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INTERN-TURN AND BEARING WEAR FAULT DETECTION IN THREE PHASE INDUCTION MOTOR MATLAB SIMULINK

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ABSTRACT

Induction Motor is one of the most widely used machines in the industries because of its simple structure and high reliability. It is backbone of modern industry, especially squirrel cage induction motor. It is used for many purposes, such as blower, compressor, fan, pump, manufacturer, transportation etc. In this paper, the dynamic mathematical modeling of 3 phase Induction motor and its simulation model using MATLAB Simulink has been developed for incipient faults viz. turn to turn fault and insulation failure. Also, the detailed simulation results using Matlab are presented.

KEYWORDS: Induction motor, incipient faults, Mathematical modeling, MATLAB Simulink.

INTRODUCTION

There are two kinds of Induction rotating motors, the squirrel –cage induction motor and the wounded rotor motor. Since the squirrel cage induction motor is low-priced, robust and rugged, simple and easy to maintain, it has become the most commonly used electrical rotating machine in industry .It is becoming increasingly important to used condition monitoring. Techniques to give early warning of imminent failure.

Under normal operating conditions. The components of Induction motor are subjected to thermal, mechanical and electrical stresses. This tresses may be increased due to transient such as load and supply variation, may cause insulation and mechanical failure of induction motors. Failure may cause large amount of loss if it is not detected and corrected in time. So the developing faults should be detected and corrected in time to prevent catastrophic failures (sudden terrible disaster)

Insulation failure Major insulation failures are caused by moisture, Over-temperature, system surge and faulty earth practice.
Moisture ingress may cause insulation failures for resin rich insulation system and their predecessors.

On small machine *over temperature* is the major contributor to insulation failure. It can be shown that for every 10 degree increase in hot spot temperature, reduced life span to 50% and exceeds the insulation system rating. Over temperature may be caused by ventilation blockage or over loading, broken rotor bar and a cracked end ring on cage machines also contributes to this problem.

System surges normally damages the first or second coil insulation, resulting in an inter-turn failure close to the line terminal.

A faulty earth may lead to neutral inversion during fault conditions causing the three phases to float away from earth to dangerously high level.

Mechanical failure: The major faults in this category can be broadly classified as follows.

On stator: Opening and shorting of one or more phase of stator winding **or** abnormal connection of same winding.

On rotor: broken rotor bars or cracked rotor end rings.

Rotor eccentricity: i) static and /or dynamic air gap irregularities ii) Bent shaft (dynamic eccentricity)-which can result in a rub between the rotor and stator, causing serious damaged to stator core and winding.

Bearing damaged: Bearing & gear box failure.

This fault produces one or more symptoms as given below:
i) Unbalanced Air gap voltage and currents.
ii) Increased torque pulsation and decrease average torque.

iii) Increased losses, excessive heating and reduction in efficiency.

iv) Specified harmonics in the line current increased.

v) Leakage flux in axial direction.

The possible detection methods to identify the motor faults are listed as below:

i) Vibration monitoring.

ii) Motor current signature analysis.

iii) Electromagnetic field monitoring using search coil.

iv) Chemical analysis.

v) Temperature measurement.

vi) Infrared measurement.

vii) Acoustic noise measurement.

viii) Radio frequency emission monitoring.

ix) Partial discharge measurement.

x) Model, artificial intelligence & neural network based technique.

Induction Machine Modelling

This model follows the complete magnetic approach by treating the current in each rotor bar as an independent variable. The effect of non-sinusoidal air gap MMF produced by both the stator and rotor currents have been incorporated into this model. This is done by use of the winding function approach.

The analysis is based on the following assumption Symmetric machine, Uniform air gap, negligible saturation and Insulated rotor bar.

Squirrel cage IM simplified scheme is given as.

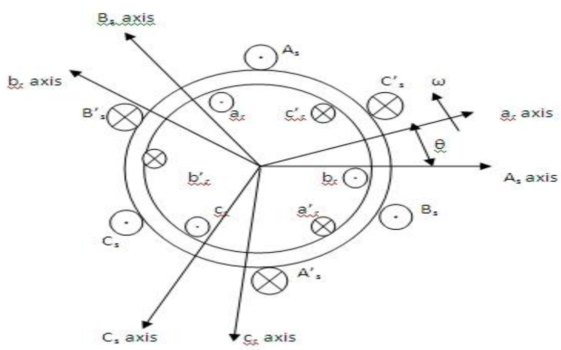


Fig. 1: Squirrel cage IM simplified scheme.

A. Stator voltage Equation.

The stator equations for the induction motor with ref. to fig. 1 can be written in vector matrix form as.

$[V_s]=[R_s][I_s]+d/dt[\lambda_s]$ (1)

Where

$[V_s] = [V_{s1}\ \ Vs_2\ Vs_3]^T$

$[I_s] = [Is_1\ \ Is_2\ Is_3]^T$ &

$[\lambda_s] = [\lambda s_1\ \ \lambda s_2\ \lambda s3]^T$ (2)

Also

$[\lambda_s]= [L_{ss}][I_s] +[L_{sr}][I_r]$ (3)

Where

$[R_s]$- Resistance of stator winding (Diagonal 3 by 3 matrix)

$[\lambda_s]$- Flux linkage of stator winding (Symmetric 3 by 3 matrix)

$[L_{ss}]$-Self-inductance of stator winding (Symmetric 3 by 3 matrix)

$[L_{sr}]$-Mutual inductance between stator coils & rotor loops (Symmetric 3 by 3 matrix)

$$[L_{rr}] = \begin{bmatrix} Lsr_{11} & Lsr_{12} \ \ldots.. & Lsr_{1n} & Lsr_{1e} \\ Lsr_{21} & Lsr_{22} \ \ldots.. & Lsr_{2n} & Lsr_{2e} \\ Lsr_{31} & Lsr_{32} \ \ldots.. & Lsr_{3n} & Lsr_{3e} \end{bmatrix} \quad (4)$$

Where

L_{srij}- Mutual inductance between the stator phase i (i=1,2 or 3) and rotor loop j

L_{srie}- Mutual inductance between the stator phase i (i=1,2 or 3) and the end ring

B. Rotor Voltage Equation

Given the structural symmetry of the rotor, it is convenient to model the cage as identical magnetically coupled circuits. For simplicity, we assume that each loop is defined by two adjacent rotor bars and the connecting portions of the end rings between them.

For the purpose of analysis, each rotor bar & segment of end rings is substituted by an equivalent circuit representing the resistive and inductive nature of the cage. Such an equivalent ckt is shown in.

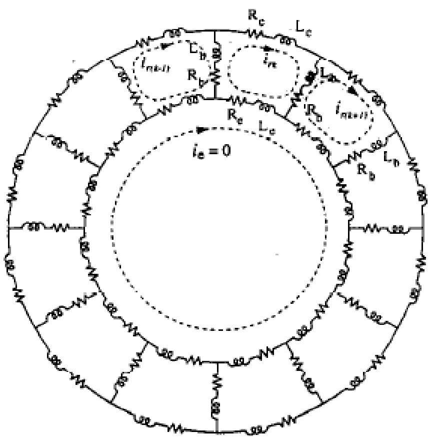


Fig. 2: Rotor cage equivalent circuit showing rotor loop currents & circulating end ring current.

From fig.No.2.The voltage equations for the rotor lops can be written in vector matrix form as,

$$[V_r]= [R_r]\,[I_r]+ d/dt\,[\lambda_r] \qquad (5)$$

Where

$$[V_r] = [V_{r1}\ V_{r2}\ \text{-------}V_{rk}\ V_{re}]^T \qquad (6)$$

Where k=1,2….n

In case of cage rotor, The rotor loop voltage V_{rk}=0 and end ring voltage V_{re}= 0

The loop equation for k^{th} rotor ckt is

$$V_{rk}=0=2(R_b+R_e)I_{rk}-R_bI_r(K-1)-R_bI_r(K+1)-R_eI_e+d\lambda_{rk}/dt \quad (7)$$

The voltage equation for the end ring is

$$V_{re}=0= -R_eI_{r1}-R_eI_{r2}-R_eI_m+nR_eI_{re}+d\lambda_{rk}/dt \qquad (8)$$

Where, Rb is the rotar bar resistance & Re is the end ring segment resistance

Since each loop is assumed to be identical, the equation (7) is valid for every loop.

Therefore the resistance matrix [Re] is symmetric (n+1) by (n-1) matrix given by

$$[R_r] = \begin{bmatrix} 2(R_b+R_e) & R_b & 0 & \cdots & 0 & -R_b & -Re \\ -R_b & 2(R_b+R_e) & -R_b & \cdots & 0 & 0 & -Re \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & 2(R_b+R_e) & -R_b & -Le \\ Ln_1\_Lb & 0 & 0 & \cdots & -R_b & 2(R_b+R_e) & -Le \\ -Re & -Re & -Re & \cdots & -Re & -Re & -nRe \end{bmatrix} \qquad (9)$$

n relation (5) the rotor flux can be written as

$$[\lambda_r]= [L_{rs}][I_s] + [L_{rr}][I_r] \qquad (10)$$

Where $[\lambda_r]$- Flux linkage of rotor

$[L_{rr}]$-Self-inductance of rotor

$[L_{rs}]$-Mutual inductance between stator coils & rotor loops

$[L_{rr}]$ =

$$\begin{bmatrix} L_{11}+2(L_b+L_e) & L_{12}-L_b & L_{13} & \dots & L_{1(n-1)} & L_{1n}-L_b & -Le \\ L_{21}-L_b & L_{22}+2(L_b+L_e) & L_{23}-L_b & \dots & L_{2(n-1)} & L_{2(n-1)} & -Le \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ L_{(n-1)} & L_{(n-1)2} & L_{(n-1)3} & \dots & L_{(n-1)(n-1)}+2(L_b+L_e) & L_{n(n-1)}-L_b & -Le \\ Ln_1-Lb & Ln_2 & Ln_3 & \dots & L_{n(n-1)}-L_b & L_{nn}+2(L_b+L_e) & -Le \\ -Le & -Le & -Le & \dots & -Le & -Le & -nLe \end{bmatrix}$$

C. Calculation of Torque

The mechanical equation of machine is

$$T_{em}-T_L= J\, d\omega_m/dt \qquad (12)$$

Where

Tem- Electromagnetic torque

T_L-Load torque

J- Inertia of the rotorWith

$$\omega_m =1/p\; d\theta/dt \qquad (13)$$

Where θ is the angular position of the rotor & p denotes the number of motor pole pairs and ω_m-mechanical speed

The electromagnetic torque is given by

$$T_{em}=PI_s^t\,\{d/d\theta[L_{sr}]\}I_r \qquad (14)$$

Inciepient Faults

There are various incipient faults occurs in induction machine as discuss above. In this paper mathematical modeling and mat lab simulation of only two types of faults are discuss such as turn to turn faults, and bearing fault.

Turn to Turn Fault in Stator Winding **(**Mathematical modeling).

Let us consider turn-to-turn fault on phase A as shown in fig.

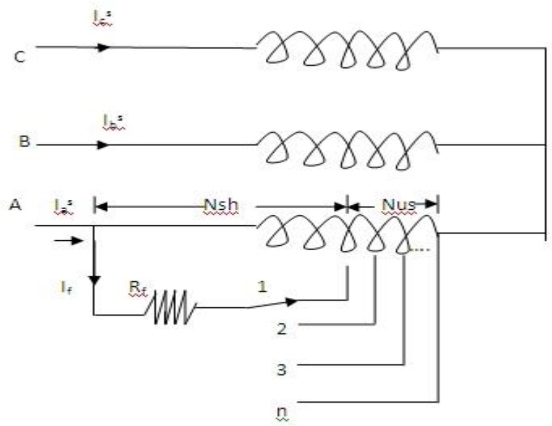


Fig. 3: Turn to turn fault on phase A.

Winding in phase A is divided on two parts, unfaulted turns winding section N_{us} and shorted turns winding section N_{sh} as in fig given. Turns sum N_{us} and N_{sh} is the total turns of the winding which is N_s ($N_s = N_{us} + N_{sh}$) of phase A. Phase B and C have the same number of turns equal N_s.

Let the impedence of stator winding per turn Z_s under healthy condition is is defined as.
$Z_s = Z/N_s$.

Where Z is stator impedance under healthy condition and N_s indicates number of stator winding turns. The rms.

value of stator input current of particular phase is normal under healthy condition and expressed as.

$$I_s \angle\theta = V_s/z$$

Where I_s is rms value of sator current at an angle θ; and V_s is rms value of supply voltage Whenever inter-turn short circuit fault take place, certain contact resistance between two turns (r_s) comes across where the short circuit is introduced as shown in fig.4. due to this short, magnitude of Z_s decreases to Z_f as expressed below.

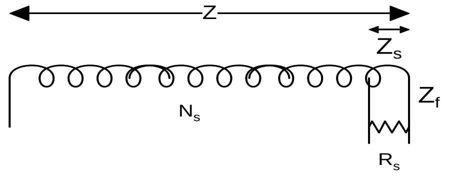


Fig. 4: Inturn-turn short circuit fault.

$$Zf = \frac{(Zs\ rs)}{(Zs + rs)} \qquad (15)$$

This affects the winding impedence Z depending upon the number of shorted turns. As more number of turns get shorted. Z decreases to Z_f. At constant load and voltage condition, the decrese in magnitude of Z increases the stator faul is current (I_{sf}).

This is expressed by following equation.

$$Isf \angle\phi = \frac{Vs}{Zf.} \qquad (16)$$

Where ϕ is phase angle of current and Z_f is the stator impedence under unhealthy condition .Equation (2) and (4) enables us to write deviation in stator intake current as follows.

$$I_{sd}\angle\delta = I_{sf}\angle\phi - I_s\angle\theta \qquad (17)$$

From above equation it is possible to establish the relation of stator intake current and stator inter-turn fault .Under healthy winding condition Isd=0 and $\angle\delta=0$. The three phase motor currents are given as,

$$\left.\begin{aligned} i_a &= I_{ma} \sin(\omega t + \theta_a) \\ i_b &= I_{mb} \sin(\omega t - \frac{2\pi}{3} + \theta_b) \\ i_c &= I_{mc} \sin(\omega t + \frac{2\pi}{3} + \theta_c) \end{aligned}\right\} \qquad (18)$$

where I_{ma} I_{mb} and I_{mc} are peak values of three phase currents , θ_a θ_b and θ_c are phase unbalanced in degrees. This current can be resolved into zero positive and negative sequence currents based on instantaneous symmentrical component theory and are expressed as below.

$$\begin{bmatrix} Ia_0 \\ Ia_1 \\ Ia_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} \qquad (19)$$

where $a=e^{\frac{j2\pi}{3}}$ is complex operator .The instantaneous vector i_{a1} and i_{a2} are complex conjugate of each other and i_{a0} is a real quantity which are positive, negative and zero sequence currents. From the observation, it is clear that the negative sequence current exhibits unbalanced of stator intake current due to intern –turn short circuit faults .the sequence components of voltage of three phase ac machine in steady state can be expressed as.

$$\begin{bmatrix} Va_0 \\ Va_1 \\ Va_2 \end{bmatrix} = \begin{bmatrix} Z_{0_0} & Z_{0_1} & Z_{0_2} \\ Z_{1_0} & Z_{1_1} & Z_{1_2} \\ Z_{2_0} & Z_{2_1} & Z_{2_2} \end{bmatrix} \begin{bmatrix} Ia_0 \\ Ia_1 \\ Ia_2 \end{bmatrix} \qquad (20)$$

Where subscript 0, 1 and 2 represents zero ,positive and negative sequence components of voltage and current phasors respectively ,and Zij represents the impedance of the i sequence due to j sequence .The Zij impedance are function of motor design ,construction and any internal deterioration and the operating speed . In this work, it is assumed that ia_o =0 beacause zero sequence current flows only when fault take place through ground and therefore concentrate on the main problem of detecting inter-turn insulation fault that does not involve ground .Thus equation (20) is written as.

$$\begin{bmatrix} Va_1 \\ Va_2 \end{bmatrix} = \begin{bmatrix} Z_{1_1} & Z_{1_2} \\ Z_{2_1} & Z_{2_2} \end{bmatrix} \begin{bmatrix} Ia_1 \\ Ia_2 \end{bmatrix} \qquad (21)$$

The above equation (21) can be modified as.

$$\begin{bmatrix} Ia_1 \\ Ia_2 \end{bmatrix} = \begin{bmatrix} Z_{1_1} & Z_{1_2} \\ Z_{2_1} & Z_{2_2} \end{bmatrix}^{-1} \begin{bmatrix} Va_1 \\ Va_2 \end{bmatrix} \qquad (22)$$

From equation (21) the steady state negative sequence voltage for induction motor with inherent asymmetries can be described as.

$$V_{a2}=Z_{21}I_{a1}+Z_{22}\,I_{a2} \qquad (23)$$

When turn fault occurs, value of Z_{21} varies since the motor becomes asymmetric and hence turn faults can be detected by continuously monitoring Z_{21}.The deviation in $Z_{21,}$ The deviation in $Z_{21,}$, which is used as a turn fault indicator is define as.

$$\Delta\, Z_{21} = Z_{21} - Z_{210} \qquad (24)$$

Thus the historical data Z_{210} is required to detect the condition of winding insulation

The sum of the phase voltages is given by the following relationship

$$V=V_a+V_b+V_c \qquad (25)$$

Where

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} Z_a & 0 & 0 \\ 0 & Z_b & 0 \\ 0 & 0 & Z_c \end{bmatrix} \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} \qquad (26)$$

For induction motor drawing balance currents, the three phase sequence impedance are equal ie

$$Z_a = Z_b = Z_c \qquad (27)$$

In the above equations , V_a , V_b and V_c are phase voltages, I_a ,I_b and I_c are phase current and Z_a, Z_b and Z_c are the impedence of each phase respectively .In a three phase connection for solidly ground ,wye –connected motor.

$$I_a + I_b + I_c = 0 \qquad (28)$$

The Equation (15), can be written as,

$$\frac{V_a}{Z_a} + \frac{V_b}{Z_b} + \frac{V_c}{Z_c} = 0 \qquad (29)$$

The unbalance in magnitude of currents and phase angles is mainly due to unbalance supply voltage, constructional imperfections in design of stator winding, instrumentation difference and inter-turn short ckt fault. If due to any of these reasons, for example, unbalance supply voltage, (let $Z_a = Z_b = Z_c$ and $V_a \neq V_b \neq V_c$) as shown in Fig. 5 equation (29) is no longer valid and it becomes

$$\frac{V_a}{Z_a} + \frac{V_b}{Z_b} + \frac{V_c}{Z_c} \neq 0$$

or

$$I_a + I_b + I_c \neq 0$$

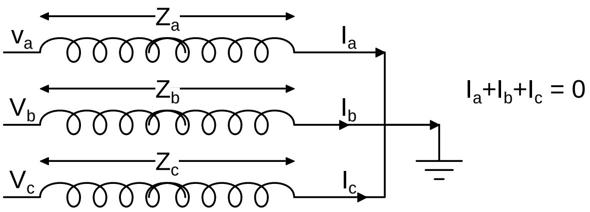


Fig. 5: Stator winding of motor under imbalance supply voltage condition.

The model of a faulty motor can be derived from standard relations

$$d\lambda_s/dt = V_s - R_s I_s \qquad (30)$$

$$d\lambda_r/dt = -R_r I_r \qquad (31)$$

As a symmetrical machine is considered it is assumed $R_s = r_s I$ and $R_r = r_r I$ where I is diagonal matrix.

$$[\lambda_s] = [L_{ss}][I_s] + [L_{sr}][I_r] \qquad (32)$$

$$[\lambda_r] = [L_{rs}][I_s] + [L_{rr}][I_r] \qquad (33)$$

Flux equation of Induction motor with turn to turn fault in stator takes the following form,

$$d\lambda_s/dt = V_s - R_s (I_s - N_f i_f) \qquad (34)$$

$$d\lambda_r/dt = -R_r I_r \qquad (35)$$

$$\lambda_s = L_{ss} (I_s - N_f I_f) + L_{sr} I_r \qquad (36)$$

$$\lambda_r = L_{rs} (I_s - N_f I_f) + L_{rr} I_r \qquad (37)$$

Where $N_f = [N_{sh}\ 0\ 0]^T$ is a vector representing position of turn to turn fault in the stator ckt.

The flux in circulated part of winding A can be calculated according to the following equation.

$$d\lambda_a^{sh}/dt = R_f i_f - N_{sh} R_s (i_a^{s} - i_f) \qquad (38)$$

Bearing Fault (Mathematical modeling)

The characteristic vibration frequencies due to bearing defects can be calculated from the rotor speed and the bearing geomentry. The typical rolling element bearing geometry is displayed in fig. The characteristic vibration frequency fv can be calculated using following equation. corresponding temperature rise in stator, thereby decreasing the life expectancy of the stator winding insulation.

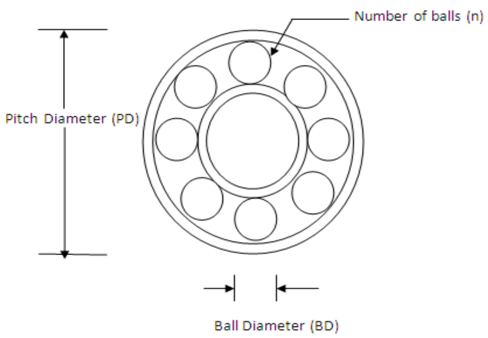


Fig. 6: The typical rolling element bearing geometry.

The outer race defect frequency, F_{OD} The ball passing frequency on the outer race is given by

$F_{OD} = n/2\ f_{rm} (1 - BD/PD \cos\varphi)$ (39)

Where φ=contact angle

PD =Pitch Diameter

BD= Ball Diameter

n=n is the number of balls

f_{rm}= rotational speed

The inner race defect frequency F_{ID} the ball passing frequency on the inner race is given by

$$F_{ID} = n/2\ f_{rm} (1 + BD/PD \cos\varphi) \qquad (40)$$

The ball defect frequency F_{BD} (The ball spin frequency is given by)

$$F_{BD} = PD/2BDf_{rm} \{1 - (BD/PD)^2 \cos^2\varphi\} \qquad (41)$$

The train defect frequency F_{TD} caused by an irregularity in the train is given by

$$F_{TD} = 1/2\ f_{rm} (1 - BD/PD \cos\varphi) \qquad (42)$$

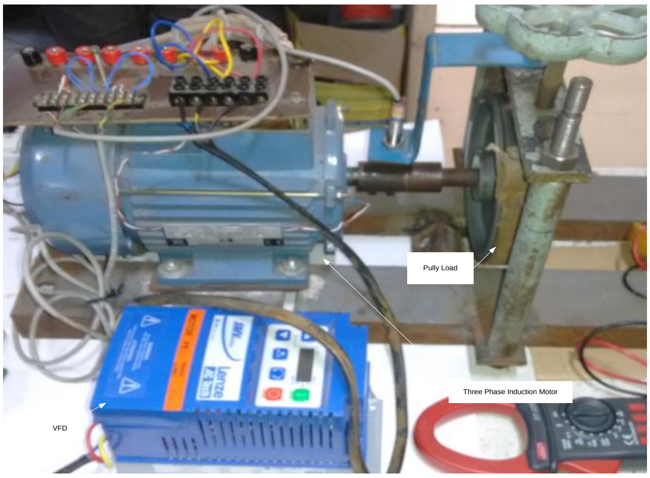
The characteristic current frequency F_{CF} due to the bearing characteristic vibration frequency fv are calculated by.

$$F_{CF} = |fe \pm mfv| \qquad (43)$$

Where m=1, 2, 3…… & fe is the power line frequency.

This latter equation represents an amplitude modulation of the stator current by the bearing vibration.

Experimental Setup



The squirrel cage Induction motor used for Matlab simulation is having the following parameters:

S. No.	Parameter	Rating
1	Ambient temperature in degree cent.	30
2	Voltage in volts	415
3	Capacity in hp	1
4	Frequency in Hz	50
5	No. of poles	4
6	Speed in rpm at no load in rpm	1500
7	Speed in rpm at full load in rpm	1400
8	Total No.of slots	24
9	Torque in N-m at noload	4.77
10	Full load torque in N-m	5.11
11	Motor efficiency at rated load in %age	72.1
12	Power factor at rated load	0.72
13	Gauge of winding	23
14	Turn of stator winding	109
15	No. of rotor bars	18
16	Length of winding in mm	320
17	Bearing numbers	6204

SIMULATED RESULT

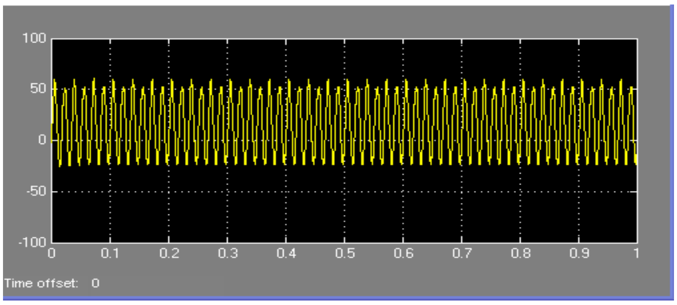
The decrease in winding equivalent turns will increase the stator –winding current as shown in fig.6 (a), thus causing increase in heating due to additional I^2R losses. The increase in heating will cause a corresponding temperature rise in stator, thereby decreasing the life expectancy of the stator winding insulation.

The stator winding insulation failure will cause additional shorted turns and further increase in temperature. This effect increases the rate of deterioration of the stator winding insulation. This insulation failure of winding may touch the body of motor which take place a ground fault passing fault current through ground .The faulted phase carry a large current through ground as shown in fig.8 (a).

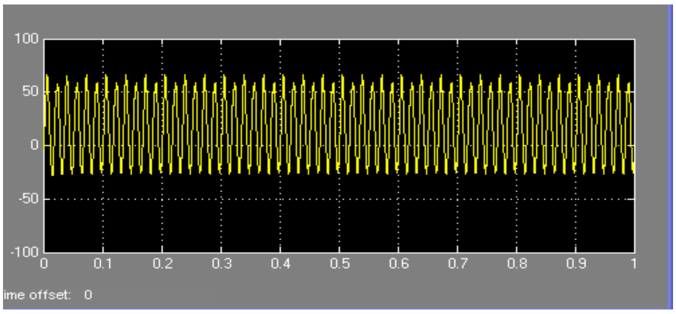
If the machine bearing is healthy in that case, motor intake current is normal. But as the bearing deteriorates, to fulfill the required load demand, the electrical torque increases. Therefore, the input current also rises.

A) Turn to turn fault

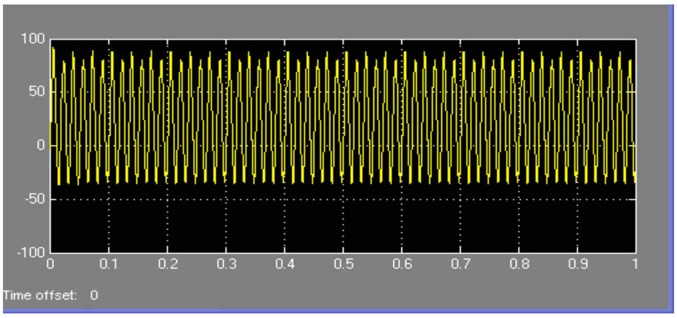
a) Current of Phase A (Turn to turn fault at total winding)



b) Current of Phase A (Turn to turn fault by shorting 20% of total winding)



c) Current of Phase A (Turn to turn fault by shorting 50% of total winding)



d) Current of Phase A (Turn to turn fault by shorting 75 % of total winding)

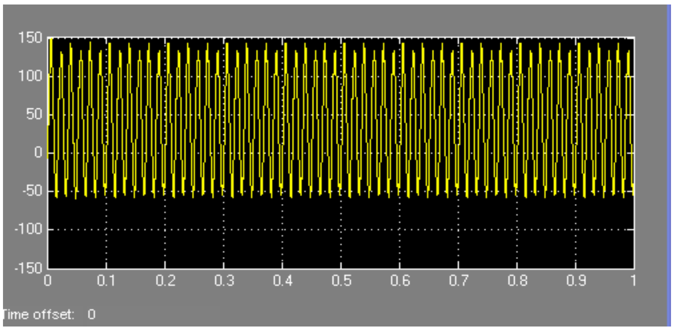
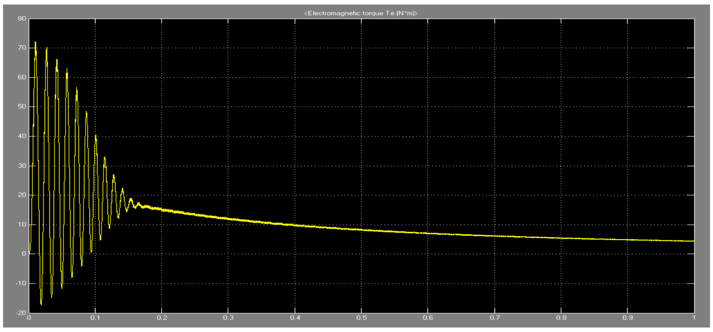


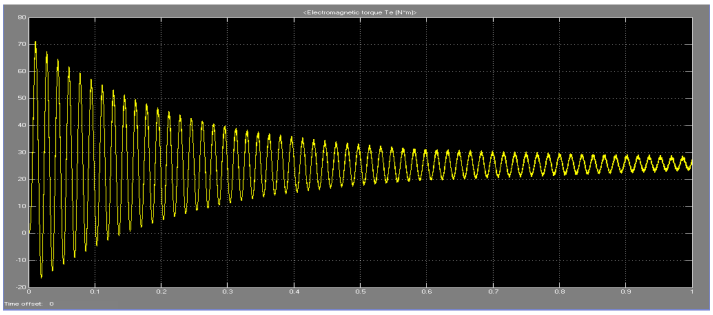
Fig. 6: Simulation of Inter-turn fault (a) Stator phase-A current at current by shorting 20% of the total winding total impedance (b) current by shorting 50% of the total winding (c) current by shorting 75% of the total winding.

(B) BearingFailure

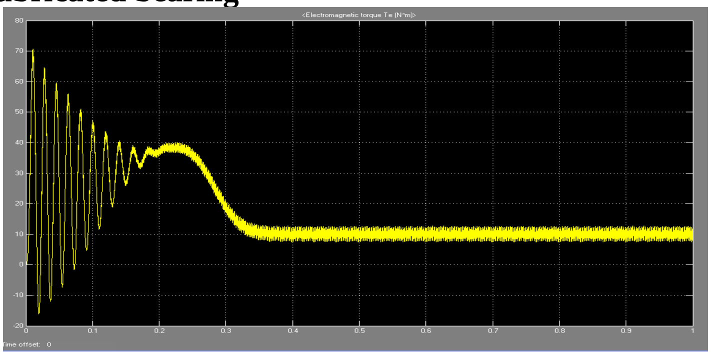
a) Torque of damage bearing



b) Torque of dry bearing



c) Torque of less lubricated bearing



d) Torque of lubricated bearing

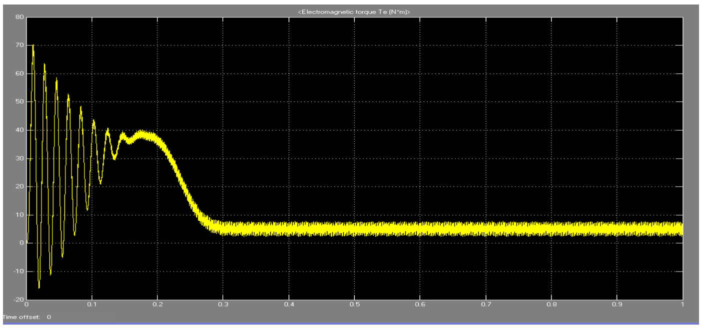
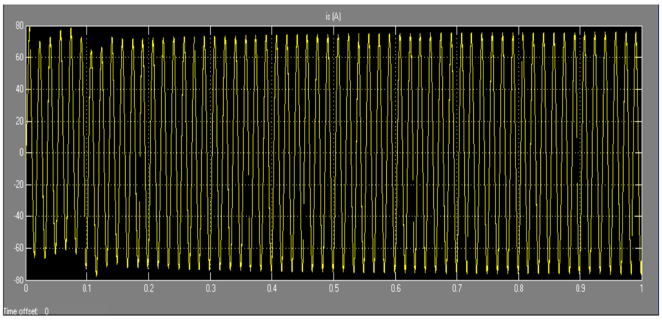
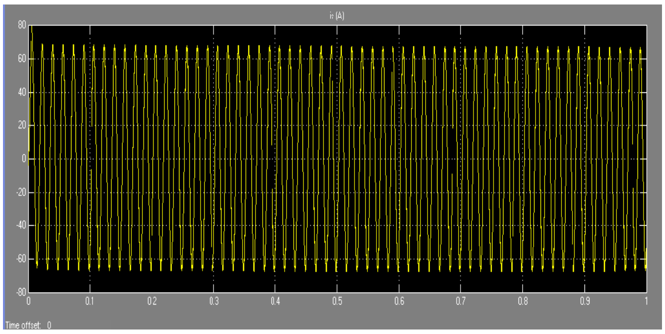


Fig. 7: Simulation of Bearing Failure (a) Torque of damage bearing (b) Torque of dry bearing (c) Torque of less lubricated bearing (d) Torque of lubricated bearing.

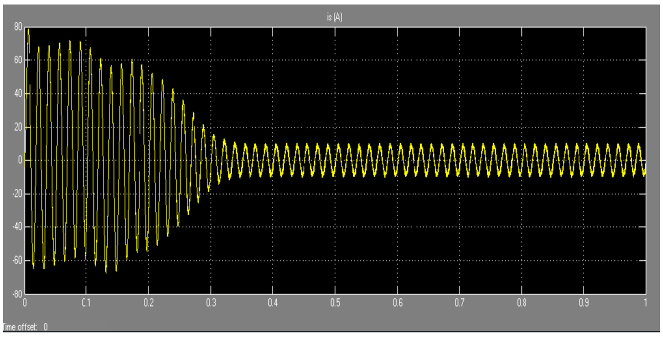
a) Current of damage bearing



b) Current of dry bearing



c) Current of less lubricated bearing



d) Current of lubricated bearing

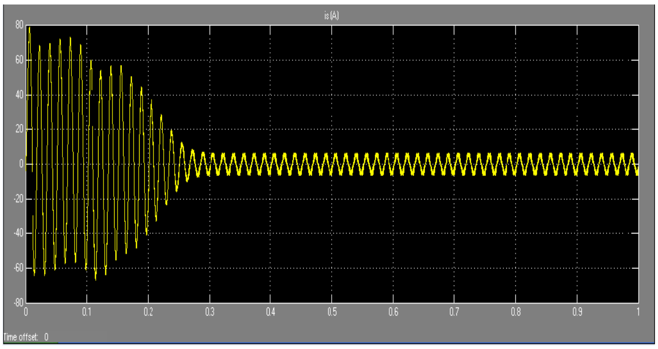


Fig. 7: Simulation of Bearing Failure (a) Stator current of damage bearing (b) Stator current of dry bearing (c) Stator current of less lubricated bearing (d) Stator current of lubricated bearing.

CONCLUSION

This paper presented the successful simulation and modeling of induction motor with traditional electrical machine models. It has been demonstrated that a generalized motor model can be used to simulate induction motor faults to a high degree of accuracy.

This paper present simulation of three phase induction motor in Matlab for two types of incipient fault i.e., intern turn and insulation failure of the winding. The simulated result shows decrease in winding equivalent turns will increase the stator –winding current of faulted phase, and thereby increase in temperature. Which further deteriorate the winding insulation causes the faulted current to flow through ground.

Also the result shows if the bearing deteriorates to fulfill the required load demand, the electrical torque increases. Therefore, the input current also rises.

The simulated result indicates that model-based fault detection and diagnosis is useful. The simulation showed that the dynamic characteristic of induction motors under different conditions can be obtained purely by Matlab simulation. With suitable model, motor faults may be simulated and predicted without any experimental analysis.

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