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ASSESSMENT OF STRESSES ON INDUCTION MOTOR UNDER DIFFERENT FAULT CONDITIONS

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ABSTRACT

This paper presents an assessment of stresses produced in an induction motor when the motor is allowed to run under open-circuit and short-circuit conditions. A generalized dynamic model of a three-phase squirrel cage induction motor has been developed using d and q variables in a synchronously rotating reference frame. This model can predict performance of the motor during open-circuit and short-circuit conditions. The simulation results are obtained from two squirrel cage induction motors, sized 3 hp and 2250 hp.

Keywords: *Modeling, Induction motor (IM), open-circuit (OC) , short-circuit (SC)*

1. INTRODUCTION

Induction machine modeling has continuously attracted the attention of researchers not only because such machines are made and used in largest numbers but also due to their varied modes of operation both under steady and dynamic states.

In an electric drive system the machine is a part of the control system elements. To be able to control the dynamics of the drive system, dynamic behavior of the machine need to be considered. The dynamic behavior of IM can be described using dynamic model of IM. The dynamic model considers the instantaneous effects of varying voltages/currents, stator frequency and torque disturbance. In this paper the dynamic model of IM is derived by using d and q variables in a synchronously rotating reference frame and also the dynamic performance of IM under open circuit and short circuit fault conditions for both low and high power machines.

Induction motors are commonly controlled by contactors, which are electromagnetic switches that are highly sensitive to voltage depressions and momentary service interruptions. Voltage depressions are huge problems for many industries, and it is probably the most pressing power quality problems today. The Voltage depressions caused by faults on the system affect the performance of induction motors, in terms of the production of both transient currents and transient torques. It is often desirable to minimize the effect of the voltage dip on both the induction motor and more importantly on the process where the motor is used. Large torque peaks may cause damage to the shaft or equipment connected to the shaft. Some common reason for voltage depressions are lightning strikes in power lines, equipment failures, accidental contact power lines, and electrical machine starts. Despite being a short duration between 10 milliseconds to 1 second event during which a reduction in the RMS voltage magnitude takes place, a small reduction in the system voltage can cause serious consequences [6].

2. MODELLING OF INDUCTION MOTOR

In this paper the mathematical model of the induction motor is modeled using matlab / simulink program based on references [1] to [5]. This model is described in space vector formulation in synchronously rotating arbitrary d-q reference frame associated with the frequency w_s of the stator excitation (using per unit description).

This model is obtained considering the induction

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motor as 6 magnetically coupled circuits. Under balanced conditions, the sum of stator currents as well as rotor currents is zero. The induction motors are modeled in d-q variables. The d-q model uses two windings for each stator and rotor of the induction motor. Only four independent variables are needed to model the induction motor. A transformation of variables can be used. The power invariant two-axes transformation is used and is defined as:

(i) 3-phase to 2-phase (abc-dq) conversion:

To convert 3-phase voltages to voltages in the 2-phase synchronously rotating frame, they are first converted to 2-phase stationary frame (α β) or in the movement with an arbitrary speed using (1) and then from the stationary frame to the synchronously rotating frame (dq) using (2). In place of voltages there may be currents or flux linkages.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos\gamma & \sin\gamma \\ -\sin\gamma & \cos\gamma \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \qquad (2)$$

Where 'γ' is the transformation angle.

(ii) 2-phase to 3-phase (dq-abc) conversion:

This conversion does the opposite of the abc-dq conversion for the current variables using (3) and (4) respectively by following the same implementation techniques as before.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos\gamma & -\sin\gamma \\ \sin\gamma & \cos\gamma \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} \qquad (3)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (4)$$

The dynamic equations in arbitrary reference frame which is rotating at speed ω in the direction of rotor rotation.

1. When ω is equal to zero, the reference frame is fixed in the stator (qs-ds ref. frame).

2. When ω is equal to ωe, the reference frame is fixed on the synchronously rotating reference frame.

3. When ω is equal to ωr, the reference frame is fixed in the rotor. That is, the reference frame is rotating at speed of ωr.

The dynamic equations used are:

Electrical system equations:

$$\overline{V_s} = R_s\overline{i_s} + \frac{1}{\omega_b}\left(\frac{d\overline{\lambda_s}}{dt}\right) + \omega_e M_{(pi/2)}\overline{\lambda_s} \qquad [5]$$

$$\overline{V_r} = R_r\overline{i_r} + \frac{1}{\omega_b}\left(\frac{d\overline{\lambda_r}}{dt}\right) + (\omega_e - \omega_r) M_{(pi/2)}\overline{\lambda_r} \qquad [6]$$

$$\overline{\lambda} = \begin{bmatrix} \lambda_s \\ \lambda_r \end{bmatrix}; \quad \overline{i} = \begin{bmatrix} i_d \\ i_q \end{bmatrix};$$

Flux linkage-current relations:

$$\overline{\lambda_s} = L_s\overline{i_s} + L_m\overline{i_r} \qquad [7.a]$$

$$\overline{\lambda_r} = L_m\overline{i_s} + L_r\overline{i_r} \qquad [7.b]$$

Where $L_s = L_m + L_{sl}$ and $L_r = L_m + L_{rl}$

Mechanical system equations:

$$T_{em} = 2H\frac{d\omega_{mec}}{dt} + B_m\omega_{mec} + T_L \qquad [8]$$

Where

$$T_{em} = \overline{\lambda_s} \otimes \overline{i_s} = M_{(pi/2)}\overline{\lambda_s} \bullet \overline{i_s} \text{ and}$$

$$\omega_{mec} = \frac{2}{p}\omega_r$$

3. SIMULINK MODEL OF INDUCTION MOTOR

The model of the induction motor in *d-q* variables is represented by (5), (6), (7) and (8). Currents or flux linkages can be used as state variables. In this paper the flux linkages are chosen as state variables and it was verified in the Matlab/Simulink software environment. The block diagram of a three-phase induction motor supplied by a three-phase power supply is shown in Fig. 1. The variable $\omega_s = \omega$ represents the speed of the common reference frame used. This speed is an arbitrary speed.

It consists of five major blocks: the 3-phase voltages, abc-dq conversion, dq-abc conversion, induction machine d-q model (Im_dq_model) and the mechanical system (mech sys) blocks.

(a) 3-phase voltages

A three-phase voltage and frequency are represented in this block.

(b) abc-dq Transformation

The abc-dq block realizes the transformations of variables defined by (1) and (2).

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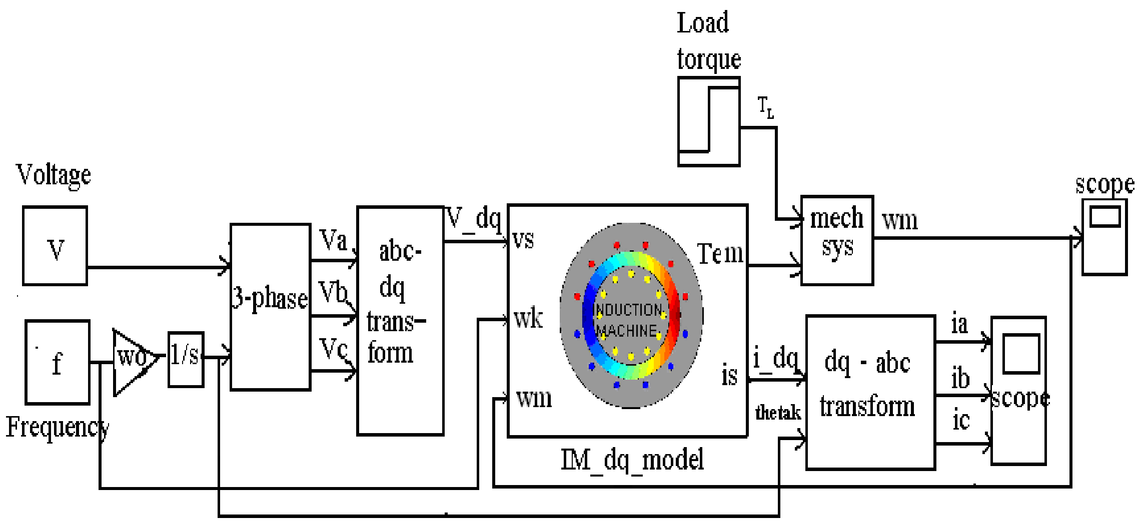

Fig.1 Block diagram of induction motor model in the arbitrary frame

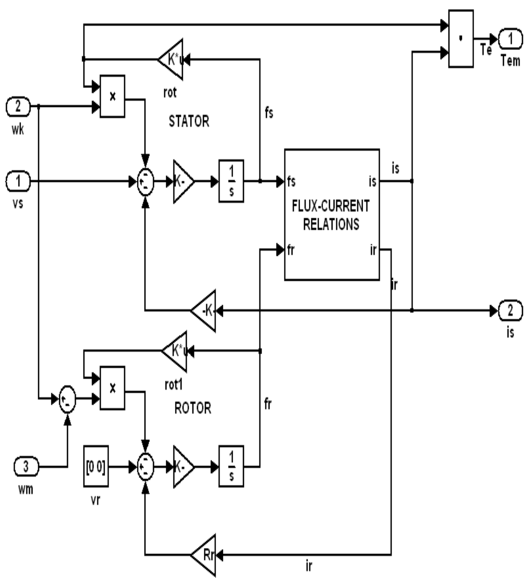

Fig. 2 DQ model of the induction machine in arbitrary reference frame (Im_dq_model)

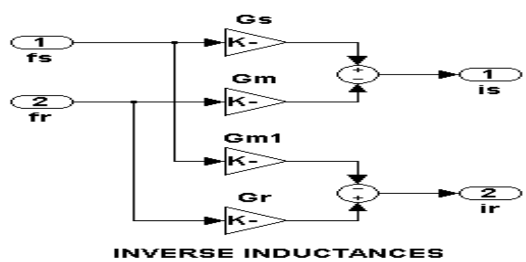

Fig.3 Flux – Currents Relations Block

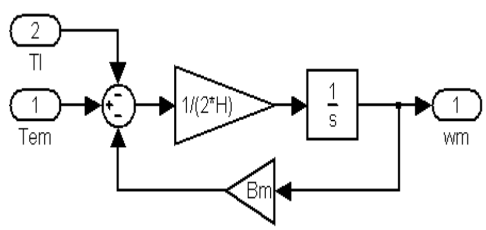

Fig. 4 mech sys block

(c) IM _dq_model

This block represents the induction motor using d-q variables in an arbitrary reference frame and is shown in fig.(2). The d-q model of the induction motor is represented using equations 5 and 6 with flux-currents relations block. The sub-block diagram of flux-currents relations using equations 7.a and 7.b is shown in Fig.3. It is used to compute the four *dq* currents using the four flux linkages and the inverse inductance matrix.

(d) dq-abc Transformation

The dq-abc block realizes the transformations of variables defined by equations (3) and (4).

(e) mech sys

The mechanical system (mech sys) block determines the electromagnetic torque using equation (8) and is shown in fig. (4)

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4. INDUCTION MOTOR UNDER SHORT CIRCUIT CONDITIONS

When a three phase short circuit fault occurs electrically close to the motor no electrical energy can enter or leave the motor. It is obvious that current can still flow in both the stator and rotor windings, thus torque can be produced. The energy stored in the magnetic field can therefore be dissipated either as mechanical energy or as heat due to copper losses in the motor.

As the fault is applied, there is a large negative torque transient associated with the transient current of a typical magnitude of 9 p.u. It is not uncommon for motors to have a maximum reverse torque impulse of up to 15 p.u [12 13]. This torque impulse reaches its maximum within few cycles, but decays rapidly. Since the flux decays rapidly, clearing of the fault and the subsequent re-establishment of the supply voltage produces transients of the same order as at startup. However if many motors are left connected to the system their combined effect could lead to a voltage depression due to large currents, and all the motors might not be able to accelerate back to full speed.

4. INDUCTION MOTOR UNDER OPEN CIRCUIT CONDITIONS

When the motor is open-circuited the rotor windings carry the current to maintain the mmf and hence the flux in the motor. Once the fault has been cleared, the motor can be reconnected to the supply.

If the motor terminals are disconnected from the supply, once again no energy can enter or leave the magnetic field via the electrical terminals. Further as there is no current in the stator, torque cannot be produced, thus energy cannot be transferred to the mechanical load. At that instant when the stator current is interrupted, the net mmf in the motor must remain constant. This mmf balance is achieved by an instantaneous increase in the current in the rotor windings which results in energy decay due to the resistance in the rotor.

6. SIMULATION RESULTS

This paper presents the modeling of the IM and its performance under different fault conditions for various ratings of the machine. The effect of electrical torque, speed, current due to sudden change in applied voltage for both 3 hp and 2250 hp induction machines are analyzed. This analysis is carried through matlab/simulink software environment.

Dynamic performance of Induction machine:

For a 3-hp and 2250 hp induction machines, the parameters are from [9] and are given in Appendix. Typical simulation results are given in figures 5 to 12 in [p.u]. Fig.5 and fig.6 shows the free acceleration characteristics of a 3-hp and 2250-hp induction motor and also the torque versus speed characteristics are shown in figures 7 and 8 respectively. For all these simulations the initial conditions are zero.

Initially the machine is starting from rest with rated voltage and no mechanical load. Because friction and windage losses are not represented, the machine accelerates to synchronous speed; under this condition the starting current is large. Due to the application of stator voltages, the instantaneous torque varies at 60-Hz about an average positive value. This decaying, 60-Hz variation in the instantaneous torque is due to the transients in the stator currents. Even though the stator currents depend upon the values of source voltages at the time of application, the instantaneous torque is independent of the balanced source voltages because the machine is symmetrical. These oscillations in the torque takes place until final operating point reached.

From the fig.7 and 8 we can observe the rotor speed is highly damped in the case of 3-hp machine and the final operating condition is attained without oscillations. Where as in the case of 2250-hp machine is an oscillatory manner.

Dynamic performance of Induction machine during a 3-phase short-circuit fault:

The dynamic performance of the 3-hp and 2250 hp induction machines is shown, respectively in fig 9 and 10 during a short-circuit (SC) fault at the terminals.

Initially the motor is running at steady state conditions with a constant load torque. The SC fault at the terminals is simulated by setting the stator voltages to zero at time t=1 sec. At that instant, the voltage passes through zero going positive. After 10 cycles i.e at t=2 sec the stator voltages are reapplied.

Figure 9 and 10 shows that stepping the supply voltage to zero volts causes a negative torque peak of approximately 9 times the rated steady state torque. It is not uncommon for motors to have a maximum reverse torque impulse of up to 15 p.u.

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Since the rotor speed and frequency also decreases once the supply voltage is removed. The magnitude of the worst torque peak and the interruption duration at which it occurs are a function of the motor and load inertia. Larger system inertia causes the rotor speed to decreases more slowly. i.e lower the magnitude of the negative torque impulse higher the load inertia.

In the case of 3-hp machine, both the stator and rotor transients are highly damped and subside before the fault is removed and the voltages are reapplied. As in the case of 2250 hp machine, which has higher leakage reactance to resistance ratio than the 3-hp machine, the stator and rotor transients are still present even though the fault is removed and the voltages are reapplied. When the voltages are reapplied the transients again occur in the stator currents.

Dynamic performance of Induction machine during an open-circuit fault:

The dynamic performance of the 3-hp and 2250 hp induction machines is shown, respectively in fig 11 and 12 during a open-circuit (OC) fault at the terminals.

In this case, the induction motor is disconnected from the supply at time (t=1sec), and then reconnected at a time (t=2 sec). Fig.11 and 12 shows the decay in the flux in the machine and also the electromagnetic torque of the motor becomes zero at the moment of disconnection, i.e there is no torque impulse. However, when the healthy supply is restored there is a large negative torque impulse.

In the case of 3-hp machine, both the stator and rotor transients are highly damped and subside before the fault is removed and the voltages are reapplied. As in the case of 2250 hp machine, which has higher leakage reactance to resistance ratio than the 3-hp machine, the stator and rotor transients are still present even though the fault is removed and the voltages are reapplied. When the voltages are reapplied the transients again occur in the stator currents.

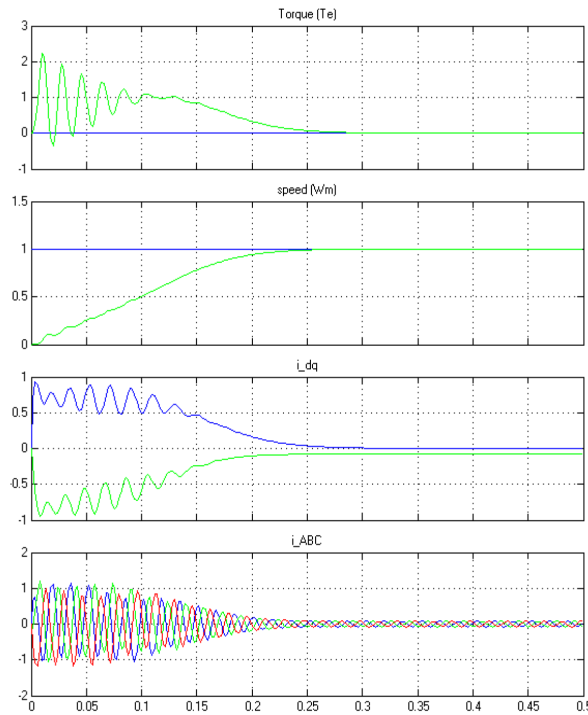

Fig.5 Machine variables during free acceleration of a 3-hp induction motor [p.u].

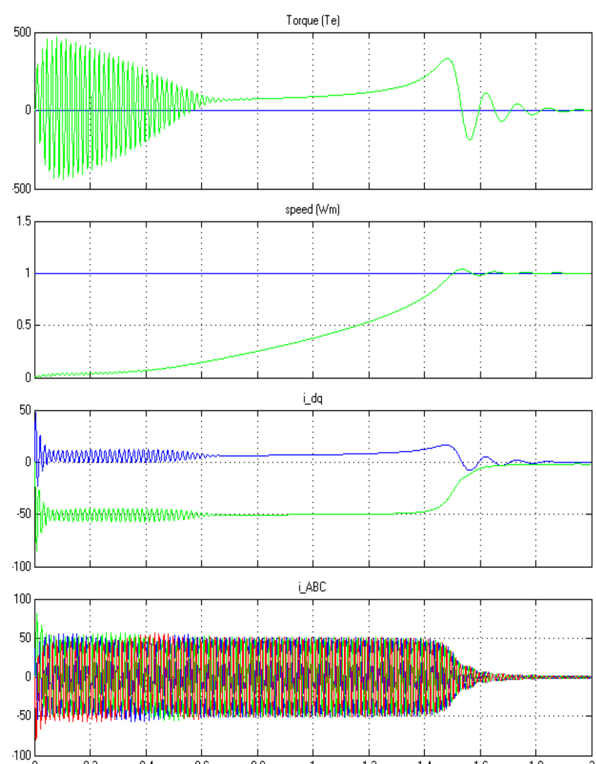

Fig.6 Machine variables during free acceleration of a 2250-hp induction motor [p.u]

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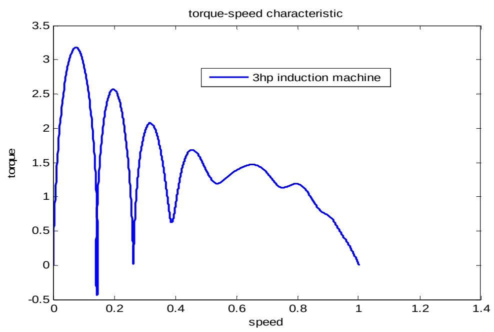

Fig .7 Torque-Speed characteristics during free acceleration: 3-hp induction motor [p.u]

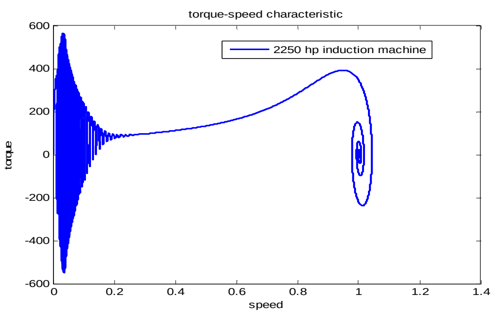

Fig .8 Torque-Speed characteristics during free acceleration: 2250-hp induction motor [p.u]

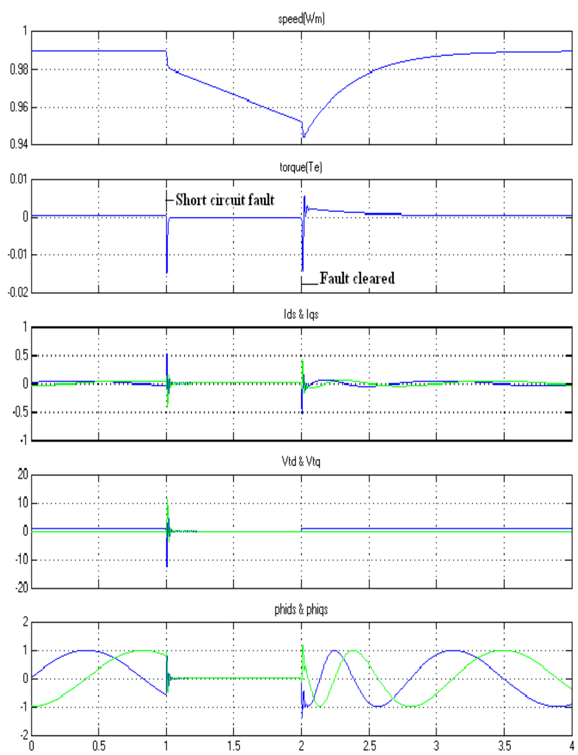

Fig .9 Dynamic performance of 3- hp induction machine during a short- circuit fault [p.u]

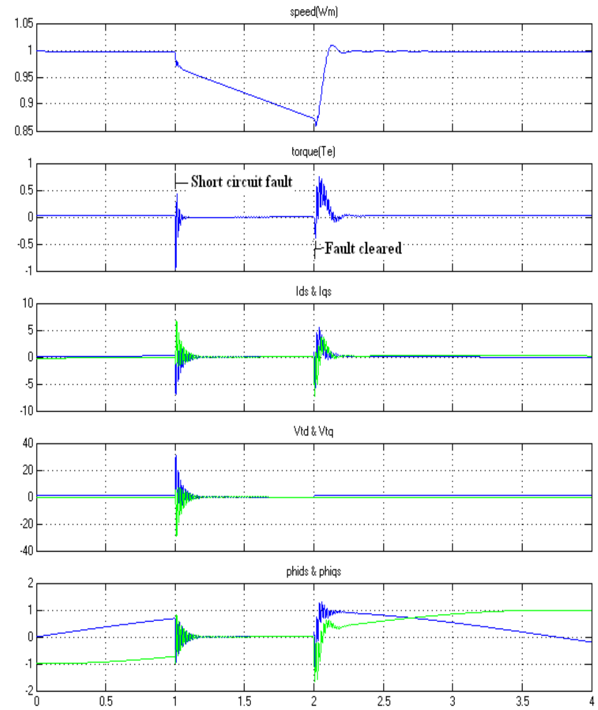

Fig .10 Dynamic performance of 2250-hp induction machine during a short-circuit fault [p.u]

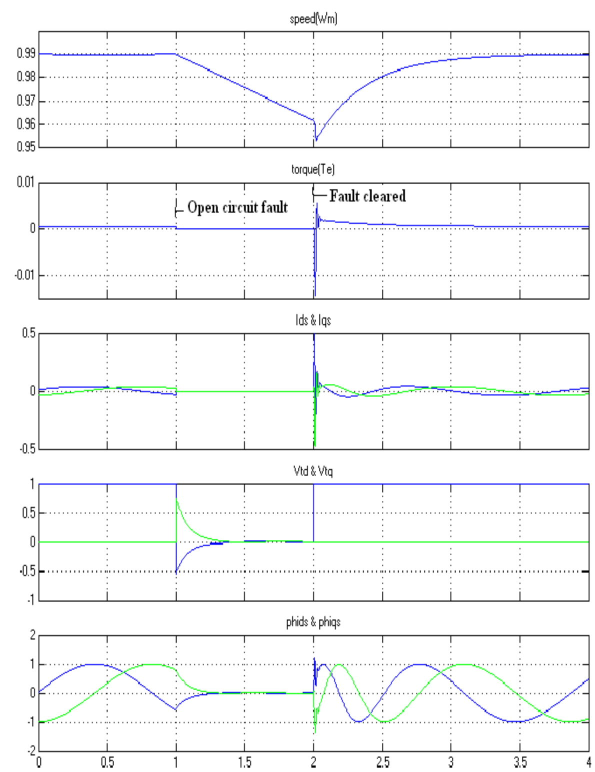

Fig .11 Dynamic performance of 3-hp induction machine during a Open-circuit fault [p.u]

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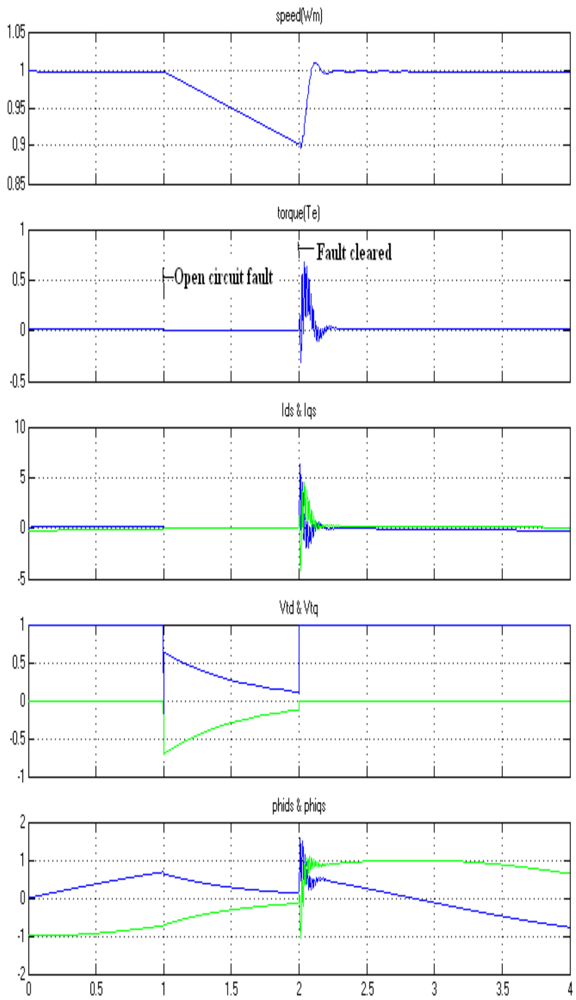

Fig .12 Dynamic performance of 2250-hp induction machine during a Open-circuit fault [p.u]

7. CONCLUSIONS

In this paper the dynamic model of induction motor has been analyzed by using d and q variables in a synchronously rotating reference frame and also the performance of IM during a short-circuit and open-circuit fault for both 3-hp and 2250-hp power machines. In both cases, there is decay in flux in the machine. It is important to note that the decay in OC fault is very much slower than for the SC fault and also the peak current is almost double the starting current. However it must be noted that the transient is of short duration and hence will not have a serious effect in terms of heating, but it can cause severe mechanical stresses on the windings of the machine. By comparing with OC and SC fault conditions, it shows that the SC fault condition can cause more severe mechanical stresses than the OC fault condition.

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APPENDIX

Each machine is a 4-pole, 60 Hz, 3-phase induction motor .The parameters are expressed in ohms using the 60-Hz value of the reactance's.

Parameters of the 3HP induction machine

p=4; V_{ds} =220; V_{qs} =0; ω_s =2*pi*60;

R_s =0.435; R_r = 0.816; L_s .= (26.13+0.754);

$L_r = L_s$; L_m =26.13; J=0.089;

Parameters of the 2250HP induction machine

p= 4; V_{ds} =2300; V_{qs} =0; ω_s =2*pi*60;

R_s =.029; R_r =0.022; L_s = (13.04+.226); $L_r = L_s$;

L_m =13.04; J=63.87;

NOMENCLATURE

$\overline{V}$ the voltage space vector,

$\bar{i}$ the current space vector,

$\overline{\lambda}$ the flux linkage space vector, *M* is the π/2 rotational matrix, $M_{pi/2} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$

R the resistance, *L* is the inductance,

V_a, V_b, V_c phase voltages in abc frame.

ω_r rotor frame freq.

ω_e dq frame freq.

ω_s synchronous frame freq.; (rad/sec)

λ_s stator flux,

λ_r rotor flux

R_s, R_r stator and rotor resistance

V_s, V_r stator and rotor voltage

i_s, i_r stator and rotor current

L_s, L_r stator and rotor inductance

L_m magnetizing inductance

L_{sl} stator leakage inductance

L_{rl} rotor leakage inductance

T_{em} electromagnetic torque

T_L load torque

B_m viscous friction coefficient.

d, q direct and quadrature axis

p number of poles

H inertia constant

J inertia of the rotor.

$V_\alpha ; V_\beta$ stator and rotor voltage in $\alpha\beta$ frame

$i_\alpha ; i_\beta$ stator and rotor current in $\alpha\beta$ frame

Operators: =cross product; • =dot Product.

BIOGRAPHY

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