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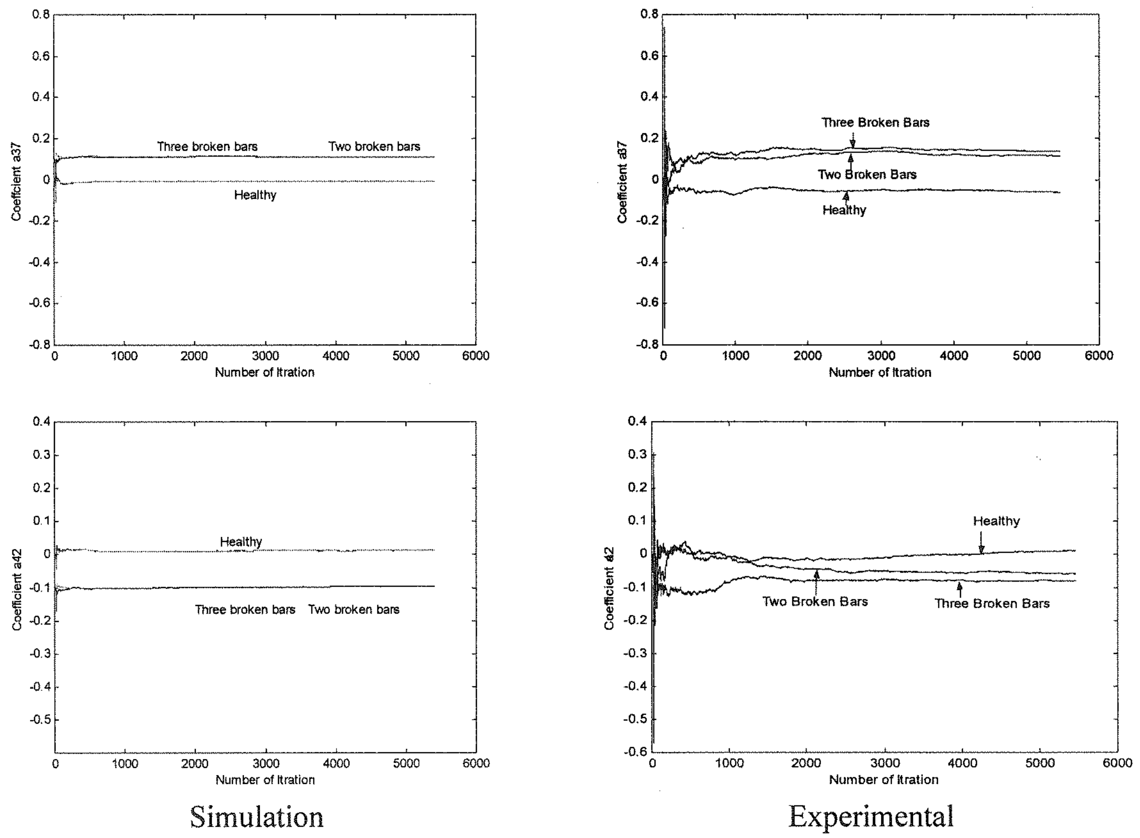

Figure (5) Variation of denumerator coefficient (Simulation & Experimental).

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6-Conclusion

This paper describes a new approach for detection of broken rotor bars in induction motors via measurement of only line-to-line stator voltages and stator currents. The detection is based on the estimation of the proposed induction motor transfer function both in healthy and broken bars cases. Simulation and experimental results and variation of the transfer function coefficient shows the effectiveness of the proposed method for broken bars detection. The broken rotor bars detector is tested experimentally using a 3-hp surreal-cage induction motors with cast aluminum rotor bars.

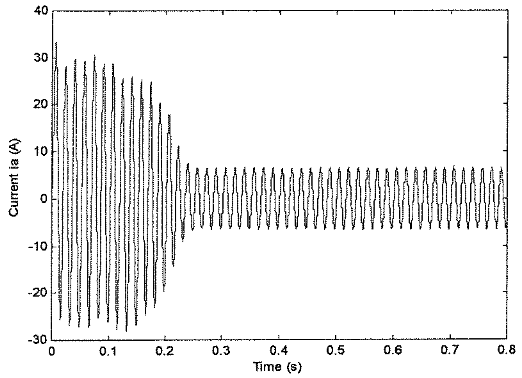


Figure (3) Stator phase current.

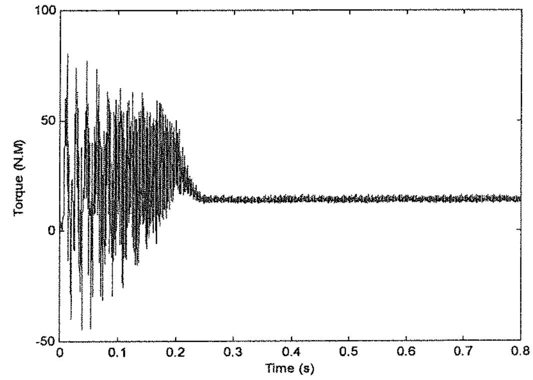
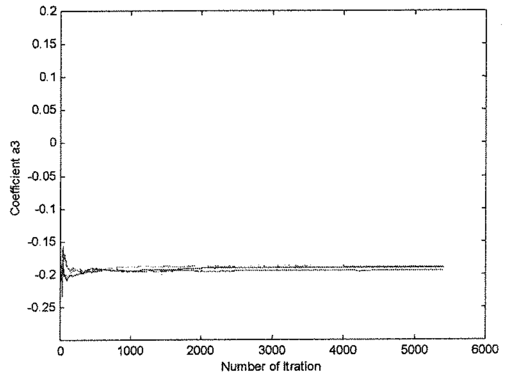
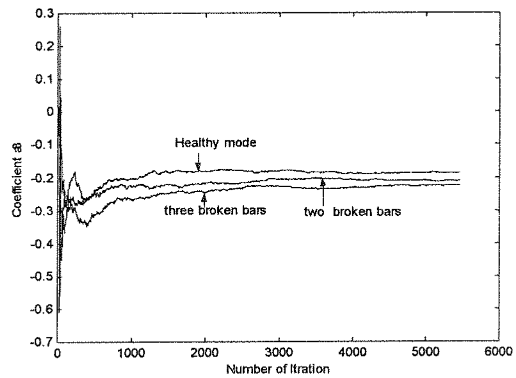
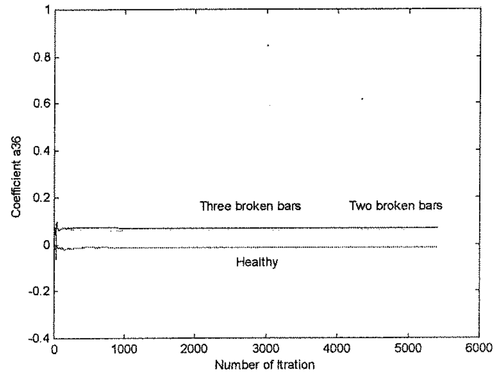
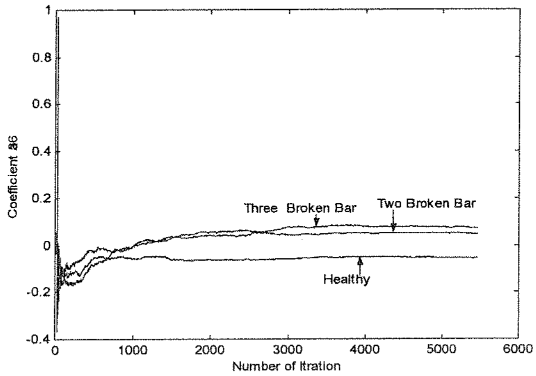


Figure (4) Electromagnetic torque.









$$F_3(Z^{-1}) = c_{10} + c_{11}.Z^{-1} + c_{12}.Z^{-2} + \dots\dots\dots + c_{1i}.Z^{-i}$$
$$F_4(Z^{-1}) = c_{20} + c_{21}.Z^{-1} + c_{22}.Z^{-2} + \dots\dots\dots + c_{2i}.Z^{-i} \qquad (23)$$
$$i = 1,2,3,\dots\dots\dots,48$$

So The main goal of this paper is to estimate the coefficients $a_{ij}, b_{ijk}, c_{1i}, c_{2i}$ properly such that broken bar detection becomes feasible.

To estimate them Weighted Recursive Least Square (W.R.L.S) technique is used. To do so, we first rewrite the system equations in the following regressor form:

$$Y = U.\theta$$
$$\theta = \begin{bmatrix} a_{1,1,1} & .. & a_{1,1,48} & b_{1,1,0} & .. & b_{1,2,0} & .. & b_{1,2,48} & c_{10} & .. & c_{47} \end{bmatrix}$$
$$U = \begin{bmatrix} y_1(k-1)\dots y_1(k-48) & U_1(k)..U_1(k-48) & U_2(k)..U_2(k-48) \\ & & w_1(k)..w_1(k-48) \end{bmatrix} \qquad (24)$$
$$\hat{y}(k) = U.\hat{\theta}$$

$\hat{y}, \hat{\theta}$ represent the estimated output and parameters respectively.

5- Simulation and Exprementai Results

To illustrate the ability of the proposed method we consider a 3-hp squirrel cage induction motor, different cases, healthy and 2,3, broken bars have been examined. Figure2 show the broken rotor bar. Figure 3,4 shows the simulation result of the current and electromagnetic torque in healthy mode. Figure 5 shows the estimated coefficients for healthy and 2, and 3 broken bars obtained from simulation and experimental measured stator voltages and currents. Variation of estimated coefficient shows the number of broken rotor bars in induction motor.

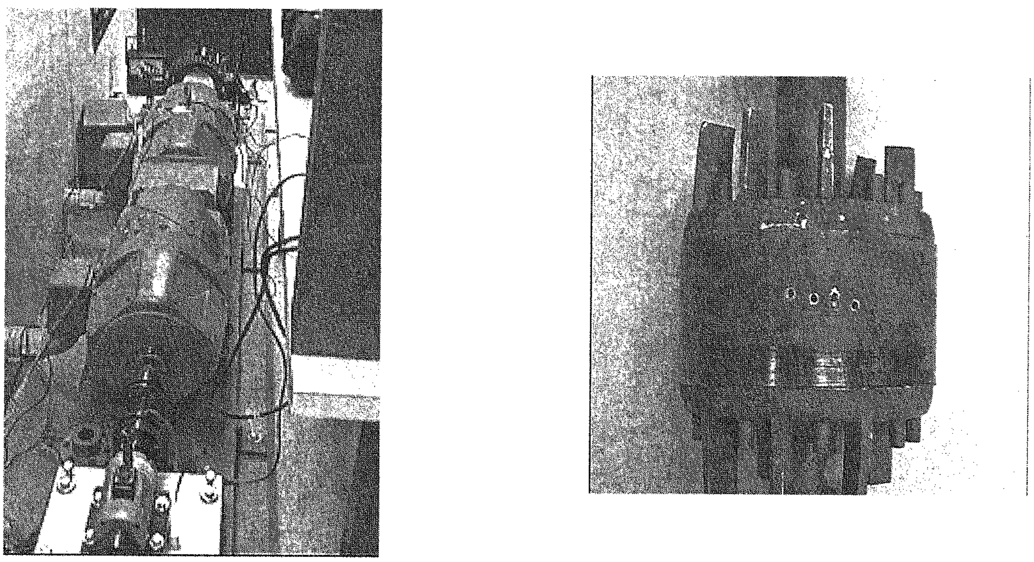


Figure (2) Test bed and broken rotor bars.

where,

$$A=\begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix}_{(n+3)\times(n+3)}, B=\begin{bmatrix} B_{11} & B_{21} \\ B_{21} & B_{22} \\ B_{31} & B_{32} \end{bmatrix}_{(n+3)\times 2} \quad C=\begin{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} & [0]_{2\times(n+1)} \end{bmatrix}_{2\times(n+3)}, D=[0]_{2\times 2}$$

$$X=\begin{bmatrix} I_a \\ I_b \\ I_r \end{bmatrix}, Y=\begin{bmatrix} I_a \\ I_b \end{bmatrix} \tag{19}$$

After linearizing the above L.T.V (Linear Time Variant) systems around the operating point (nominal speed and torque), we obtain the following discrete time systems:

$$Y(z^{-1})=C(Z.I-A)^{-1}.B.U \tag{20}$$

4-Motor Identification

It can be easily observed that the system given in (20) represents a multi-input multi-output system (MIMO) with I_a, I_b as outputs and V_{ab}, V_{bc} as inputs, where these signals can be easily measured. The objective here is to estimate the system transfer function coefficients. Using the experimental data obtained from the above, which are usually contaminated by measurement noise for estimation purposes Auto Regressive Moving Average with auxiliary input (ARMAX) modeling is used. The ARMAX model has the following general form:

$$F_1(Z^{-1}) * y(k) = F_2(Z^{-1}).U(k) + F_3(Z^{-1}).w(k) \tag{21}$$

where:

$F_i(Z^{-1}), i=1,2,3$ are polynomial functions and $y(k), u(k), w(k)$ are present output, input and noise, respectively. This model for our case can be rewritten as follow:

$$\begin{aligned} F_1(Z^{-1}).Y_1(k) &= F_{11}(Z^{-1}).U_1(k)+F_{12}(Z^{-1}).U_2(k)+F_3(Z^{-1}).w(k) \\ F_2(Z^{-1}).Y_2(k) &= F_{21}(Z^{-1}).U_1(k)+F_{22}(Z^{-1}).U_2(k)+F_4(Z^{-1}).w(k) \end{aligned} \tag{22}$$

where,

$$\begin{aligned} F_2(Z^{-1}) = F_1(Z^{-1}) &= 1 + a_{11}.Z^{-1} + a_{12}.Z^{-2} + \dots\dots\dots + a_{1i}.Z^{-i} \\ F_{11}(Z^{-1}) &= b_{110} + b_{111}.Z^{-1} + b_{112}.Z^{-2} + \dots\dots\dots + b_{11i}.Z^{-i} \\ F_{12}(Z^{-1}) &= b_{120} + b_{121}.Z^{-1} + b_{122}.Z^{-2} + \dots\dots\dots + b_{12i}.Z^{-i} \\ F_{11}(Z^{-1}) &= b_{210} + b_{211}.Z^{-1} + b_{212}.Z^{-2} + \dots\dots\dots + b_{21i}.Z^{-i} \end{aligned}$$

In the light of figure (equivalent circuit of the rotor) we will have:

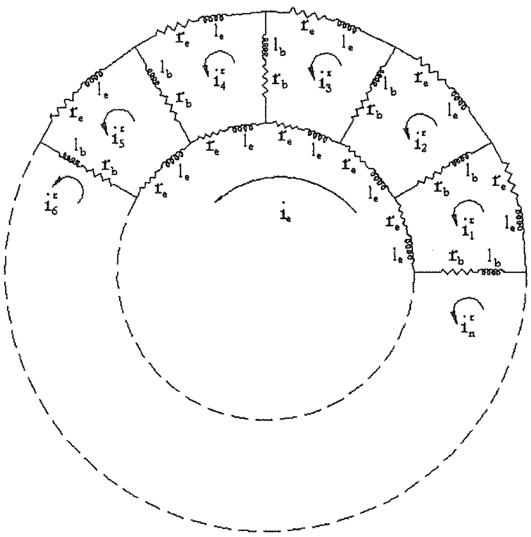


Fig.(1) Equivalent circuit of rotor cage.

$$r_r I_r + l_{rr}\frac{dI_r}{dt} + w_{rm}\left(\frac{dL_{ra}}{d\theta_{rm}} - \frac{dL_{rc}}{d\theta_{rm}}\right).I_a + \left(L_{ra} - L_{rc}\right)$$
$$+\left(\frac{dL_{rb}}{d\theta_{rm}} - \frac{dL_{rc}}{d\theta_{rm}}\right).I_b + \left(L_{rb} - L_{rc}\right).\frac{dI_b}{dt} = 0 \tag{16}$$

From (15)-(16) and after some algebra we may establish the following model:

$$\begin{aligned}
\frac{dI_a}{dt} &= A_{11}.I_a + A_{12}I_b + A_{13}.I_c + B_{11}.V_{ab} + B_{12}.V_{bc} \\
\frac{dI_b}{dt} &= A_{21}.I_a + A_{22}I_b + A_{23}.I_c + B_{21}.V_{ab} + B_{22}.V_{bc} \\
\frac{dI_r}{dt} &= A_{31}.I_a + A_{32}I_b + A_{33}.I_c + B_{31}.V_{ab} + B_{32}.V_{bc}
\end{aligned} \tag{17}$$

where,
$A_{11}, A_{12}, A_{21}, A_{22}$ are scalar; A_{13}, A_{23} are $1\times(n+1)$; A_{13}, A_{23} are $(n+1)\times 1$; A_{33} is $(n+1)\times(n+1)$; B_{31}, B_{32} are $(n+1)\times 1$ and $B_{11}, B_{12}, B_{21}, B_{22}$ are scalar quantities.
This model has the following state space form:

$$\begin{aligned}
\dot{X} &= A.X + B.U \\
Y &= C.X + D.U
\end{aligned} \tag{18}$$

The mechanical equation of motion depends upon the characteristics of the load. For simplicity, it is assumed that the torque, which opposes with the produced torque is the load torque. In this case the mechanical equation of motion is:

$$J\frac{d^2\theta_{rm}}{dt^2} = T_e - T_L \tag{12}$$

where T_L is the load torque and T_e is the electromagnetic torque produced by the machine. The electrical torque can be obtained from the magnetic coenergy W_{co} as:

$$T_e = \left[\frac{\partial W_{co}}{\partial \theta_{rm}}\right]_{(I_s, I_r \text{ constant})} = I_s^t \frac{\partial L_{sr}}{\partial \theta} I_r \tag{13}$$

L_{sr} is a $m \times n$ matrix consisting of the mutual inductance between the stator coils and rotor loops .

3-State Space Modeling of Induction Motor

In this section, we rewrite the main equations (1)-(2) obtained in Section IIin a proper way suitable for identification which will be fully discussed in Section IV. We assume constant speed and torque and we consider motor voltage and stator current as input and output measurement signals respectively. These equations become as follows:

$$\begin{aligned} V_{ab} &= R_a I_a + \frac{d}{dt}\left[(L_a - L_{ac})I_a + (L_{ab} - L_{ac})I_b + L_{ar}.I_r\right] - R_b.I_b \\ &\quad - \frac{d}{dt}\left[(L_{ab} - L_{bc})I_a + (L_b - L_{bc})I_b + L_{br}.I_r\right] \\ V_{bc} &= R_b I_b + \frac{d}{dt}\left[(L_{ab} - L_{bc})I_b + (L_b - L_{bc})I_b + L_{br}.I_r\right] + R_c.(I_a + I_b) \\ &\quad - \frac{d}{dt}\left[(L_{ac} - L_c)I_a + (L_{bc} - L_c)I_b + L_{cr}.I_r\right] \end{aligned} \tag{14}$$

where, subscripts a, b, c denotes a, b and c phases respectively.
From equation (14) as follow:

$$\begin{aligned} V_{ab} &= R_a I_a - R_b.I_b + (L_a + L_{bc} - L_{ac} - L_{ab})\frac{dI_a}{dt} \\ &+ (L_{ab} + L_{ac} - L_b - L_{bc})\frac{dI_b}{dt} + (L_{ar} - L_{br})\frac{dI_r}{dt} \\ &+ W_{mr}..I_r.\frac{d}{d\theta_m}(L_{ar} - L_{br}) \\ V_{bc} &= R_c I_a (R_b + R_c).I_b + (L_{ab} - L_{bc} + L_c - L_{ac})\frac{dI_a}{dt} \\ &+ (L_b - L_{bc} + L_c)\frac{dI_b}{dt} + (L_{br} - L_{cr})\frac{dI_r}{dt} \\ &+ W_{mr}.I_r.\frac{d}{d\theta_m}(L_{br} - L_{cr}) \end{aligned} \tag{15}$$

The representation of an induction machine with a cage rotor is the same as one with a phase wound rotor, where it is assumed that the cage rotor can be replaced by a set of mutually coupled loops. The voltage equations for the rotor loops are

$$V_r = R_r I_r + \frac{d\lambda_r}{dt} \tag{7}$$

where

$$V_r = \begin{bmatrix} v_1^r & v_2^r & L & v_n^r & v_e \end{bmatrix}^T \tag{8}$$

In a cage rotor, $V_r = \underline{0}$. The rotor flux linkage λ_r can be written as:

$$\lambda_r = L_{rs} I_s + l_{rr} I_r \tag{9}$$

where the matrix L_{rs} is the mutual inductance matrix between rotor circuits and stator phases. The matrix r_r and l_{rr} are as follows:

$$r_r = \begin{bmatrix} 2(r_b+r_e) & -r_b & 0 & L & 0 & -r_b & -r_e \\ -r_b & 2(r_b+r_e) & -r_b & 0 & L & 0 & -r_e \\ M & M & M & M & M & M & M \\ M & M & M & M & M & M & M \\ 0 & L & 0 & -r_b & 2(r_b+r_e) & -r_b & -r_e \\ -r_b & 0 & 0 & L & -r_b & 2(r_b+r_e) & -r_e \\ -r_e & -r_e & -r_e & L & -r_e & -r_e & nr_e \end{bmatrix} \tag{10}$$

$$L_{rr} = \begin{bmatrix} l_{mr}+2(l_b+l_e) & -l_b & 0 & L & 0 & -l_b & -l_e \\ -l_b & l_{mr}+2(l_b+l_e) & -l_b & 0 & L & 0 & -l_e \\ M & M & M & M & M & M & M \\ M & M & M & M & M & M & M \\ 0 & L & 0 & -l_b & l_{mr}+2(l_b+l_e) & -l_b & -l_e \\ -l_b & 0 & 0 & L & -l_b & l_{mr}+2(l_b+l_e) & -l_e \\ -l_e & -l_e & -l_e & L & -l_e & -l_e & nl_e \end{bmatrix} \tag{11}$$

In the above relations R_e and R_b are end ring segment resistance and rotor bar resistance respectively, l_{mr} is the magnetizing inductance of each rotor loop, l_b is the rotor bar leakage inductance, l_e is the rotor end ring leakage inductance, and $l_{r_i r_j}$ is the mutual inductance between two rotor loops (i and j).

Consider initially a general m-n winding machine with the following assumptions:
1- Linear and high permeability magnetic core,
2- Negligible eddy current,
3- Insulated rotor bars,
4- A uniform (magnetically smooth) air-gap

The cage rotor can be viewed as *n* identical and equally spaced rotor loops. For example the first loop may consist of the 1st and *(k+1)th* rotor bars and the connecting portion of the end rings between them, where k is any arbitrary chosen integer *(1<k<n)*, and the second loop consist of the 2nd and *(k+2)th* rotor bars and the connecting portion of the end rings between them, and so on. For a cage having n bars, the current distribution can be specified in terms of n independent rotor currents. These currents comprise (n-1) arbitrary rotor loop currents, (i_k^r), plus a circulating current in one of the end rings (i_e). Obviously, sum of the rotor bars currents becomes zero, and in a motor with complete end rings, i_e would be equal to zero.

The voltage equations for the stator loops in vector-matrix form can be written as:

$$V_s = R_s I_s + \frac{d\lambda_s}{dt} \tag{1}$$

where the stator flux linkage is given by

$$\lambda_s = L_{ss} I_s + L_{sr} I_r \tag{2}$$

The stator current vector, rotor current vector, and stator voltage are

$$I_s = \begin{bmatrix} i_1^s & i_2^s & L & L & i_m^s \end{bmatrix}^T \tag{3}$$

$$I_r = \begin{bmatrix} i_1^r & i_2^r & L & i_n^r & i_e \end{bmatrix}^T \tag{4}$$

$$V_s = \begin{bmatrix} v_1^s & v_2^s & L & L & v_m^s \end{bmatrix}^T \tag{5}$$

In the above, R_s is an m-dimensional diagonal matrix consisting of resistance of each stator circuits. L_{ss} is the stator circuits inductance matrix, and L_{sr} is the mutual inductance matrix between the stator coils and the rotor loops which is defined by:

$$L_{sr} = \begin{bmatrix} L_{11}^{sr} & L_{12}^{sr} & L & L_{1n}^{sr} & L_{1e}^{sr} \\ L_{21}^{sr} & L_{22}^{sr} & L & L_{2n}^{sr} & L_{2e}^{sr} \\ L & L & L & L & L \\ L_{m1}^{sr} & L_{m2}^{sr} & L & L_{mn}^{sr} & L_{me}^{sr} \end{bmatrix} \tag{6}$$

(mainly fabricated rotors),
- Magnetic stresses caused by electromagnetic forces, unbalanced magnetic pull, electromagnetic noise and vibration,
- Residual stresses due to manufacturing problems,
- Dynamic stresses arising from shaft torque, centrifugal forces and cyclic stresses,
- Environmental stresses caused for example by contamination and abrasion of rotor material due to chemicals or moisture,
- Mechanical stresses due to loose laminations, fatigued parts, bearing failure etc.

With such advance automatic supervisory of induction machine, it is possible to improve further automation of technical processes with the following features:
- Early detection and diagnosis of developing faults (also incipient fault diagnosis),
- Early detection and diagnosis of further fault expansion,
- Preventive maintenance,
- Maintenance on request.

One may refer to Tavner and Penman [2] for a comprehensive study of condition monitoring of electrical machines. Since 1980 rotor bar fault detection has become a challenging issue and it still attracts attention. Different diagnostic techniques have been developed to identify rotor bar faults, most of which are strongly dependent on detecting the twice slip frequency modulation in the speed or torque through stator current [3]-[4]. Most of the published work related to rotor bar failure in squirrel cage induction machine is based on the motor current signature analysis (MCSA) [6].

In short, broken rotor bars in squirrel cage induction machine results in arising of two sidebands at frequency $(1 \pm 2s)f$ around the main frequency component in the stator current spectrum [6]-[10]. The success of these methods depends not only on their accuracy of measurement, but also on their ability to discriminate between normal and fault conditions [11]. Recent efforts in fault diagnosis include time domain analysis of the electromagnetic torque and field which are suitable for variable speed drives [12]-[13], temperature measurement, infrared recognition, radio frequency (RF) emission monitoring vibration, and air gap magnetic flux monitoring with search coils installed in top of stator slots are several procedures for fault diagnosis in induction motor [14]-[15].

Other researchers have proposed model-based techniques for fault diagnosis, which have received less attention in the rotating machinery literature. The model-based fault diagnosis requires a model that describes the behavior of motor in various conditions [16]-[17] with the major advantage of having the capability to distinguish between faulty and normal modes.

This paper presents a novel model-based fault diagnosis approach via parameter estimation. The paper is organized as follow:

Section II summarizes the procedure for simulating the squirrel cage induction motor in both normal and faulty modes. Section III presents the method for detecting the broken bar faults in the motor. Simulation results given in the section IV verify the accuracy of method for broken rotor bar detection.

2-Dynamic Modeling of Induction Machines with m-Stator phases and n-Rotor Bars

In [18], the dynamic equations of an m-phase induction machine with n rotor bars were derived. This model is based on coupled magnetic approach, where the current in each bar is considered an independent variable. The effects of non-sinusoidal air-gap MMF produced by both the stator and the rotor current have been incorporated into the model.

A New Approach to Broken Rotor Bar Detection in Squirrel Cage Induction Motor Via Model-Based Parameter Estimation

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Abstract

This paper studies a novel approach for the detection of broken rotor bars in induction motors. The hypothesis on which the detection is based is the model-based parameter estimation technique. A high order transfer function is obtained for the induction motor. This transfer function is introduced between the stator voltages as inputs and stator currents as outputs. Then to detect the broken bars, stator voltages and stator currents have been measured at nominal torque and speed. This measurement processed by a near-least-square-error estimation and Auto Regressive Moving Average with Auxiliary input (ARMAX) to produce estimated motor state and parameter. In particular, estimated coefficient of appropriate motor transfer function has been compared with its nominal value during healthy operation. Estimation of the coefficient is presented experimentally for three different motor cases; healthy, two and three broken bars by milling into the 3-hp squirrel cage rotor. Simulation and experimental results show the effectiveness of the proposed method for broken rotor bar detection in squirrel cage induction motors.

Keywords

electrical motor, broken bars, faulty motor, winding function, ARMAX model, and recursive least square.

1-Introduction

The most popular way of converting electrical energy to mechanical one is squirrel cage induction motor. These motors play a crucial role in modern industrial plants, however there are adverse service conditions. The risk of motor failing can be remarkably reduced if normal service conditions can be arranged in advance. In other words, one may avoid very costly expensive downtime of plant by proper time scheduling of motor replacement or repair if warning of impeding failure can be obtained.

In recent years, rotor fault diagnosis has become a challenging topic for many machine researchers. The majority of all rotor failures are caused by combination of various stresses [1], namely:

-Thermal stresses due to thermal overload and unbalance, hot spots or excessive losses, sparking