil. The mutual inductance of two stator coils 'i' and 'j'$(i\neq j)$ is given.

Fig 40 shows the function winding of a rotor loop related to a given rotor position θ_i and θ_{i+1} indicate the position of the two bars which from the rotor loop. This function is defined by (40):

$$\begin{cases} -\frac{\propto_r}{2\pi} & 0\leq\varphi\leq\theta_i \\ 1-\frac{\propto_r}{2\pi}\theta_i\leq\varphi\leq\theta_i & \\ -\frac{\propto_r}{2\pi}\theta_{i+\&}\leq\varphi\leq 2\pi & \end{cases} \quad (40)$$

Substituting (37) and (39) in (38) the mutual inductance between a stator winding 'j' and a rotor loop 'i' is expressed by (41):

$$M_{sirj}=L_m cos\left(\theta_r+\frac{p(2i-1)}{2}-(j-1)\frac{2\pi}{3}\right) \quad (41)$$

Where

$$L_m=L_{ms}\frac{4sin\left(\frac{\propto_r}{2}\right)}{\pi N_s} \quad (42)$$

The rotor loop inductance L_{rp} and the mutual inductance between two rotor loops are respectively given by (43) and (44):

$$L_{rp} = \frac{\mu_0 l r \alpha_r}{g}\left(1 - \frac{\alpha_r}{2\pi}\right) \quad (43)$$

$$M_{rr} = \frac{\mu_0 l r}{g}\left(-\frac{\alpha_r}{2\pi}\right) \quad (44)$$

V. ANALYTICAL MODEL RESULTS OF BROKEN BAR ROTOR AND END RING FAULT

To simulate the squirrel cage induction machine model, a computer program written in MATLAB was used. The differential equation was resolved using the fourth order Rung-Kutta method. The proposed model of standards squirrel cage induction machine was used to simulate a machine of 1.1 Kw, 2-poles, 24 stator slots, 30 bars which the detailed parameters are given in the appendix.

The curves of electromagnetic torque (figure 2), speed (figure 3), current stator (figure 4) and rotor (figure 5) versus time are plotted with applied constant load at 1.5s. It is considered that the failure of a bar starts at the moment t0 = 3sec. In all cases we can observe incipient oscillations on the speed, torque and stator current. These oscillations will be increased when the bar fissure increases, because the distribution of the rotor bar currents become unbalanced.

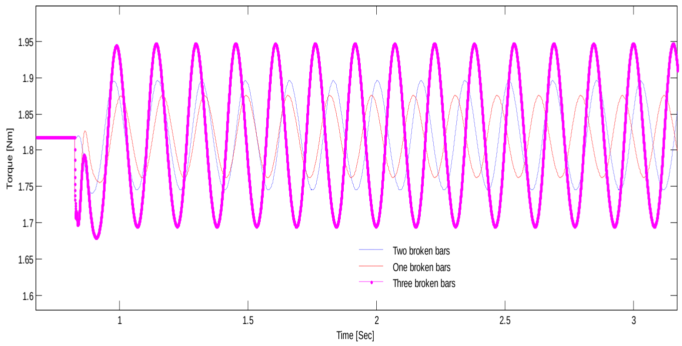

Fig. 2. Electromagnetic torque under one, two and three broken bar fault

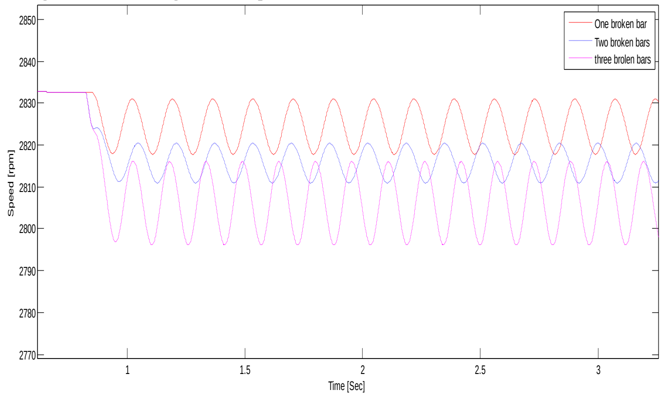

Fig. 3. Speed under one, two and three broken bar fault

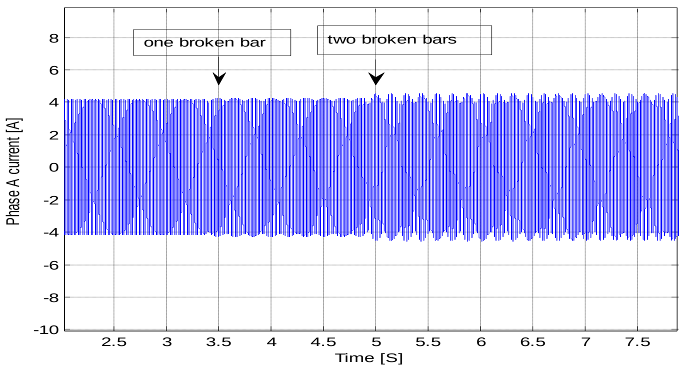

Fig. 4. Stator current under one, and two broken bar fault

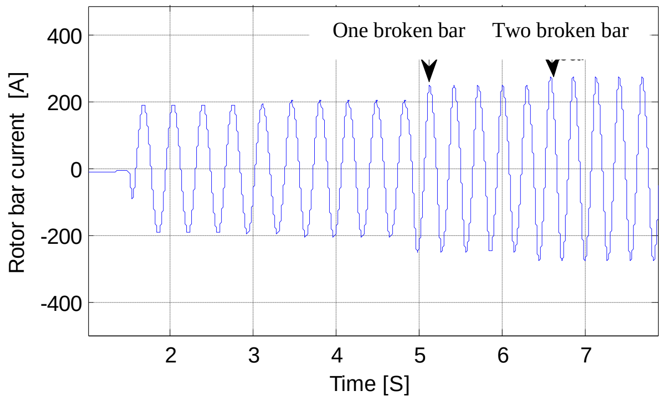

Fig. 5. Rotor bar under one, two and three broken bar fault

VI. CONCLUSION

In this paper, a coupled magnetic circuit theory based global model has been employed to simulate faulty induction machines under rotor broken faults. The inductances calculation based on magnetic energy consideration was exposed. The proposed global methods give a robust model of simulation for the model based fault diagnosis. The result shows success by designed analytical model for this type of fault.

Parameters Rated Values Unit

The parameters used in the simulation of the detailed mesh model of squirrel cage, and the proposed one are:

Output power	1.1 (kW)
Stator voltage	220/380 (V)
Stator frequency	50 (Hz)
Pole number	*1*
Stator resistance	*7.828 (Ω)*
Rotor bar resistance	*150* (*μ Ω*)
Rotor bar inductance	0.1 (*μ* H)
Resistance of end ring segment	*0.1* (*μ* H)
Leakage inductance of end ring	*0.1* (*μ* H)
Length of the rotor	65 (mm)
Air-gap mean diameter	*0.25* (mm)
Number of rotor bars	16
Number of turns per stator phase	160
Inertia	*0.0056093 (Kgm2)*

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