# Calculation of UMP and Effects of Breakage Faults Location on Performance Induction Machine

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***Abstract:*** ***This paper develops the foundations of a technique for diagnosis and characterization of effects of location breakage faults in squirrel-cage induction motors based on the time stepping coupled finite element method FEM. These studies are performed by using the model to compute healthy state, and four cases adjacent breakage fault the performance data, which contains time variations of torque, unbalanced magnetic pull and the distribution of magnetic field. The unbalanced magnetic pull UMP is the resultant global magnetic force that acts on the rotor due to an asymmetric magnetic field distribution in the air gap as faults condition. It can be computed by normally found during finite element analysis using Maxwell's stress method. From these data the faulty signatures are extracted. Furthermore, this method, which could help to develop diagnostics of faults and performance evaluation of induction motors, has great potential in future applications.***

***Key words--Unbalance magnetic pull; faults diagnosis; induction motors; FEM***

## I. INTRODUCTION

Fault diagnosis methods are widely utilized for maintenance and protection of induction motors. The principle of any reliable fault recognition technique is steady-state analysis of electrical, magnetic and mechanical behavior of the motor under fault conditions; modeling is the first step for studying this phenomenon. The FEM method enables one to calculate the magnetic field distribution within the motor using its exact geometry and magnetic characteristics. Knowing the magnetic field distribution, other quantities of the motor such as variations stator current waveform, air gap magnetic flux density and different inductances can be obtained [1]. A finite element coupled method has been used to analyze and diagnose a faulty induction motor [2],[3] .Modeling of the motor to simulate performance of the faulty motor, selection of proper signal for processing and feature extraction are necessary. The technique that has been used over many years for mechanical fault diagnosis is based on the temperature and vibration changes [4].However; it is clear that electrical signals such as stator current can be used for the same purpose. Particularly, processing stator current spectrum for diagnosis of the rotor faults such as broken rotor bars and eccentricity has been widely used [5],[6]. In fact, stator current is the most convenient signal for fault diagnosis; the reasons are its sensitivity to the fault, availability of suitable sensors from the quality and cost point of views, capability of considering the fault conditions in the model, capability of the model in computation of the chosen signal variations against fault conditions and finally fault severity have a unique influence upon the signal characteristics. To this end, the stator current spectra are analyzed to detect different kinds of faults [7]. In [8] and [9] magnitude of side band components at frequencies around the supply frequency in the stator current spectrum has been used as a criterion for broken rotor bar. In [10],[11] and [12], magnitude of the side band components at frequencies around the principal slot harmonic has been employed to detect different types of eccentricities. In many published papers for diagnosis and analysis of broken rotor bars of induction motor, current of the broken bars is taken to be zero, while this means considerable increase of current in the bars adjacent to the broken bars [13] and [14].

The torque frequency spectrum of a faulted 3induction motor has been obtained for various cases of the bars breakage location and shown that the bars breakage location influences the amplitudes of harmonic components in the torque frequency [15]. It is indicated that the location of the rotor bars has significant effect upon the torque of the faulty motor and waveform flux density distribution in air gap .when the broken bars concentrate over one pole of the motor comparison with another location, the torque of faulty motor oscillates more. Now make comparison between different cases for distribution of broken bars under poles and discussion what happen for motor component [16].

In this modeling, we discuss geometrical and characteristics of all parts of the motor and effected distribution of rotor faults over different poles of the motor at the current stator and another components due to the fault, spatial distribution of stator windings, field distribution and flux density concentration.

## II. CONCEPT OF FAULTS

Some of the more common secondary effects of broken rotor bars are [17]:

- If one or more rotor bars are broken, the healthy bars are forced to carry additional current leading to rotor core damage from persistent elevated temperatures in the vicinity of the broken bars and current passing through the core from broken to healthy bars.
- Broken bars cause torque and speed oscillations in the rotor, provoking premature wear of bearings and other driven components.
- Large air pockets in die-cast aluminium alloy rotor windings can cause no uniform bar expansion leading to rotor bending and imbalance that causes high vibration levels from premature bearing wear.
- As the rotor rotates at high radial speed, broken rotor bars can lift out of the slot due to centrifugal force and strike

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against the stator winding causing a catastrophic motor failure.

Rotor asymmetry (the rotor rotating off-centre), both static and dynamic, could cause the rotor to rub against the stator winding leading to rotor core damage and even a catastrophic fault.

## III. PROCESSING AND ANALYSING CASES

Generally there are three major methods for modeling, analysis and diagnosis of faults in induction motor, winding function method (WFM), equivalent magnetic circuit method (MECM) and finite element method (FEM).

In recent years the finite element method (FEM) becomes widely used in the design and analysis of electric machines and of her electromagnetic devices. So far a lot of program packages for computation of magnetic field, especially for two dimensional (2D) analysis have been developed [18]. This method it is based on Maxwell's equations for magnetic and electric field [19]:

$$\nabla \times H = J \text{ and } \nabla \times E = -\frac{dB}{dt} \qquad (1)$$

Where $H$ is the magnetic field strength (A/m), $E$ is the electric field strength (V/m), $J$ is the electric current density (A/m$^2$), $B$ is the magnetic flux density (T). Moreover the electric and magnetic field quantities are related with the material properties expressed by the following relations:

$$J = \sigma . E \text{ and } B = \mu . H \qquad (2)$$

Where $\sigma$ is the electrical conductivity [S/m], $\mu$ is the magnetic permeability [H/m]. Based on these equations FEM based programs compute the magnetic field distribution of any electrical machine. In the case of the 2D analysis the computations are performed for a transversal plane to the axes of the machine.

The use of simulation tools helps the researchers to emphasize the effects caused by faults in an electrical machine and to develop efficient fault detection methods. Using FEM analysis the changes in electric,

Magnetic and mechanic behavior of the machine due to any fault can be easily observed without the need of destroying a machine, or experimenting in laboratories machines with different fault types. The main idea was to understand the electric, magnetic and mechanical behavior of the machine in the healthy state and under fault condition.

## IV. MATHEMATICAL FRAMEWORK

Induction motor is a highly symmetrical electromagnetic system. Any fault will induce a certain degree of asymmetry. Rotor faults in induction motors can cause asymmetry in the resistances of rotor phases. Which results in asymmetry of the rotating electromagnetic field in the air gap between the motor stator and rotor? In turn, this will eventually induce frequency harmonics in the stator current. Therefore, in the mathematical model, an additional resistance is added into each of the rotor phases to simulate rotor faults (20).

$$\Delta r_{ra,b,c} = \frac{3n_{bb}}{N_b - 3n_{bb}} r_r \qquad (3)$$

Where $\Delta r_{ra,b,c}$ rotor resistance changes in phases *a, b* and *c,* respectively, due to rotor faults, and $n_{bb}$ and $N_b$ are reminded as the number of breakage and the total bars, respectively defined as [21].

The function of rotor resistance change $\Delta r_{ra,b,c}$ due to rotor defects is derived based on the assumption that the rotor faults are contiguous, neither the end ring resistance nor the magnetizing current are taken account. The rotor phase equivalent resistance of a healthy induction motor is given as [22].

$$r_r = \frac{(2N_s)^2}{N_b/3}\left[r_b + \frac{2}{N_b(2\sin\frac{\alpha}{2})^2} r_e\right] \qquad (4)$$

where $r_b$ and $r_e$ represent the rotor bar and end-ring resistances, respectively, and $N_s$ is the equivalent stator winding turns. As in the assumptions, when $r_e$ is neglected, $r_r$ then simplifies to;

$$r_r \approx \frac{(2N_s)^2}{N_b/3} r_b \qquad (5)$$

Then, the resistance of one phase rotor with $n_{bb}$ contiguous broken rotor bars becomes

$$r^*_r \approx \frac{(2N_s)^2}{\frac{N_b}{3} - n_{bb}} r_b \qquad (6)$$

and the increment $\Delta_r$ is obtained as

$$\Delta_r = r^*_r - r_r = \frac{3n_{bb}}{N_b - 3n_{bb}} r_r \qquad (7)$$

$$\Delta I = f(\Delta_r) \qquad (8)$$

The second quantitative fault evaluation equation is proposed by (19) as;

$$\frac{I_{bb}}{I} = \frac{\sin\alpha}{P(2\pi - \alpha)} \qquad (9)$$

where $I_{bb}$ and $I$ are the amplitudes of the sideband and the fundamental frequencies in the stator current spectrum, respectively, $P$ is the number of motor poles, $\alpha$ is the electrical angle of a contiguous group of broken rotor bars, given by;

$$\alpha = \frac{\pi P n_{bb}}{N_b} \qquad (10)$$

When the motor loads, and consequently the rotor speed, are not constant, $I_{bb}$ should be replaced by the sum of the amplitudes of the two sideband frequencies $(1 \pm 2s)f_s$.

## V. SIMULATION RESULTS

Concentrating rotor faults over one pole such as case one leads to an increase of the amplitude of harmonic components because the rotor faults cause asymmetry of magnetic field distribution which leads to the higher harmonics. While, when spreading four cases over different poles such as case two and case three and four leads to decrease of the amplitude of harmonic components because the rotor faults caused less asymmetry of magnetic field distribution which leads to the less amplitude of harmonic frequency eventually leads to reduce amplitude of currents. Rotor faults produce certain frequencies in the flux waveform, and the rotating flux waves can induce currents with the same frequency in the stator current.

Figure 1 presents the time variations of torque for a healthy and faulty induction motor with four faults. Comparison of healthy and faulty state indicates that the fault increases the oscillation of the developed torque. One can easily notice that



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in the case of the motor having more faults the torque has the highest value. One can also notice the time variation of torque profile increases in faulty state comparison with healthy state i.e. higher torque ripples in induction motor having rotor faults. This is due to the fact that under rotor faults condition and load, the non-zero backward-rotating field interacts with the rotor currents to produce a torque variation at twice the slip frequency. This torque is then superimposed on the torque produced by the forward-rotating field resulting in the modulating effect of the steady-state developed torque.

Here, the developed torque profile are given in Figure 1 Similarly, by comparison of all cases, one can notice the torque increased in the case when rotor faults concentration over one pole. Furthermore, the computed average value of the torque, we notice that the developed torque for all cases depended of location of rotor faults regarding of pole in motor.

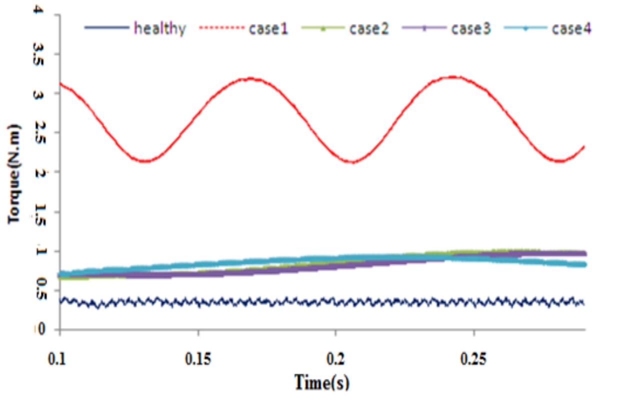


**Figure 1.Time variation torque with four cases Faults**

## VI. MAGNETIC PULL CAUSED BY DIFFERENT FAULTS CASES

The unbalanced magnetic pull is the resultant global magnetic force that acts on the rotor due to an asymmetric magnetic field distribution in the air gap as rotor faults condition are given in figure 2. It can be computed by finite element analysis using Maxwell's stress tensor method. The force components $F_x$ and $F_y$ which act on a rotor having an axial length $l_a$ can be computed by evaluating the following expressions along a surface of radius r in the middle of air gap;

$$F_x = \frac{rl\alpha}{2\mu_0}\int_0^{2\pi}[(B_\alpha^2 - B_r^2)\cos\alpha + 2B_rB_\alpha\sin\alpha]d\alpha \qquad (11)$$

$$F_y = \frac{rl\alpha}{2\mu_0}\int_0^{2\pi}[(B_\alpha^2 - B_r^2)\cos\alpha + 2B_rB_\alpha\cos\alpha]d\alpha \qquad (12)$$

Where

$F_x$= force component on axial x

$F_y$= force component on axial y

$l_a$ = axial length

$B_\alpha$=circumferential flux density components

$B_r$ = Radial flux density components

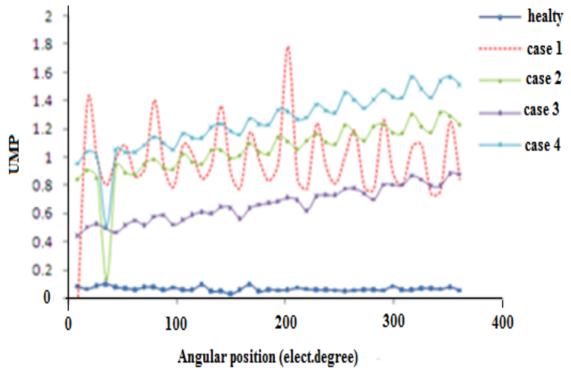


**Figure2. Output relationships between location faults and UMP**

The number of broken bars can lead to a more asymmetry in the flux density distribution in air-gap as shown in figure3.

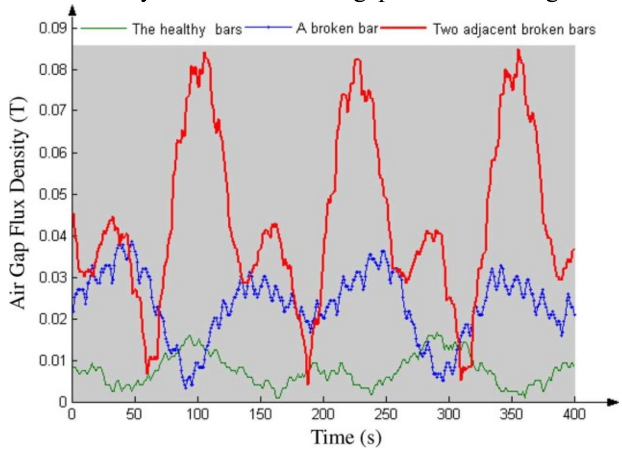


**Figure3.waveform flux density distribution in air gap induction motor**

In faulty motor, many harmonics components are injected into the stator current. Amplitudes of the time variations of current components are increased by increase of the fault percentage. In this paper, influence of the rotor faults upon the amplitudes of harmonics was investigated. Therefore, for signal processing of the stator current of the healthy and faulty motor, spectrum analysis of the stator current signal is necessary. It is notice that the amplitudes of harmonics due to rotor faults placed on one pole are larger than the in case which the rotor faults are distributed on four poles. Also in all cases presents the time variations of torque and waveform flux density for a faulty induction motor with four cases faults are depended of the location faults over poles when taken in account with another cases.

Table 1 is explain the values of the output relationship between rotor faults, rang amplitude of current , midair gap flux density, average of torque and unbalanced magnetic pull.



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**Table 1: Output relationship between cases broken rotor bars and motor condition**

| Induction motor condition | Cases of faults | Current in RMS value | THD% of the current | Average torque (N.m) | Average value of UMP | Torque ripple |
|---|---|---|---|---|---|---|
| Healthy case | Healthy | 1.27 | 40.45% | 0.4 | 0 | 0.4 |
| Faulty Case1 | 4 broken bars on 1 pole | 1.69 | 39.88% | 2.5 | 88.4 | 1.875 |
| Faulty Case2 | 3 broken bars on 1 pole | 1.50 | 39.34% | 2.06 | 67.6 | 1.143 |
| Faulty Case3 | 2 broken bars on 1pole | 1.37 | 39.80% | 1.02 | 36.4 | 1.04 |
| Faulty Case4 | 1 broken bar on pole | 1.30 | 39.18% | 0.75 | 14.2 | 0.8 |

## VI. CONCLUSION

In this work Influence of faults location on induction motor performance under milt breakage fault was modeled very precisely and with minimum simplifying assumptions using FEM. This modeling provided accessibility to the stator current signal very accurately. Component of the current and waveform flux density distribution in air gap induction motor was used to precisely diagnose the fault and depended on location of the broken bars. It was shown that the distribution of the broken bars over different poles increases the amplitude of the current components. It was shown that the broken bars increase the oscillation of the developed torque of the motor and stator current, waveform flux density when four broken bars are concentrated on one pole. It was proved that the location of the rotor bars has considerable effect on the performance and concentration of the broken bars on one pole of the motor increases the motor oscillation.

## REFERENCES


1. Nandi S, Bharadwaj R, Tolivat HA, Parlos AG. Study of three phase induction motors with in cipient rotor cage faults under different supply conditions, In; proceedings of the IEEE-IAS 1999 annual meeting, vol.3
2. J. Faiz, B.M. Ebrahimi and M.B.B. Sharifian, Different faults and their diagnosis techniques in three phase squirrel-cage induction motors – a review, J Electromag 26 (2006),
3. G.L. Paoletti and A. Rose, Improving existing motor protection for medium voltage motors, IEEE Trans Ind Appl 25 (3) (1989),
4. R. Fiser, Application of a finite element method to predict damage induction motor performance, IEEE Trans Magn 37 (5) (2001),
5. R.J. Povinelli, J.F. Bangura, N.A.O. Demerdash and R.H. Brown, Diagnostics of bar and end-ring connector breakage faults in poly phase induction motors through a novel dual track of time-series data mining and time-stepping coupled FE – state space modeling, IEEE Trans Energy Convers 17 (1) (2002),
6. J.F. Bangura, R.J. Povinelli, N.A.O. Demerdash and R.H. Brown, Diagnostics of eccentricities and bar/end-ring connector breakages in poly phase induction motors through a combination of time series data mining and time-stepping coupled FE – state space techniques Industry Applications, IEEE Trans Ind Appl 39 (4) (2003),
7. J. Faiz, B.M. Ebrahimi and M.B.B. Sharifian, Time stepping finite element analysis of rotor broken bars fault in a three-phase squirrel-cage induction motor, Progr Electromag Res PIER 68 (2007),
8. B. Mirafzal and N.A.O. Demerdash, Effects of load magnitude on diagnosis broken bar faults in induction motors using the pendulous oscillation of the rotor magnetic field orientation, IEEE Trans Ind Appl 41 (3) (2005),
9. O. Ondel, E. Boutleux and G. Clerc, A method to detect broken bars in induction machine pattern recognition techniques, IEEE Trans Ind Appl 42 (4) (2006),
10. M. Haji and H.A. Toliyat, Pattern recognition – a technique for induction machines rotor broken bar detection, IEEE Trans Energy Convers 16 (4) (2001),
11. J.F. Bangura and N.A. Demerdash, Diagnosis and characterization of effects of broken bars and connectors in squirrel-cage induction motors by a time-stepping coupled finite element – state space modeling approach, IEEE Trans Energy Convers 14 (4) (1999),
12. A.G. Innes and R.A. Langman, The detection of broken rotor bars in variable speed induction motor drives, ICEM94 (1994),
13. [13] S.F. Legowski and A.M. Trzynadlowski, Instantaneous stator power as a medium for the signature analysis of induction motors, IEEE IAS 95 (1995),
14. Trzynadlowski AM, Ghasezadeh M, Legowski SF. Diagnostics of mechanical abnormalities in induction motors using instantaneous electric power. IEEE 1997; MBI 9.1–9.3.
15. S.C. Ho, C.G. Hong and G.J. Hwang, Transient and steady state performance of a squirrel-cage induction motor, *IEEE Proc Part B* **136** (3) (1989),
16. Bentounsi and A. Nicolas, "On line diagnosis of defaults on squirrel cage motor using FEM," *IEEE Trans. Magn.*, vol. 34, no. 3,pp. 3511–3514, May 1998.
17. FIŠER, R., MAKUC, D., AMBROŽIČ, V.: Evaluation of the induction motor cage fault stage using finite element method. Record of IEEE SDEMPED'2001, The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, Grado (Italy), pp. 627-631.
18. Charles I. Hubert P. E, Prentice Hall, Electric machines, theory, operation, applications, adjustment, and control, second edition, TK2182. H83 2002.
19. Theodore wildi, Electrical machines, drives, and power systems, fourth systems, Tk2182. W53 2000.
20. Santos, P. M., Correa, M. B. R., Jacobina, C. B., Silva, E. R. C., Lima, A. M. N., Didiery, G., Raziky, H., and Lubiny, T. (2006). A simplified induction machine model to study rotor broken bar effects and for detection. In PESC'06, 37th IEEE, p.216-641.
21. Stephen J. Chapman British Aerospace Australia, Electric Machinery Fundamentals, Third Edition, MCGRAW-HILL
22. Tata McGraw-Hill, ELECTRIC MACHINES, Third Edition, Publishing Company Limited(NEW DELHI), Third reprint 2005 RYLQCRABRCAQZ.


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