Performance of Three Phase Induction Motor on Voltage Unbalance and Stator Inter-Turn Short Circuit Fault

Shamal S. Dhamal[1], S.S. Khule[2], S.S.Dhamal[3]

[1]*Student M.E. Electrical Power Systems, Matoshri college of Engineering & Research Centre, Eklahare, Nashik*
[2]*Professor, Matoshri college of Engineering & Research Centre, Eklahare, Nashik*
[3]*Asst. Professor, Jawahar Institute of Technology, Management, Research, Nashik*

Abstract— *The induction motor operate satisfactory on balanced normal conditions. It is low operating and maintenance cost and energy efficient electro-mechanical drive. It is used in all industrial processes as there is no alternative to induction motor in industry. During operation, various stresses are developed in induction motor which may cause failure of motor. So, there is wastage of time and revenue loss. There is continuous variation in supply system due to small unbalance in distribution system. Due to some reasons, if the voltage unbalance exceed the 3 % then it will be harmful for induction motors. It is essential to diagnose the performance of motor on unbalanced supply conditions and stator inter turn short circuit fault. In this paper induction motor model is derived for symmetrical and asymmetrical conditions to diagnose the performance at unbalanced supply voltage and stator inter turn short circuit fault.*

Keywords— Induction motor, inter-turn faults, diagnosis, balanced and unbalanced conditions.

1. Introduction

The induction motors are very simple, robust in constructions, strong durability, easy for maintenance, low manufacturing cost and easy to transform electrical power into mechanical power through the air gap. There is no electrical connection between stator and the rotor so the failure rate as compared to other electromechanical drives is less and also it is efficient. So Induction motors are widely used in all industrial processes and thus problems of their maintenance and fault detection become more and more important. The failure of the motor can cause substantial revenue losses and even damages of the whole drive system. As per literature review the induction motor faults are: Stator Related Faults: 38%, Rotor Related Faults: 10%, Bearing Related Faults: 40%, other Faults: 12%. So the stator related faults is one of the major fault in Induction Motor. Sometimes undetected stator inter-turn fault progresses and breakdown occurs. [1],[2] Stator winding turn faults, are caused by gradual deterioration of turn insulation due to a combination of electromechanical force induced, vibrations, high dv/dt voltage surges, thermal overload, and/or contamination. If the turns of the stator are shorted, a large circulating fault current is induced in the shorted turn leading to localized thermal overloading. [3],[4]. The modelling of induction motors is done at steady state and transient conditions. The stator turns are shorted for the detection of stator inter-turn faults. The MATLAB simulation is carried out on symmetrical, balanced and asymmetrical induction motor. The generally the researchers are applying the generalized theory of electrical machines to detect the various faults in electrical machines. In the present work the Park's dq0 transformation is used for simulation purpose. The simulation results on healthy motor and with shorted stator turns are presented in the paper.[6] In industrial plants the lighting loads connected between phase-to-neutral. Proper balancing of single-phase loads among the three phases on both branch circuits and feeders is necessary to keep the load unbalance and the corresponding phase-voltage unbalance within reasonable limits. When unbalanced phase voltages are applied to three-phase motors, the unbalance voltage causes additional negative-sequence currents to circulate in the motor, increasing the heat losses. The most severe condition occurs when one phase is opened and the motor runs on this condition for sufficiently long time, the motor winding may burn. When a motor trips out, the first step in determining the cause is to check the running current after it has been restarted to make sure that the motor is not overloaded. The next step is to measure phase voltages to determine the voltage unbalance. If the phase-voltage unbalance exceeds 2%, the motor will overheated if it is operating close to full load. [7]. Motor voltage unbalance will increase motor losses due to a negative sequence voltage that causes a rotating magnetic field in the opposite direction of motor rotation. A 2% voltage unbalance will increase losses by 8%, a 31/2% unbalance will increase losses by 25%, and a 5% unbalance will increase losses by 50%. Many motors, especially in the high hp ratings, can be seriously damaged by negative-sequence current heating. Therefore, phase unbalance protection is required for all motors where its cost can be justified relative to the cost and importance of the motor. Phase unbalance protection should be provided in all applications where single phasing is a strong possibility due to factors such as the presence of fuses, overhead distribution lines subject to conductor breakage, or disconnect switches [8].

2. THE MATHEMATICAL MODEL OF THREE PHASE SQUIRREL CAGE INDUCTION MOTOR

The three phase squirrel cage induction motor mathematical model for various stator turns short circuited is presented below. The machine is assumed to have uniform air gap and no magnetic saturation in the magnetic circuit.

The magnetically coupled stator and rotor, the stator voltage equations can be written as:

$$v_s^{abc} = r_s^{abc} i_s^{abc} + p\lambda_s^{abc}$$ and

$$0 = r_r^{abc} i_r^{abc} + p\lambda_r^{abc}$$

Rotor resistances, $r_{ar} = r_{br} = r_{cr} = r_r$ and $v_{ar} = v_{br} = v_{cr} = 0$

The flux linkages of the stator and rotor windings in terms of winding inductances and currents may be written compactly as

$$\begin{bmatrix} \lambda_s^{abc} \\ \lambda_r^{abc} \end{bmatrix} = \begin{bmatrix} L_{ss}^{abc} & L_{sr}^{abc} \\ L_{rs}^{abc} & L_{rr}^{abc} \end{bmatrix} \begin{bmatrix} i_s^{abc} \\ i_r^{abc} \end{bmatrix}$$

where

$$\lambda_s^{abc} = (\lambda_{as} \quad \lambda_{bs} \quad \lambda_{cs})^t$$

$$\lambda_r^{abc} = (\lambda_{ar} \quad \lambda_{br} \quad \lambda_{cr})^t$$

$$i_s^{abc} = (i_{as} \quad i_{bs} \quad i_{cs})^t$$

$$i_r^{abc} = (i_{ar} \quad i_{br} \quad i_{cr})^t$$

Superscripts t denotes the transpose of array.

The sub-matrices of the stator to stator and rotor to rotor winding inductances are of the form:

$$L_{ss}^{abc} = \begin{bmatrix} L_{ls} + L_{ss} & L_{sm} & L_{sm} \\ L_{sm} & L_{ls} + L_{ss} & L_{sm} \\ L_{sm} & L_{sm} & L_{ls} + L_{ss} \end{bmatrix}$$

The above matrix for rotor inductances can be written as:

$$L_{rr}^{abc} = \begin{bmatrix} L_{lr} + L_{rr} & L_{rm} & L_{rm} \\ L_{rm} & L_{lr} + L_{rr} & L_{rm} \\ L_{rm} & L_{rm} & L_{lr} + L_{rr} \end{bmatrix}$$

$$L_{ss}^{abc} = \begin{bmatrix} L_{asas} & L_{asbs} & L_{ascs} \\ L_{bsas} & L_{bsbs} & L_{bscs} \\ L_{csas} & L_{csbs} & L_{cscs} \end{bmatrix}$$

$$L_{asas} = L_{bsbs} = L_{cscs}$$

and

$$L_{rr}^{abc} = \begin{bmatrix} L_{arar} & L_{arbr} & L_{arcr} \\ L_{brar} & L_{brbr} & L_{brcr} \\ L_{crar} & L_{crbr} & L_{crcr} \end{bmatrix}$$

$$L_{arar} = L_{brbr} = L_{crcr}$$

$$L_{arbr} = L_{arcr} = L_{brar} = L_{brcr} = L_{crar} = L_{crbr}$$

The self-inductance are:

$$L_{asas} = L_{bsbs} = L_{cscs},\ L_{arar} = L_{brbr} = L_{crcr}$$

and the mutual inductances are:

$$L_{arbr} = L_{arcr} = L_{brar} = L_{brcr} = L_{crar} = L_{crbr}$$

and $L_{arbr} = L_{arcr} = L_{brar} = L_{brcr} = L_{crar} = L_{crbr}$

The mutual inductances between the stator and rotor windings are dependent on the rotor angle.

$$L_{sr}^{abc} = \left[L_{rs}^{abc}\right]^t = L_{sr} \begin{bmatrix} Cos\theta_r & Cos(\theta_r + 2\pi/3) & Cos(\theta_r - 2\pi/3) \\ Cos(\theta_r - 2\pi/3) & Cos\theta_r & Cos(\theta_r + 2\pi/3) \\ Cos(\theta_r + 2\pi/3) & Cos(\theta_r - 2\pi/3) & Cos\theta_r \end{bmatrix}$$

The stator flux linkages are obtained applying Tqd0 (θ) to stator abc flux linkages. Using appropriate inverse transformations to replace the abc stator and rotor currents by their corresponding qd0 currents

$$\lambda_s^{qd0} = \begin{bmatrix} L_{ls} + \frac{3}{2}L_{ss} & 0 & 0 \\ 0 & L_{ls} + \frac{2}{3}L_{ss} & 0 \\ 0 & 0 & L_{ls} \end{bmatrix} i_s^{qd0} + \begin{bmatrix} \frac{3}{2}L_{sr} & 0 & 0 \\ 0 & \frac{3}{2}L_{sr} & 0 \\ 0 & 0 & 0 \end{bmatrix} i_r^{qd0}$$

and

$$\lambda_r^{qd0} = \begin{bmatrix} \frac{3}{2}L_{sr} & 0 & 0 \\ 0 & \frac{3}{2}L_{sr} & 0 \\ 0 & 0 & 0 \end{bmatrix} i_s^{qd0} + \begin{bmatrix} L_{lr} + \frac{3}{2}L_{rr} & 0 & 0 \\ 0 & L_{lr} + \frac{3}{2}L_{rr} & 0 \\ 0 & 0 & L_{lr} \end{bmatrix} i_r^{qd0}$$

The stator and rotor flux linkage relationships can be expressed in compact as:

$$\begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{0s} \\ \lambda'_{qr} \\ \lambda'_{dr} \\ \lambda'_{0r} \end{bmatrix} = \begin{bmatrix} L_{ls} + L_m & 0 & 0 & L_m & 0 & 0 \\ 0 & L_{ls} + L_m & 0 & 0 & L_m & 0 \\ 0 & 0 & L_{ls} & 0 & 0 & 0 \\ L_m & 0 & 0 & L'_{lr} + L_m & 0 & 0 \\ 0 & L_m & 0 & 0 & L'_{lr} + L_m & 0 \\ 0 & 0 & 0 & 0 & 0 & L'_{lr} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \\ i'_{qr} \\ i'_{dr} \\ i'_{0r} \end{bmatrix}$$

The primed rotor quantities are referred to the stator side.

2.1 DETERMINATION OF MOTOR INDUCTANCES:

For a balanced three phase induction motor, $N_{as}=N_{bs}=N_{cs}=N_s$ and $N_{ar}=N_{br}=N_{cr}=N_r$, the stator & rotor turns per phase. The stator winding self and mutual inductances are-

$$L_{asas} = \frac{N_a^2}{N_b^2}\left(L_{ls} + \frac{2}{3}L_{ss}\right) = N_a^2 L_{mls}$$

$$L_{bsbs} = N_b^2 L_{mls}$$

$$L_{cscs} = N_c^2 L_{mls}$$

The stator mutual inductances between stator phases-

$$L_{asbs} = L_{bsas} = N_a N_b L_{mls}$$

$$L_{ascs} = L_{csas} = N_a N_c L_{mss}$$

$$L_{bscs} = L_{csbs} = N_c N_b L_{mss}$$

The rotor winding self-inductance and mutual inductances are-

$$L_{arar} = L_{brbr} = L_{crcr} = L_{ls} + L_{rr}$$

and rotor mutual inductances between phases

$$L_{arbr} = L_{arcr} = L_{brcr} = L_{crbr} = L_{crar} = L_{brar} = L_{brcr}$$

Due to rotor symmetry the mutual inductances between stator and rotor windings are- $L_{asar} = L_{asbr} = L_{ascr}$,

$L_{bsar} = L_{bsbr} = L_{bscr}$ and $L_{csar} = L_{csbr} = L_{cscr}$

Let θr the angle between the stator phase axis a_s and rotor phase axis a_r

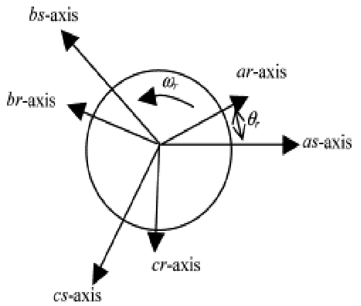

Figure 1 Induction machine winding displacement

The mutual inductances vary with angle θr. The max. mutual inductances from above are-

$$L_{asar} = L_{asbr} = L_{ascr}$$

$$L_{bsar} = L_{bsbr} = L_{bscr}$$

$$L_{csar} = L_{csbr} = L_{cscr}$$

$$L_{asar} = L_{asbr} = L_{ascr} = \frac{2}{3}\left(N_r L_m N_a / N_s^2\right) = N_a L_{msr}$$

$$L_{bsar} = L_{bsbr} = L_{bscr} = N_b L_{msr}$$

$$L_{csar} = L_{csbr} = L_{cscr} = N_c L_{msr}$$

Where $L_{msr} = \frac{2}{3} N_r L_m / N_s^2$

2.2 Simulation model with asymmetrical induction motor:

The stator voltages in qd reference frame as-

$$v_s^q = \frac{2}{3}\left(v_{as} - \frac{1}{2}\left(v_{bs} + v_{cs}\right)\right)$$

and

$$v_s^d = \frac{1}{\sqrt{3}}\left(-v_{bs} + v_{cs}\right)$$

The flux linkages are as-

$$\lambda_s^q = \int\left(v_s^q - r_{11}^s i_s^q - r_{12}^s i_s^d\right)dt$$

$$\lambda_s^d = \int\left(v_s^d - r_{21}^s i_s^q - r_{22}^s i_s^d\right)dt$$

$$\lambda_r^q = \int\left(\omega_r \lambda_r^d - r_r^r i_r^q\right)dt$$

$$\lambda_r^d = -\int\left(\omega_r \lambda_r^q + r_r^r i_r^q\right)dt$$

The speed of the machine from the equation-

$$\omega_r(t) = \left(\frac{p}{2J}\right)\int\left(T_{em} + T_{mech} - T_{damp}\right)dt$$

The electromechanical torque developed by the induction motor

$$T_{em} = \frac{3}{2}\frac{p}{2}\left(\lambda_s^d i_s^q - \lambda_s^q i_s^d\right)$$

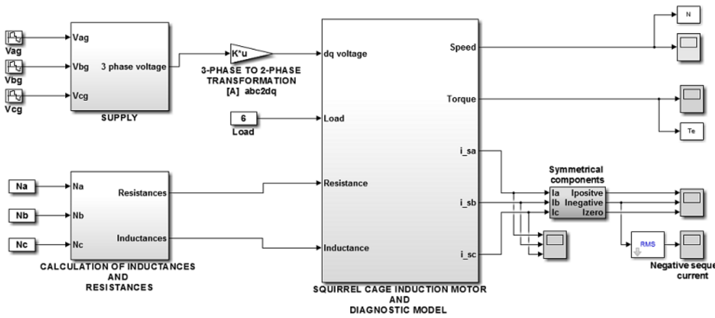

Figure 2 Effect of stator inter-turn short circuit on the characteristic of an induction motor

3. Induction motor mathematical model when stator inter-turn short circuit-

The stator turns per phase, $N_{as}=N_{bs}=N_{cs}=N_s$
The stator turns for phase C, $N_{cs}= N_{us} + N_{sh}=N_s$
Where,
N_{us}= unshorted turns in phase C
N_{sh}=shorted turns in phase C
The severity of faults depend on the inductance and the resistance of shorted turns.
Transforming abc quantities to qd0 axis for stator inter-turn short circuit. The self-inductances for stator phase are-

$L_{cscs} = \left(L'_{cscs} + L_{cssh}\right) + \left(L_{cssh} + L_{shsh}\right)$ and

$L_{bsbs} = L_{asas} = N_s L_{mls}$

L'_{cscs} = unshorted turns self-inductance

L_{cssh} = mutual inductance between shorted and unshorted turns.

L_{shsh} = SHORTED TURNS SELF-INDUCTANCE

THE STATOR WINDING MUTUAL INDUCTANCES-

$$L_{csbs} = L'_{csbs} + L_{shsh}$$

$$L_{ascs} = L_{bsas} = L_{csas}$$

$$L_{bscs} = L_{csbs} = -L_m / 3$$

The stator to rotor mutual inductances-

$$L_{asar} = L_{asbr} = L_{ascr} = L'_{cscr} + L_{shcr}$$

$$L_{bsar} = L_{bsbr} = L_{csar} = L_{csbr} = L_{cscr}$$

$$= \frac{2}{3}\left(\frac{N_s N_r}{N_s^2}\right) L_m$$

$$L'_{csar} = \frac{2}{3}\left(\frac{N_{us} + N_r}{N_s^2}\right) L_m$$

$$L_{shar} = \frac{2}{3}\left(\frac{N_{sh} + N_r}{N_s^2}\right) L_m$$

After the stator inter-turn short circuit of phase C, the winding parameters are changing. Considering the new winding parameters, the self- and mutual inductances. The new matrices after the transformation from abc to qd0-

$$L_{ss}^{qd0} = \begin{bmatrix} L_{ss}^{11} & 0 & L_{ss}^{13} \\ 0 & L_{ss}^{22} & 0 \\ L_{sr}^{31} & 0 & L_{ss}^{33} \end{bmatrix} \text{ and}$$

$$L_{sr}^{qd0} = \begin{bmatrix} L_{sr}^{11} & 0 & 0 \\ 0 & L_{sr}^{22} & 0 \\ L_{sr}^{31} & 0 & 0 \end{bmatrix}$$

Where

$$L_{ss}^{11} = \left(L_s^q + L_{ssh}^q\right) + \left(L_{sr}^q + L_{ssh}^q\right)$$

$$L_{ss}^{22} = L_s^d L_{sr}^{11}$$

$$L_{sr}^{22} = L_{sr}^d$$

Similarly the rotor self and mutual inductances after the transformation of abc into qd0.

$$L_{rr}^{qd0} = \begin{bmatrix} L_{rr}^{11} & 0 & 0 \\ 0 & L_{rr}^{22} & 0 \\ 0 & 0 & L_{rr}^{33} \end{bmatrix}$$

$$L_{rs}^{qd0} = \begin{bmatrix} L_{rr}^{11} & 0 & L_{sr}^{31}/2 \\ 0 & L_{sr}^{22} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Where

$$L_{rr}^{11} = L_r^q$$

$$L_{rr}^{22} = L_r^d$$

The stator and rotor flux linkages in the matrix form after the transformation can be expressed as-

$$\begin{bmatrix} \lambda_{sh}^q \\ \lambda_s^q \\ \lambda_s^d \\ \lambda_r^q \\ \lambda_r^d \end{bmatrix} = \begin{bmatrix} L_{sh}^q & L_{ssh}^q & 0 & L_{shr}^q & 0 \\ L_{ssh}^q & L_s^q & 0 & L_{sr}^q & 0 \\ 0 & 0 & L_s^d & 0 & L_{sr}^d \\ L_{shr}^q & L_{sr}^q & 0 & L_r^q & 0 \\ 0 & 0 & L_{sr}^d & 0 & L_r^d \end{bmatrix} \begin{bmatrix} i_{sh}^q \\ i_s^q \\ i_s^d \\ i_r^q \\ i_r^d \end{bmatrix}$$

The stator resistances are-

$$r_{cs} = r'_{cs} + r_{sh}$$

$$r_{bs} = r_{as} = r_s$$

Where r_{sh} = resistance of shorted winding

$$r_{sh} = \left(\frac{N_{sh}}{N_s}\right) r_s \text{ and}$$

$$r'_{cs} = \left(\frac{N_c}{N_s}\right) r$$

The flux linkages are-

$$\lambda_{sh}^q = \int (v_{sh}^q - r_{sh}\, i_{sh}^q)\,dt$$

$$\lambda_s^q = \int (v_s^q - v_{sh}^q - s_s^{11} i_s^q - r_s^{12} i_s^d)\,dt$$

$$\lambda_s^d = \int (v_s^d - r_s^{21} i_s^q - r_s^{22} i_s^d)\,dt$$

$$\lambda_r^q = \int (\omega_r \lambda_r^d - r_r^r i_s^q)\,dt$$

$$\lambda_r^d = \int -(\omega_r \lambda_r^q + r_r^r i_r^d)\,dt$$

4. Results from simulation

The mathematical model developed for symmetrical and asymmetrical condition is simulated MATLAB Simulink for full load condition of squirrel cage induction motor for unbalanced supply voltages. The stator currents, current sequence components, negative sequence current, torque developed and speed are presented. The simulation results when the motor is symmetrical as below. With shorted three turns of phase C of stator winding, the negative sequence current developed is producing torque which causes the ripple in torque and vibrations so the more mechanical stress on the bearing which increases the noise and the bearing heating, bearing life decreases.

Simulation results on unbalanced voltages and symmetrical three phase stator winding:

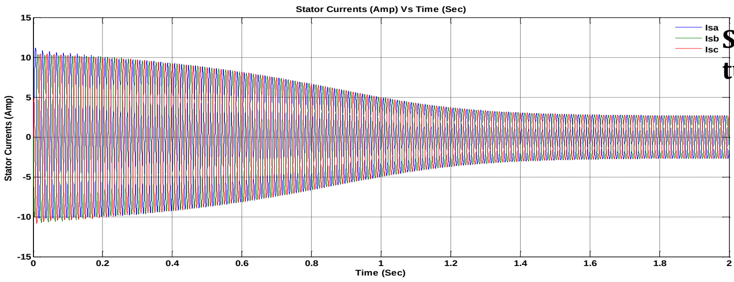

Figure 3.Stator currents Vs. time

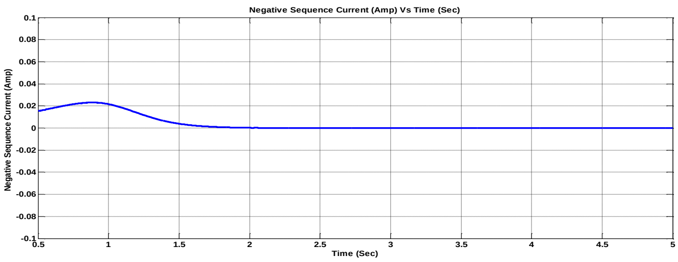

Figure 4.Negative sequence current Vs. Time

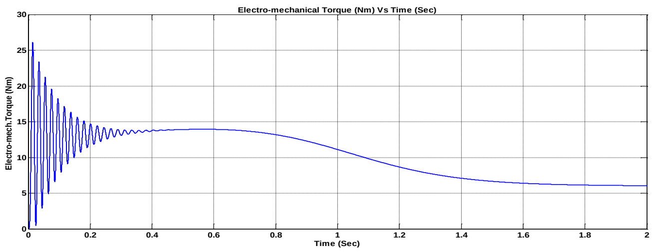

Figure 5. Electromechanical torque Vs. Time

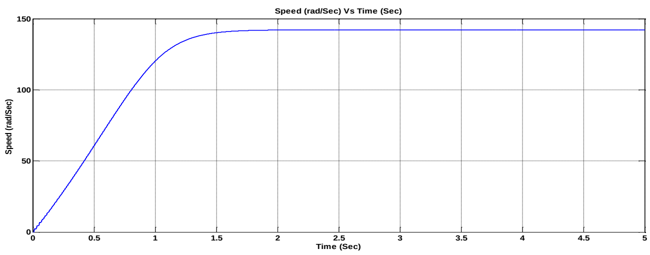

Figure 6. Speed Vs. Time

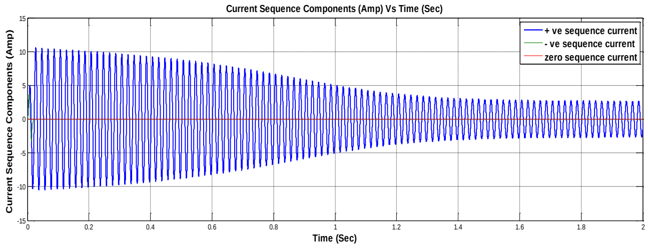

Figure 7. Current sequence components Vs. Time

Simulation results on unbalanced voltages and three turns of phase C of stator winding short circuited:

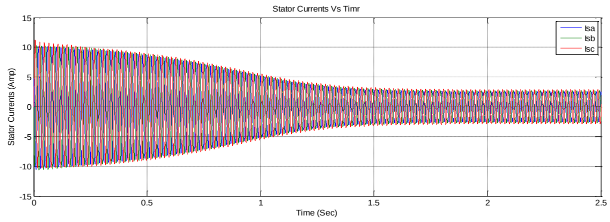

Figure 8 Stator currents Vs. time

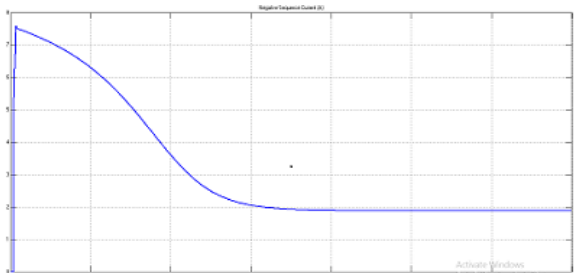

Figure 9 Negative sequence current Vs. Time

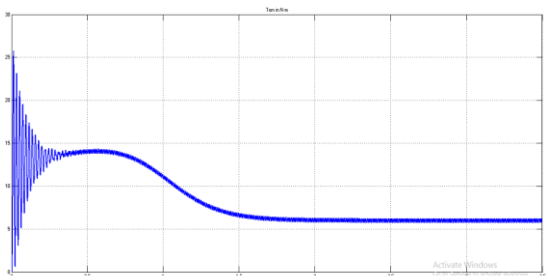

Figure 10 Electromechanical torque Vs. Time

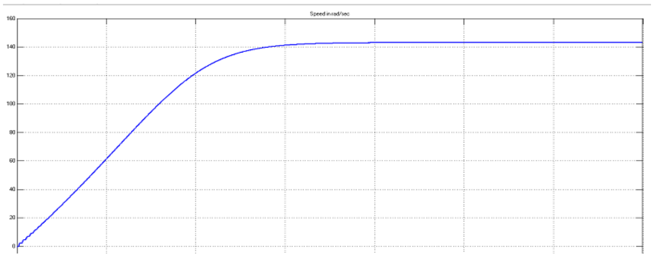

Figure 3. Speed Vs. Time

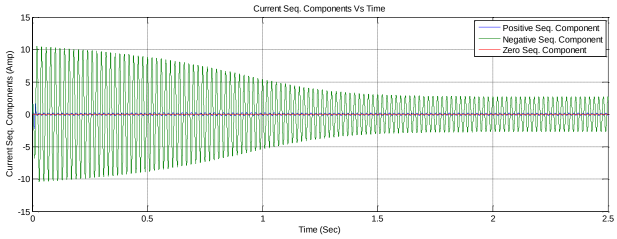

Figure 12. Current sequence components Vs. Time

5. CONCLUSION

The induction motor model is developed for symmetrical and asymmetrical conditions. The results are presented for full load conditions. In healthy symmetrical conditions and asymmetrical conditions. The three turns of phase C are short circuited and unbalanced voltage is provided for the simulation purpose. At asymmetrical conditions the negative sequence component of current produce the oscillatory torque. The oscillatory torque produce more stress on the bearing which causes failure of bearings.

Appendix:

A.1s: The motor nameplate specifications-

Volts: 415, HP/kW: 1/0.75, Hz: 50, Amp: 2.1, Pole: 4, Class of insulation: B, Duty: S1, Connection: Star, Frame: 80, Make: Link Servo-Systems Pvt. Ltd.

Total turns per coil: 80, Coils per phase: 2, Turns per phase: 160

Stator winding resistance per phase: 13.8 Ω

Rotor winding resistance per phase r.t. stator side: 13.0 Ω

Rotor leakage inductance= 0.03033 H,

Stator leakage induction= 0.03033 H

Magnetizing reactance: 212.757 Ω

Rotor inertia: 0.06 kg.m^2

A.2: MATLAB simulation is carried out for following voltages.

Voltage Simulation Results When Voltage is unbalanced.

V_{ab} line =415V,

V_{bc} line: 410 V and

V_{ca} line=400 V and 3 inter-turns of phase C are short circuited.

REFERENCES

[1] W. T. Thomson and M. Fenger,”Current Signature Analysis to Detect Induction Motor Faults,” IEEE Industry Applications Magazine, vol.7, no.4. 2001, pp. 26-34, Jul./Aug.

[2] W. T. Thomson, ”On-Line MCSA to Diagnose Shorted Turns in Low Volt- age Stator Windings of 3-Phase Induction Motors Prior to Failure,” in Proc. 2001 IEEE IEMDC01, pp. 1-8.

[3] A. H. Bonnett and G. C. Soukup, Cause and analysis of stator and rotor failures in three-phase squirrel-cage induction motors, IEEE Trans. Ind. Applicat., vol. 28, pp. 921937, July/Aug. 1992.

[4] S. Williamson, and K. Mirzoian, Analysis of cage induction motors with stator winding faults, IEEE Trans. Power Apparat. Syst., vol. PAS-104, pp. 18381842, July 1985.

[5] Chee Mung Ong, Dynamic simulation of electric machinery.

[6] M. Arkan, D. Kostic-Perovie, P.J. Unsworth: Modelling and simulation of induction motors with inter-turn faults for diagnostics.

[7] IEEE Std 141-1993: IEEE Recommended Practice for Electric Power Distribution for Industrial Plants.

[8] IEEE Std 242-2001: IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems.