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DESIGN OF COMPUTER APPLICATION FOR 3 PHASE VECTOR CONTROL INDUCTION MOTOR DRIVE

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Abstract

Development in the field of microelectronics and control has resulted in Vector control of Induction motor. The Induction motors are used in many adjustable speed applications. In order to understand and analyze the vector control of Induction motors, the dynamic model of the machine is necessary along with the steady state analysis and design of the Induction motors. It is the objective to explain the various forms in a concise way to understand clearly. In addition, the fundamental dynamic performance of the machine in the synchronous frame is developed along with the principles of closed loop vector control is discussed in general terms and simulation has been carried out on a laboratory model.

1 Introduction

An ac motor drive using a squirrel cage induction motor has the advantages of high power to weight ratio, lower inertia, inexpensive, available at all power ratings and less maintenance requirements. The dynamic model equations have been developed to describe the characteristics of Induction motor.

The objective of the article is to derive and explain the Induction motor model in relatively simple terms. It is proved that rotor flux lies on d –axis when synchronous reference frame has been chosen. Compared to the DC motor, dynamic equations of the Induction Motor have been simplified. This report provides detailed procedure of closed loop vector control for the 3.7KW, 4 pole, 415V, 7.5A, 50 Hz, 1430 rpm 3Ph, Cage rotor.

In a squirrel cage induction motor the stator phase current is a vector sum of the flux and torque producing the current components. So, in order to achieve a dynamic performance similar to DC drive, a decoupling of the stator phase current in to the flux producing and torque producing current components is essential. This requires complicated signal processing of three phase currents under all dynamic condition. Recent developments in microelectronics such has micro controllers and digital signal processing (DSP) chips have made it possible, to achieve a dynamic performances, from an induction motor drive, similar to that of a conventional dc drive. The decoupling of flux and torque control in an AC machine is popularly known has Field Oriented Control.

2 Steady State Performance of the Induction Motor

The real power transmitted from the stator[1], P_i to the air gap P_a is the difference between the total input power to the stator winding and copper losses in the stator and is given as,

$$P_a=P_i-3I_2^2R_s \text{Watts} \tag{1}$$

Neglecting the core losses, the air gap power is equal to the total power dissipated in R_r/s in the three phases of the machine.

It is given as

$$P_a = 3I_r^2\left(\frac{R_r}{s}\right) \tag{2}$$

The above equation can also be written as

$$P_a = 3I_r^2R_r + 3I_r^2R_r\left(\frac{1-s}{s}\right) \tag{3}$$

From equation 27 the first term gives the rotor copper loss and the second term gives the power converted to mechanical form.

$$sP_a=3I_r^2R_r \tag{4}$$

Therefore the rotor copper losses are equal to the product of the slip and air gap power and hence are referred to as slip power.

The mechanical power output P_m is obtained as follows,

$$P_m = 3I_r^2 R_r \left(\frac{1-s}{s}\right) \text{Watts} \tag{5}$$

The mechanical power output is equal to the product of the electromagnetic torque and rotor speed, therefore

$$P_m = T_e \omega_m \tag{6}$$

Where Te is the internal or electromagnetic torque.

The electromagnetic or air gap torque is obtained as follows:

$$T_e = 3I_r^e R_r \left(\frac{1-s}{s\omega_m}\right) \tag{7}$$

Therefore,

$$T_e = 3\left(\frac{P}{2}\right)\frac{I_r^2 R_r}{s\omega_s} \tag{8}$$

The shaft power output of the machine P_s can be obtained by subtracting the windage and friction losses of the rotor from the mechanical output power of the machine which can be written as follows:

$$P_s=P_m-P_{fw} \tag{9}$$

Where P_{fw} is the windage and friction losses of the rotor.

There are also losses due to stray magnetic fields in the machine; they are covered by *stray load* losses. The stray load losses vary from 0.25 to 0.5 percent of the rated machine output.

$$R_r=Z_{sc}Cos\O_{sc}-R_s \tag{10}$$

$$X_{eq} = Z_{sc}Sin\O_s \tag{11}$$

Where X_{eq} is the sum of the stator referred rotor leakage reactance given as

$$X_{eq}=X_{ls}+X_{lr} \tag{12}$$

3 Dynamic Modeling of Induction Machines

The dynamic model of the induction motor is derived by using a two phase motor in direct and quadrature axes as shown in Fig.1. This approach is desirable because of conceptual simplicity obtained with two sets of windings one on the stator and other on the rotor. The equivalence between the three phase and two phase models[3] is derived from simple observation, and this approach is suitable for extending it to model an n – phase machine means of two phase machine. The concept of power invariance is introduced: the power must be equal in the three phase machine and its equivalent two phase model.

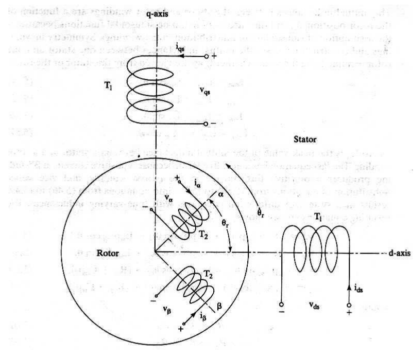

Figure 1: Stator and Rotor windings of a two Phase Induction Motor

The following assumptions are made to derive the dynamic model:

- Uniform air gap.
- Balanced rotor and stator windings, with sinusoidally distributed mmf.
- Inductance versus rotor position in sinusoidal and
- Saturation and parameter changes are neglected.

A two phase induction machine with stator and rotor windings is as shown figure, the winding are displaced in space by 90 electrical degrees, and the rotor winding, α, is at an angle θ_r from the stator d axis winding.

The number of turns per phase in the stator and rotor respectively are T_1 and T_2. A pair of poles is assumed for this figure. θ_r is the electrical rotor position at any instant, obtained by multiplying the mechanical rotor position by pair of electrical poles.

The terminal voltages of the stator and the rotor windings can be expressed as the sum of voltage drops in resistances and rate of change flux linkages which are the products of the currents and the inductances, given as

$$V_{qs}=R_q i_{qs}+ p(L_{qq}i_{qs}) + p(L_{qd}i_{ds}) + p(L_{q\alpha}i_{\alpha}) + p(L_{q\beta}i_{\beta}) \quad (13)$$

$$V_{ds}=R_q i_{ds}+ p(L_{dq}i_{qs}) + p(L_{dd}i_{ds}) + p(L_{d\alpha}i_{\alpha}) + p(L_{d\beta}i_{\beta}) \quad (14)$$

$$V_{\alpha}=R_{\alpha}i_{\alpha} + p(L_{\alpha q}i_{qs}) + p(L_{\alpha d}i_{ds}) + p(L_{\alpha\alpha}i_{\alpha}) + p(L_{\alpha\beta}i_{\beta}) \quad (15)$$

$$V_{\beta} =R_{\beta}i_{\beta} + p(L_{\beta q}i_{qs}) + p(L_{\beta d}i_{ds}) + p(L_{\beta\alpha}i_{\alpha}) + p(L_{\beta\beta}i_{\beta}) \quad (16)$$

Where p is the differential operator d/dt

V_{qs}, V_{ds} are the terminal voltages of the stator q axis and d axis respectively.

V_{α}, V_{β} are the terminal voltages of the rotor α and β windings respectively.

i_{qs}, i_{ds} are the stator q axis and d axis currents respectively.

i_{α}, i_{β} are the rotor q axis and d axis currents respectively.

L_{qq}, L_{dd} self inductance of the stator q and d axis windings respectively.

$L_{\alpha\alpha}$, $L_{\beta\beta}$ self inductance of the rotor α and β windings respectively.

The mutual inductances between any two windings are denoted by L with two subscripts, the first subscript denoting the winding at which the emf is measured due to the current in the other winding indicated by the second subscript. Assuming uniform air gap, the self inductances are independent of angular positions.

Therefore,

$$L_{\alpha\alpha}=L_{\beta\beta}=L_{rr,} \quad (17)$$

$$L_{dd}=L_{qq}=L_s \quad (18)$$

The mutual inductance between the rotor windings are zero, because the flux set up by a current in one winding will not link with the other winding displaced in space by 90 degrees.

Therefore,

$$L_{\alpha\beta}=L_{\beta\alpha}=0 \quad (19)$$

$$L_{dq}=L_{qd}=0 \quad (20)$$

The mutual inductances between the stator and the rotor windings are a function of the rotor position θ_r, and they are assumed to be sinusoidal functions because of the assumption of sinusoidal mmf distribution in the windings.

Symmetry in windings and construction causes mutual inductances between one stator and one rotor winding to be same whether they are viewed from the stator or the rotor.

$$L_{\alpha d}=L_{d\alpha}=L_{sr}Cos\theta_r \quad (21)$$

$$L_{\beta d}=L_{d\beta}=L_{sr}Sin\theta_r \quad (22)$$

$$L_{\alpha q}=L_{q\alpha}=L_{sr}Sin\theta_r \quad (23)$$

$$L_{\beta q}=L_{q\beta}=-L_{sr}Cos\theta_r \quad (24)$$

Where L_{sr} is the peak value of the mutual inductance between a stator and rotor winding. The last equation has a negative term, because a positive current in β winding produces a negative flux linkage in the q axis winding and vice versa.

$$V_{qs} = R_q i_{qs} + pL_s i_{qs}+ p\ (0*i_{ds}) + pL_{sr}\, sin\theta_r i_{\alpha}+ p(-L_{sr})cos\theta_r i_{\beta} \quad (25)$$

$$V_{qs} = (R_q + pL_s)i_{qs}+ pL_{sr}sin\theta_r i_{\alpha} - pL_{sr}cos\theta_r i_{\beta} \quad (26)$$

$$V_{ds} = R_d i_{ds}+ p\ (0*i_{qs}) + pL_s i_{ds} + pL_{sr}cos\theta_r i_{\alpha}+ pL_{sr}sin\theta_r i_{\beta} \quad (27)$$

$$V_{ds} = (R_d+ pL_s)i_{ds} + pL_{sr}cos\theta_r i_{\alpha}+ pL_{sr}sin\theta_r i_{\beta} \quad (28)$$

$$V_{\alpha} = R_{\alpha}i_{\alpha} + pL_{sr}sin\theta_r\, i_{qs}+ pL_{sr}\, cos\theta_r i_{ds}+ pL_{rr}i_{\alpha} + p(0*i_{\beta}) \quad (29)$$

$$V_{\alpha} = (R_{\alpha}+ p\ L_{rr})i_{\alpha} + pL_{sr}sin\theta_r\, i_{qs}) + pL_{sr}\, cos\theta_r i_{ds} \quad (30)$$

$$V_{\beta} = R_{\beta}i_{\beta} + p\ (-L_{sr)\ cos\theta riqs}+ pL_{sr}\, sin\theta_r i_{ds} + p(0*i_{\alpha}) + pL_{rr}i_{\beta} \quad (31)$$

$$V_{\beta} = (R_{\beta} +pL_{rr})i_{\beta} -pL_{sr}\, (cos\theta_r i_{qs}) + pL_{sr}\, (sin\theta_r i_{ds}) \quad (32)$$

Assuming,

$$R_s=R_q=R_d \quad (33)$$

$$R_{rr}=R_{\alpha}=R_{\beta} \quad (34)$$

Therefore we have,

$$V_{qs} = (R_s + pL_s)i_{qs}+ pL_{sr}sin\theta_r i_{\alpha} - pL_{sr}\, cos\theta_r i_{\beta} \quad (35)$$

$$V_{ds} = (R_s+ pL_s)i_{ds} + pL_{sr}\, cos\theta ri_{\alpha} + pL_{sr}\, sin\theta_r i_{\beta} \quad (36)$$

$$V_{\alpha} = (R_{rr}+ pL_{rr})i_{\alpha} + pL_{sr}sin\theta_r\, i_{qs} + pL_{sr}\, cos\theta_r i_{ds} \quad (37)$$

$$V_{\beta} = (R_{rr} +pL_{rr})i_{\beta} -pL_{sr}\, cos\theta_r i_{qs} + pL_{sr}\, sin\theta_r i_{ds} \quad (38)$$

A. Three phase to two phase transformation

The dynamic model for the three phase induction machine can be derived from the two phase machine if the equivalence between three and two phases is established. The equivalence is based on the equality of the mmf produced in the two – phase windings and equal current magnitudes. Assuming that each of the three phase windings has T1 turns per phase and equal current magnitudes, the two phase windings will have 3/2 T1 turns per phase for mmf equality. The d and q axes mmfs are formed by resolving the mmfs of the three phases along the d and q axes.

The q axis is assumed to be lagging the a axis by θ_c. The relation between the dqo and abc currents is as follows

$$\begin{bmatrix} i_{qs} \\ i_{ds} \\ i_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} Cos\theta_c & Cos\left(\theta_c - \frac{2\pi}{3}\right) & Cos\left(\theta_c + \frac{2\pi}{3}\right) \\ Sin\theta_c & Sin\left(\theta_c - \frac{2\pi}{3}\right) & Sin\left(\theta_c + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (39)$$

The current i_o represents the imbalances in the a, b and c phase currents and can be recognized as the zero sequence component of the current and is given as follows:

$$i_o = \frac{1}{3}\left[i_{as} + i_{bs} + i_{cs}\right] \quad (40)$$

In a balanced three phase machine, the sum of the three phase currents is zero and is given as:

$$i_{as} + i_{bs} + i_{cs} = 0 \quad (41)$$

Therefore under balanced conditions, we have

$$i_o = \frac{1}{3}\left[i_{as} + i_{bs} + i_{cs}\right] \quad (42)$$

Where

$$i_{qdo} = \left[T_{abc}\right] i_{abc} \quad (43)$$

$$i_{qdo} = \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_o \end{bmatrix} \quad (44)$$

$$i_{abc} = \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \quad (45)$$

And the transformation from abc to dqo variables is

$$\left[T_{abc}\right] = \frac{2}{3}\begin{bmatrix} Cos\theta_c & Cos\left(\theta_c - \frac{2\pi}{3}\right) & Cos\left(\theta_c + \frac{2\pi}{3}\right) \\ Sin\theta_c & Sin\left(\theta_c - \frac{2\pi}{3}\right) & Sin\left(\theta_c + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (46)$$

The zero – sequence current, i_o, does not produce a resultant magnetic field.

The transformation from two – phase currents to three – phase currents can be obtained as

$$i_{abc} = \left[T_{abc}\right]^{-1} i_{dqo} \quad (47)$$

This transformation[4] could also be thought of as a transformation from three (*abc*) axes to three new (*dqo)* axes. Under balanced conditions only; there are four system equations given in equation. Under balanced conditions there are two more equations one for the stator zero sequence voltage and other for the rotor zero sequence voltage.

$$\begin{aligned} v_{os} &= R_s + pL_{ls}i_{os} \\ v_{or} &= R_r + pL_{lr}i_{or} \end{aligned} \quad (48)$$

Where in the variables the first subscript denotes the zero sequence components and the second subscript denotes the stator(s) and rotor(r). Only leakage inductances and phase resistances influence the zero sequence voltages and currents. It is usual to align the q axis with the phase a winding; this implies that the qd frames are fixed to the stator. The model is known as Stanley's model or the stator reference frame model.

$$T_{ab}^{s} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (49)$$

B. Derivation of commonly used induction motor models

There are three particular cases of the generalized model of the induction motor in arbitrary reference frames and they are given as below:

- Stator reference frames model,
- Rotor reference frames model,
- Synchronously rotating reference frames model.

C. Stator reference frames model

The speed of the reference frames is that of the stator, which is zero.

Therefore $\omega_c = 0$

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & 0 & pL_m & 0 \\ 0 & R_s + pL_s & 0 & pL_m \\ pL_m & -\omega_r L_m & R_r + pL_r & -\omega_r L_r \\ \omega_r L_m & pL_m & \omega_r L_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (50)$$

For convenience the superscript is omitted for the stator reference frames model.

The torque equation is,

$$T_e = \frac{3}{2}\frac{P}{2} L_m \left[i_{qs} i_{dr} - i_{ds} i_{qr} \right] \quad (51)$$

D. Rotor reference frames model

The speed of the rotor reference frames is

$$\omega_c = \omega_r \quad (52)$$

And the angular position is

$$\theta_c = \theta_r \quad (53)$$

Electromagnetic torque is given by,

$$T_e = \frac{3}{2}\frac{P}{2} L_m \left[i^r_{qs} i^r_{dr} - i^r_{ds} i^r_{qr} \right] \quad (54)$$

The transformation from *abc* to *dqo* variables is obtained, Therefore,

$$\left[T^r_{abc} \right] = \frac{2}{3} \begin{bmatrix} Cos\theta_r & Cos\left(\theta_r - \frac{2\pi}{3}\right) & Cos\left(\theta_r + \frac{2\pi}{3}\right) \\ Sin\theta_r & Sin\left(\theta_r - \frac{2\pi}{3}\right) & Sin\left(\theta_r + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (55)$$

The rotor reference frames model is useful where switching elements and power are controlled on the rotor side.

E. Synchronously rotating reference frames model

The speed of the reference frames is

$\omega_c = \omega_s =$ Stator supply angular frequency rad/sec.

And the instantaneous angular position is

$$\theta_c = \theta_s = \omega_s t$$

$$\begin{bmatrix} v^e_{qs} \\ v^e_{ds} \\ v^e_{qr} \\ v^e_{dr} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & \omega_s L_s & pL_m & \omega_s L_m \\ -\omega_s L_s & R_s + pL_s & -\omega_s L_m & pL_m \\ pL_m & (\omega_s - \omega_r) L_m & R_r + pL_r & (\omega_s - \omega_r) L_r \\ -(\omega_s - \omega_r) L_m & pL_m & -(\omega_s - \omega_r) L_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} i^e_{qs} \\ i^e_{ds} \\ i^e_{qr} \\ i^e_{dr} \end{bmatrix} \quad (56)$$

The electromagnetic torque is,

$$T_e = \frac{3}{2}\frac{P}{2} L_m \left[i^e_{qs} i^e_{dr} - i^e_{ds} i^e_{qr} \right] \quad (57)$$

The transformation from *abc* to *dqo* variables is found by,

$$\left[T^e_{abc} \right] = \frac{2}{3} \begin{bmatrix} Cos\theta_s & Cos\left(\theta_s - \frac{2\pi}{3}\right) & Cos\left(\theta_s + \frac{2\pi}{3}\right) \\ Sin\theta_s & Sin\left(\theta_s - \frac{2\pi}{3}\right) & Sin\left(\theta_s + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (58)$$

It may be seen that the synchronous reference frames transform the sinusoidal inputs into dc signals[5]. This model is useful where the variables in steady state need to be dc quantities, as in the development of small – signal equations. Some high – performance control schemes use this model to estimate the control input; this led to a major breakthrough in induction – motor control by decoupling the torque and flux channels for control in a manner similar to that for separately excited dc motor drives.

F. Dynamic simulation flowchart

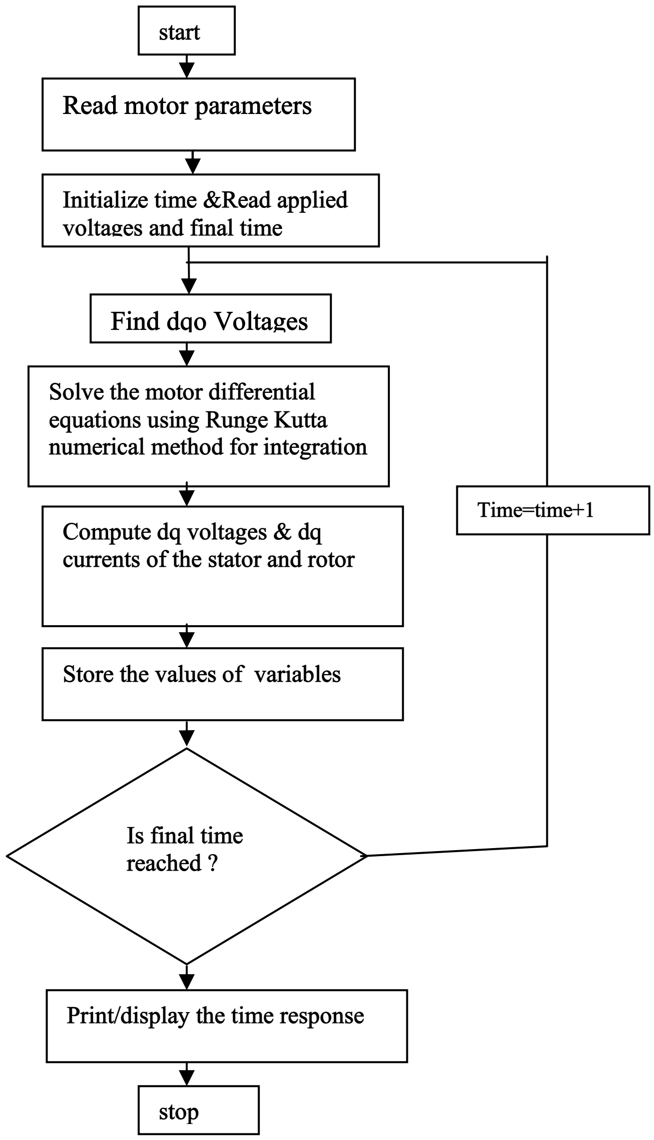

Figure 2: Flowchart for the dynamic simulation of an Induction motor

G. Flow chart for the computation of transfer function and plotting of root locus.

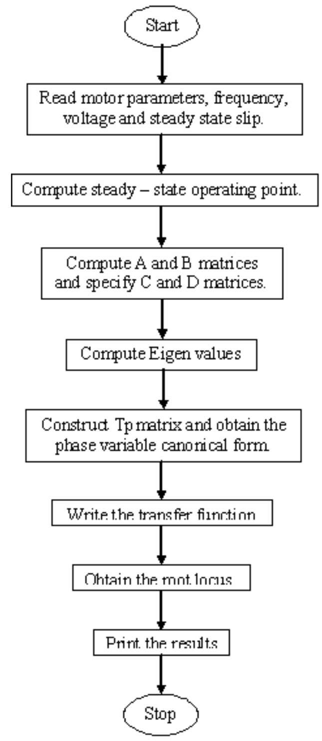

Figure 3: Flowchart for the computation of transfer function

4 Implementation of Vector Control Scheme

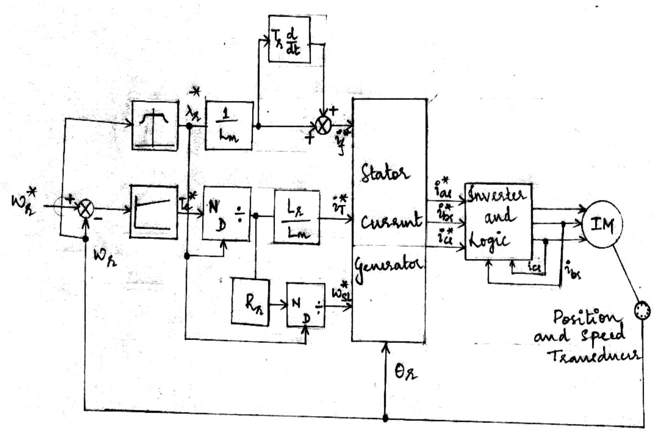

Figure 4: The implementation of vector control scheme

5 Speed Controller Design for Vector Controlled Drive

An implementation of vector – controlled induction motor is shown in Fig. 4. The torque command is generated as a function of the speed error signal, generally processed through a PI controller. The flux command[2] for a simple drive strategy is made to be a function of speed, defined by

$$\lambda_r^* = \lambda_b ; 0 \le \pm\omega_r \le \pm\omega_{rated}$$

$$= \frac{\omega_b}{|\omega_r|}\lambda_b ; \pm\omega_b \le \pm\omega_r \le \pm\omega_{r(\max)} \, and \, |\omega_r| \ge \omega_b \quad (59)$$

Where λ_b and ω_b are the rated or base rotor flux linkages and rotor speed, respectively. The flux is kept at rated value up to rated speed; above that, the flux is weakened to maintain the power output at a constant, very much as in the DC motor drive. In such a case, the rotor flux linkages programming is complex task. The three – phase stator current commands are generated. These commands are simplified through a power amplifier, which can be any standard converter – inverter arrangement.

The rotor position, θ_r, is measured with an encoder/ synchronous resolver converted into necessary digital information for feedback. Some transducers are currently available to convert the rotor position information into velocity; they can be used to eliminate a tachogenerator to obtain the velocity information. The controllers are implemented with microprocessors.

6 Simulation Studies and Experimental Results

Simulation studies presented in this section are obtained using MATLAB/SIMULINK simulation package.

Experimental results are obtained for the laboratory model of the following specification: 3.7KW, 4 pole, 415V, 7.5A, 50Hz., 1430 rpm ,3Ph, Cage rotor.

Stator Resistance : 1.115Ω
Stator Inductance : 0.005974H
Rotor Resistance :1.083 Ω
Rotor Inductance :0.005974
Mutual Inductance : 0.2037H
Inertia : 0.02 Kg m^2
Friction Factor : 0.05752 N.m.s

Fig. 5 to Fig.10 shows various characteristics of the above model

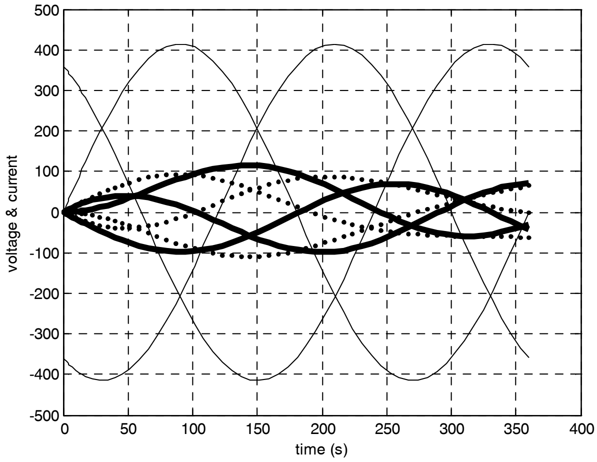

Figure 5: Stator and rotor voltages and currents in the stationary frame

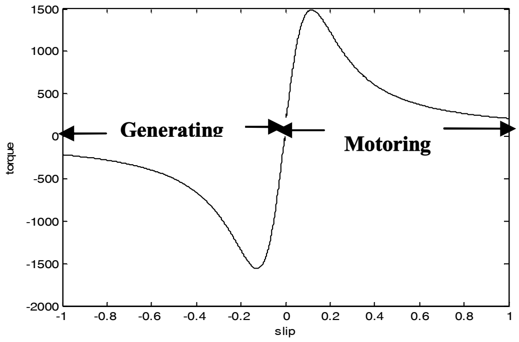

Figure 6: Generation & Braking Characteristics of Induction Motor

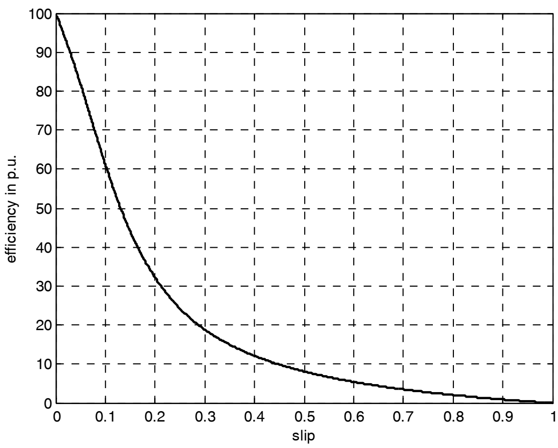

Figure 7: Efficiency Vs. Slip

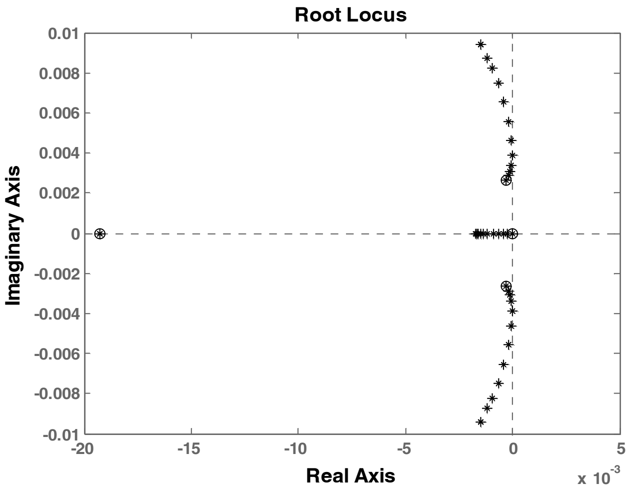

Figure 8: Root Loci in the space phasor Induction machine Model

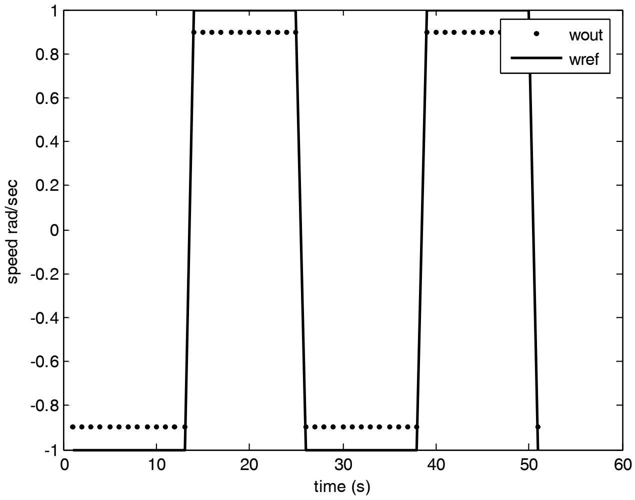

Figure 9: Output characteristics for a speed controller

7 Conclusion

With the dynamic and steady state analysis the operating stability of an induction motor can be obtained. Hence we can decide that for the given parameters the operation of the Induction Motor is

1. Stable or not
2. If not by designing the proper controllers operation can be made stable under dynamic conditions
3. Simulations is carried out on 3 Phase Induction motor

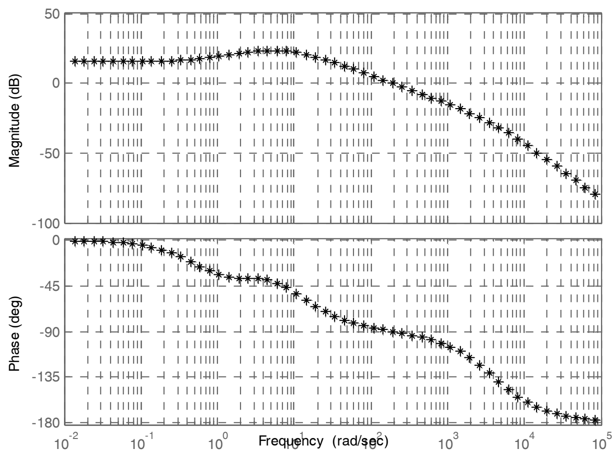

Figure 10: Frequency Response of a complete simplified current Loop

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