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Stability Analysis of Three Phase Induction Motor Drive Using Different Stability Criteria

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ABSTRACT
In this paper stability analysis of three phase induction motor drive is carried out using different stability criteria of control system. The mathematical model of motor is described by different differential equations. One of the major goal of this paper is to derive the mathematical equations of motor by describing the dynamics of the drive under sudden change of load. This model is developed in direct-quadrature axes using two phase motor. The mathematical equations which are developed with the help of this model are non-linear in nature. With the help of perturbation technique, these equations are linearized around an operating point. Based on different input-output combinations a number of transfer functions are obtained. In this paper the transfer function between T_e (proportional to ω_r) and ω_s is developed and the stability analysis is carried out using this transfer function. MATLAB codes are used to carryout this analysis.
KEYWORDS: Stability, Transfer Function, Three Phase Induction Motor, MATLAB Codes, Mathematical Model
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I. INTRODUCTION

In the late 19th century, the induction motor was invented. During this period the principle of electromagnetic induction and rotating magnetic field was discovered [16,5,4,15,14,10]. The phenomenon of rotating magnetism was discovered by French physicist D.F. Arago in 1824. The phenomenon was further elaborated on the basis of induced currents by M. Faraday in 1831. In 1879 W. Baily developed a motor; the rotating magnet was replaced by a rotating magnetic field, generated by alternative switching of four pole pieces to d.c. supply. In 1888, N. Tesla and G. Ferraris [17,9] introduced a rotating magnetic field produced by an alternating two phase current in stationary winding of stator. The analysis of stability is one of the major technological challenges in the design of electrical motors. Stability of the motor means the ability of the motor to regain a steady state after disturbances of the initial mode such as a change of supply voltage, change of the load etc. Stability is a major qualitative characteristic of a motor, providing the reliability of the work. Steady state stability is a necessary condition for the proper operation of the drive. The dynamic model of the motor drive is derived by using a two-phase motor in direct-quadrature axes for stability analysis. The conceptually simple and desirable approach is obtained with the help of two sets of windings of the motor. This two phase machine model can be extended to n-phase machine model suitably. The power ratings of the three phase and equivalent two phase motor model should be the same.

Stability analysis of rectifier-inverter induction motor was carried out by Lipo and Crause [12]. Neglecting the effect of harmonics, Fall side and Wortley [8] has tested the non stability of induction motor driven by variable frequency inverter. Root locus criteria are applied to carry out the stability study on a symmetrical induction machine [13]. Based on transfer technique Cornel and Lipo [7] has carried out the stability study on controlled current induction motor drive system. The different mathematical models developed by researchers are based on voltage-current relationship. The voltage and flux linkage model of three phase and five phase induction motor drive is developed [1,2,3] and the transfer function approach is utilized to carry out the stability analysis. The dynamic model of three-phase induction motor drive is developed [6,11]. The transfer function between electromagnetic torque and stator speed so developed is applied to analyze the stability of the motor drive.

II. MODEL OF INDUCTION MOTOR

The synchronous reference frame model is applied in the analysis of the three-phase induction motor drive. This frame is taken as a starting point. The dynamic equations of the induction motor in arbitrary reference frames can be presented by using flux-linkages as variables. This involves the

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reduction of a number of variables in the dynamic equations. Which ultimately facilitates their solution by using analogue and digital computers? When the voltages and currents are discontinuous, the flux - linkages are continuous. This gives the benefit of differentiating these variables with numerical stability. Further, the flux linkages representation is used in motor drives to highlight the decoupling process of flux and torque channels in the induction and synchronous machines.

The stator and rotor flux linkages in the arbitrary reference frame are defined as

$\psi_{qs} = L_s.I_{qs}+L_mI_{qr}$ (1) $\psi_{ds} = L_s.I_{ds}+L_mI_{dr}$ (2)

$\psi_{qr} = L_rI_{qr}+L_mI_{qs}$ (3) $\psi_{dr} = L_rI_{dr}+L_mI_{ds}$ (4)

The zero sequence flux linkages are

$\psi_{os} = L_{ls}I_{os}$ (5) $\psi_{or} = L_{lr}I_{or}$ (6)

The quadrature axis stator voltage in the arbitrary reference frame is

$$V_{qs}= R_s.I_{qs}+\omega_r(L_s.I_{ds}+L_mI_{dr})+L_m\, p\, I_{qr}+L_s\, p\, I_{qs} \quad (7)$$

By substituting the defined flux linkages into the voltage equations results

$$V_{qs}= R_s.I_{qs}+ \omega_r \psi_{ds} + p\, \psi_{qs} \quad (8)$$

These equations can be represented in equivalent circuits. The mathematical relationship between electromagnetic torque and flux linkages is given by

$$T_e = P\,(\psi_{qs}\psi_{dr} - \psi_{ds}\psi_{qr}) \quad (9)$$

The rotor currents can be substituted in terms of the stator currents and stator flux linkages as:

$\psi_{ds} = L_s.I_{ds}+L_mI_{dr}$ Hence $(\psi_{ds} - L_sI_{ds})=L_mI_dr$ (10)

Similarly

$$(\psi_{qs} - L_s.I_{qs})=L_mI_{qr} \quad (11)$$

Using above equations, we can get the torque in stator flux-linkages and currents as

$$T_e = (3/2)\,.\,(P/2)\,.\,(I_{qs}.\psi_{ds} - I_{ds}.\psi_{qs}) \quad (12)$$

The relation between voltage and flux Linkages can be expressed by the currents in terms of flux-linkages. To derive the relation, voltages, currents and flux linkages vectors are specified in an arbitrary reference frame. The voltage- current relation is expressed by

$$\begin{pmatrix} V^e_{qs} \\ V^e_{ds} \\ V^e_{qr} \\ V^e_{dr} \end{pmatrix} = \begin{pmatrix} R_S+L_Sp & \omega_s L_s & L_m p & \omega_s L_m \\ \omega_s L_s & R_S+L_Sp & -\omega_s L_m & L_m p \\ -L_m p & (\omega_s-\omega_r)L_m & R_r+L_r p & (\omega_s-\omega_r)L_r \\ -(\omega_s-\omega_r)L_m & -L_m p & (\omega_s-\omega_r)L_r & R_r+L_r p \end{pmatrix} \begin{pmatrix} I^e_{qs} \\ I^e_{ds} \\ I^e_{qr} \\ I^e_{dr} \end{pmatrix} \quad (13)$$

the relation between flux linkage and the current is calculated by

$$\begin{pmatrix} \psi^e_{qs} \\ \psi^e_{ds} \\ \psi^e_{qr} \\ \psi^e_{dr} \end{pmatrix} = \begin{pmatrix} L_s & 0 & L_m & 0 \\ 0 & Ls & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{pmatrix} \begin{pmatrix} I^e_{qs} \\ I^e_{ds} \\ I^e_{qr} \\ I^e_{dr} \end{pmatrix} \quad (14)$$

After further simplification gives the relationship between voltage and flux as:

$$\begin{pmatrix} V^e_{qs} \\ V^e_{ds} \\ V^e_{qr} \\ V^e_{dr} \end{pmatrix} = \begin{pmatrix} R_S.L_r/D+p & \omega_e & -L_m R_s/D & 0 \\ -\omega_s & R_S L_r/D+p & 0 & -R_s L_m/D \\ -R_r L_m/D & 0 & R_r.L_s/D+p & (\omega_s-\omega_r) \\ 0 & -R_r L_m/D & -(\omega_s-\omega_r) & R_r L_s/D+p \end{pmatrix} \begin{pmatrix} \psi^e_{qs} \\ \psi^e_{ds} \\ \psi^e_{qr} \\ \psi^e_{dr} \end{pmatrix} \quad (15)$$

Where $D = L_sL_r-L_m^2$.

Which is the required relation between the flux-linkage vector and the applied voltage across the induction motor expressed in the d-q axis form.

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III. LINEARIZATION OF THE MODEL.

The control characteristics of an induction machine consist of its stability characteristics and time responses. The characteristic of the motor can be obtained by the determination of various transfer functions. The model of motor is developed in the state variable form. Additional subscript 'o' is added with the variables voltages, currents, flux linkages, torque, stator frequency and rotor speed in their steady state. The perturbed increments are designated by a δ preceding the variables and used as coefficient. The drive variables after perturbation are defined as

$$v_{qs}^{e} = v_{qso}^{e} + \delta v_{qs}^{e} \qquad v_{ds}^{e} = v_{dso}^{e} + \delta v_{ds}^{e}$$

$$\psi_{qs}^{e} = \psi_{qso}^{e} + \delta\psi_{qs}^{e} \qquad \psi_{ds}^{e} = \psi_{dso}^{e} + \delta\psi_{ds}^{e}$$

$$\psi_{qr}^{e} = \psi_{qro}^{e} + \delta\psi_{qr}^{e} \qquad \psi_{dr}^{e} = \psi_{dro}^{e} + \delta\psi_{dr}^{e}$$

$$T_e = T_{eo} + \delta T_e \qquad \omega_s = \omega_{so} + \delta\omega_s$$

$$\omega_r = \omega_{ro} + \delta\omega_r$$

The q-d-axis stator voltage in synchronous frame is calculated as

$$\begin{bmatrix} v_{qso}^{e} \\ v_{dso}^{e} \\ v_{o}^{e} \end{bmatrix} = [A_s] \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \tag{16}$$

Where, A_s is the transformation matrix from abc to qdo frame

$$[A_s] = \frac{2}{3}\begin{bmatrix} \cos(\theta_c) & \cos(\theta_c - \frac{2\pi}{3}) & \cos(\theta_c + \frac{2\pi}{3}) \\ \sin(\theta_c) & \sin(\theta_c - \frac{2\pi}{3}) & \sin(\theta_c + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{17}$$

θ_c=angle between q-axis and d-axis

Therefore,

$$\begin{bmatrix} v_{qso}^{e} \\ v_{dso}^{e} \\ v_{o}^{e} \end{bmatrix} = \begin{bmatrix} 0 \\ \sqrt{2}V \\ 0 \end{bmatrix}; \ note: \frac{2}{3} * \frac{3}{2} * \sqrt{2}V = \sqrt{2}V \tag{18}$$

The mathematical relations of perturbed voltage and flux-linkage vectors is given below
The standard voltage equations in dqo frame;

$$\overline{\delta V} = \left[\delta v_{qs}^{e} \quad \delta v_{ds}^{e} \quad \delta v_{qr}^{e} \quad \delta v_{dr}^{e}\right]$$

$$\overline{\delta\psi} = \left[\delta\psi_{qs}^{e} \quad \delta\psi_{ds}^{e} \quad \delta\psi_{qr}^{e} \quad \delta\psi_{dr}^{e}\right] \tag{19}$$

$$V_{qs} = (R_s L_r / D + .)\psi_{qs} + \omega_{so}.\psi_{ds} - R_s L_m / D.\psi_{qr}$$

$$V_{ds} = -\omega_{so}.\psi_{qs} + (R_s L_r / D + p)\psi_{ds} - R_s L_m / D.\psi_{dr}$$

$$V_{qr} = -RrL_m / D.\psi_{qs} + (R_r L_s / D + p)\psi_{qr} + (\omega_{slo} - \omega_r).\psi_{dr}$$

$$V_{dr} = -R_r L_m / D.\psi_{ds} - (\omega_{slo} - \omega_r).\psi_{qr} + (R_r L_s / D + p)\psi_{dr} \tag{20}$$

Therefore $[\overline{V}] = [\overline{Z}][\psi]$

The matrix $[\overline{Z}]$ in synchronous reference frame is;

Note: In synchronous reference frame the term $p = \frac{d}{dt}$;

$$[\overline{Z}] = \begin{bmatrix} R_s.L_r / D + p & \omega_{so} & -R_s L_m / D & 0 \\ -\omega_{so} & R_s.L_r / D + p & 0 & -R_s L_m / D \\ -R_r.L_m / D & 0 & R_r L_s / D + p & (\omega_{slo} - \omega_r) \\ 0 & -R_r L_m / D & -(\omega_{slo} - \omega_r) & R_r.Ls / D + p \end{bmatrix} \tag{21}$$

R_s, R_r are stator and rotor resistances, L_s, L_r are stator and rotor inductances and L_m the magnetizing inductance.

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$$[\overline{V}] = [0 \quad v^e_{dso} \quad 0 \quad 0] \tag{22}$$

The flux-linkage matrix in synchronous reference frame;

$$[\overline{\psi}] = [\overline{Z}]^{-1} * [\overline{V}] \tag{23}$$

Where

$$[\overline{\psi}] = \begin{bmatrix} \psi^e_{qso} \\ \psi^e_{dso} \\ \psi^e_{qro} \\ \psi^e_{dro} \end{bmatrix} \tag{24}$$

The steady state torque is given by

$$T_{eo} = 3/2 * P/2 * L_m / D * (\psi^e_{qso} * \psi^e_{dro} - \psi^e_{dso} * \psi^e_{qro}) \tag{25}$$

Application of perturbation technique gives the following equations

$$\left(V^e_{qso} + \delta.V^e_{qs}\right) = \left(R_s.L_r / D + p\right).\left(\psi^e_{qso} + \psi i^e_{qs}\right) + \omega_{so}.\left(\psi^e_{dso} + \delta\psi^e_{ds}\right) - L_m.R_s / D\left(\psi^e_{qro} + \delta\psi^e_{qr}\right)$$

Simplifying we get;

$$\delta V^e_{qs} = \left(R_s L_r / D. + p\right)\delta i^e_{qs} + \omega_{so}.\delta\psi^e_{ds} - R_s L_m / D.\delta\psi^e_{qr} + \left(.\psi^e_{dso}\right)\delta\omega_s$$

$$\delta V^e_{ds} = -\omega_{so}.\delta\psi^e_{qs} + \left(R_s L_r / D + p\right)\delta\psi^e_{ds} - R_s L_m / D.\delta\psi^e_{dr} - \left(.\psi^e_{qso}\right)\delta\omega_s$$

$$\delta V^e_{qr} = -R_r L_m / D.\delta\psi^e_{qs} + \left(R_r L_s / D + .p\right)\delta\psi^e_{qr} + \omega_{slo}.\delta\psi^e_{dr} - \left(.\psi^e_{dro}\right)\delta\omega_r + \left(.\psi^e_{dro}\right)\delta\omega_s$$

$$\delta V^e_{dr} = -R_r L_m / D.\delta\psi^e_{ds} - \omega_{slo}\delta\psi^e_{qr} + \left(R_r L_s / D + p\right)\delta\psi^e_{dr} + \left(\psi^e_{qro}\right)\delta\omega_r - \left(\psi^e_{qro}\right)\delta\omega_s$$

$$Now, J.p.\delta\omega_r + B\delta\omega_r = \frac{P}{2}\left(\delta T_e - \delta T_l\right)$$

$$\delta T_e = 3/2 * P./2 * L_m / D\left(\psi^e_{qso}.\delta\psi^e_{dr} + \psi^e_{dro}.\delta\psi^e_{qs} - \psi^e_{dso}.\delta\psi^e_{qr} - \psi^e_{qro}.\delta\psi^e_{ds}\right)$$

Therefore

$$[\overline{R_1}] \quad [\overline{U}] = [\overline{K}] \quad [\overline{X}]$$

Where;

$$[\overline{X}] = \left[\delta\psi^e_{qs} \quad \delta i\,\psi^e_{ds} \quad \delta\psi^e_{qr} \quad \delta\psi^e_{dr} \quad \delta\omega_r\right]$$

$$[\overline{U}] = \left[\delta v^e_{qs} \quad \delta v^e_{ds} \quad \delta v^e_{qr} \quad \delta v^e_{dr} \quad \delta\omega_s \quad \delta T_L\right] \tag{26}$$

$$[\overline{K}] = \begin{bmatrix} p + R_s L_r / D & \omega_{so} & -R_s L_m / D & 0 & 0 \\ -\omega_{so} & p + R_s L_r / D & 0 & -R_s L_m / D & 0 \\ -R_r L_m / D & 0 & p + R_r L_s / D & \omega_{slo} & -C3 \\ 0 & -R_r L_m / D & -\omega_{slo} & p + R_r L_s / D & C4 \\ -k1 * \psi^e_{dro} & k1 * \psi^e_{qro} & k1 * \psi^e_{dso} & -k1 * \psi^e_{qso} & pJ + B \end{bmatrix} \tag{27}$$

$$[\overline{K}] = \left(p[\overline{P_1}] - [\overline{Q}]\right)$$

$$[\overline{P_1}] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad \& \quad [\overline{Q}] = \begin{bmatrix} -R_s L_r / D & -\omega_{so} & R_s L_m / D & 0 & 0 \\ \omega_{so} & -R_s L_r / D & 0 & R_s L_m / D & 0 \\ R_r L_m / D & 0 & -R_r L_s / D & -\omega_{slo} & C3 \\ 0 & R_r L_m / D & \omega_{slo} & -R_r L_s / D & -C4 \\ k1 * \psi^e_{dro} & -k1 * \psi^e_{qro} & -k1 * \psi^e_{dso} & k1 * \psi^e_{qso} & -B \end{bmatrix}$$

The system matrix is given below,

$$p[\overline{P_1}] * [\overline{X}] = [\overline{Q}] * [\overline{X}] + [\overline{R_1}] * [\overline{U}]$$

Where

$$[\overline{R_1}] = \begin{bmatrix} 1 & 0 & 0 & 0 & -C_1 & 0 \\ 0 & 1 & 0 & 0 & C_2 & 0 \\ 0 & 0 & 1 & 0 & -C_3 & 0 \\ 0 & 0 & 0 & 1 & C_4 & 0 \\ 0 & 0 & 0 & 0 & 0 & -P/2 \end{bmatrix}$$

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$$C_1 = \psi^e_{dso} \qquad C_2 = \psi^e_{qso}$$
$$C_3 = \psi^e_{dro} \qquad C_4 = \psi^e_{qro}$$
$$k1 = (P)^2 * L_m \tag{28}$$

The system matrix can be written as;

$$p[\overline{X}] = [\overline{A}][\overline{X}] + [\overline{B}][\overline{U}].$$

Where,

$$[\overline{A}] = [\overline{P_1}]^{-1} * [\overline{Q}]$$
$$[\overline{B}] = [\overline{P_1}]^{-1} * [\overline{R_1}]$$

$\delta V_{dso}, \delta\omega_s$ and δT_L terms represents 2nd, 5th and 6th column of matrix $[R_1]$. The other input voltages are zero. Incremental currents, torque and speed are the output variables of the motor. The response of the drive due to changes in parameter such as voltage, load torque and synchronous speed is calculated. At a time one quantity is considered to determine the response. The incremental flux linkage, torque, & rotor speed vectors are;

$$\begin{aligned}
[\overline{\delta\psi^e_{qso}}] &= [\overline{C}][\overline{X}] = [1 \quad 0 \quad 0 \quad 0 \quad 0][\overline{X}] \\
[\overline{\delta\psi^e_{dso}}] &= [\overline{C}][\overline{X}] = [0 \quad 1 \quad 0 \quad 0 \quad 0][\overline{X}] \\
[\overline{\delta\psi^e_{qro}}] &= [\overline{C}][\overline{X}] = [0 \quad 0 \quad 1 \quad 0 \quad 0][\overline{X}] \\
[\overline{\delta\psi^e_{dro}}] &= [\overline{C}][\overline{X}] = [0 \quad 0 \quad 0 \quad 1 \quad 0][\overline{X}] \\
\delta T_e &= [\overline{C}][\overline{X}] = [k2*\psi^e_{dro} \quad -k2*\psi^e_{qro} \quad -k2*\psi^e_{dso} \quad k2*\psi^e_{qso} \quad 0][\overline{X}] \\
\delta\omega_r &= [\overline{C}][\overline{X}] = [0 \quad 0 \quad 0 \quad 0 \quad 1][\overline{X}]
\end{aligned} \tag{29}$$

Where, $k_2 = P*L_m$

The evaluation of transfer function is made simple if the canonical or phase variable form of the state equation $p\vec{X} = \vec{A}*\vec{X} + b_i u_i$ is found. This is done with the following transformation,

$$\vec{X} = \vec{T_p} * \vec{X_p} \tag{30}$$

Then the state and output equations are transformed to

$$\begin{aligned}
p\vec{X_p} &= \vec{A_p} * \vec{X_p} + \vec{B_p} * u_i \\
y &= \vec{C_p} * \vec{X_p} + d_i * u_i
\end{aligned} \tag{31}$$

Where

$$\begin{aligned}
\vec{A_p} &= (\vec{T_p})^{-1} * \vec{A} * \vec{T_p} \\
\vec{B_p} &= (\vec{T_p})^{-1} * b_i \\
\vec{C_p} &= \vec{C} * \vec{T_p}
\end{aligned} \tag{32}$$

These matrices and vectors are of the form

$$\vec{A_p} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ -m_1 & -m_2 & -m_3 & -m_4 & -m_5 \end{bmatrix} \tag{33}$$

$$\begin{aligned}
\vec{B_p} &= [0 \quad 0 \quad 0 \quad 0 \quad 1] \\
\vec{C_p} &= [n_1 \quad n_2 \quad n_3 \quad n_4 \quad n_5]
\end{aligned} \tag{34}$$

And the transfer function by observation is written as

$$\frac{y(s)}{u_i(s)} = \frac{n_1 + n_2 s + n_3 s^2 + n_4 s^3 + n_5 s^4}{m_1 + m_2 s + m_3 s^2 + m_4 s^3 + m_5 s^4 + s^5} + d_i \tag{35}$$

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IV. TRANSFER FUNCTION OF THE MODEL

By changing output variables and input variables a number of transfer functions can be originated.

a. $\frac{\delta \omega r(s)}{\delta \omega_s(s)}$ b. $\frac{\delta T_e(s)}{\delta \omega_s(s)}$ c. $\frac{\delta T_e(s)}{\delta T_L(s)}$ d. $\frac{\delta \omega r(s)}{\delta V_S(s)}$

V Simulation Results

Simulation is done to investigate the transfer function $\frac{\delta T_e}{\delta \omega_s}$.

Transfer function (for $\mathbf{f_r}$**=50 Hz**)

13.07 s^4 + 3068 s^3 + 1.374e006 s^2 + 1.067e008 s + 1.313e007
-- --------------------------------
s^5 + 426 s^4 + 1.498e005 s^3 + 1.751e007 s^2 + 8.957e008 s + 1.736e010

Transfer function (for $\mathbf{f_r}$**=45 Hz**)

13.07 s^4 + 3068 s^3 + 1.373e006 s^2 + 1.205e008 s - 7.569e007
----
s^5 + 426 s^4 + 1.501e005 s^3 + 1.76e007 s^2 + 1.115e009 s + 1.005e010

Transfer function (for $\mathbf{f_r}$**=40 Hz**)

13.07 s^4 + 3068 s^3 + 1.372e006 s^2 + 1.343e008 s - 2.026e008
----
s^5 + 426 s^4 + 1.526e005 s^3 + 1.823e007 s^2 + 1.573e009 s + 2.518e009

Transfer function (for $\mathbf{f_r}$**=37 Hz**)

13.07 s^4 + 3068 s^3 + 1.372e006 s^2 + 1.427e008 s - 2.611e008
s^5 + 426 s^4 + 1.551e005 s^3 + 1.887e007 s^2 + 1.968e009 s - 9.138e008

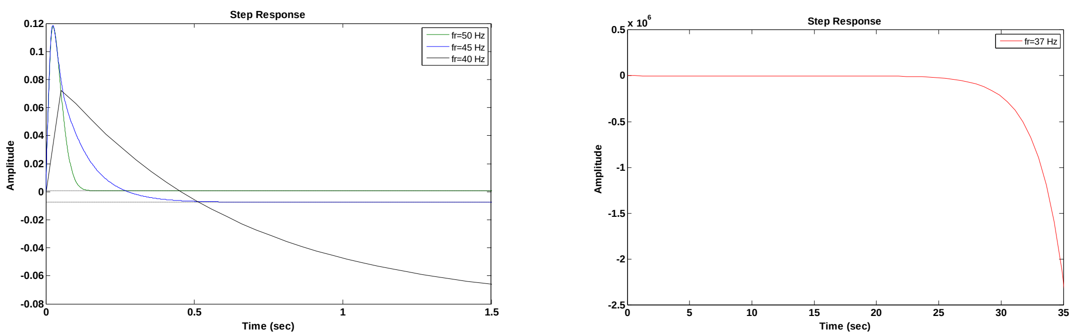
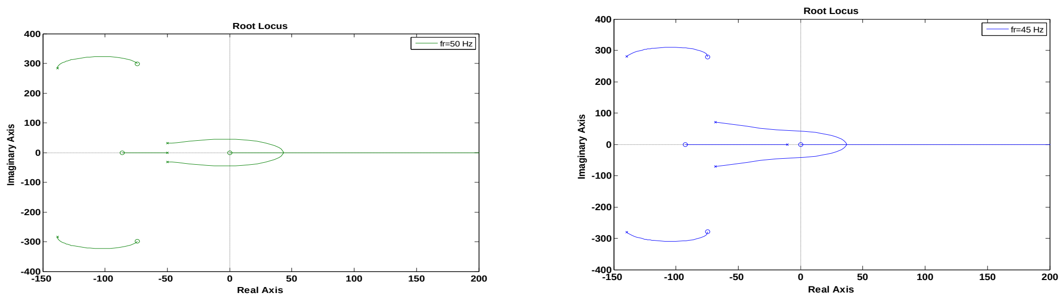


Fig 1 Step Response for the transfer function G(s) =(δTe/δω$_s$)



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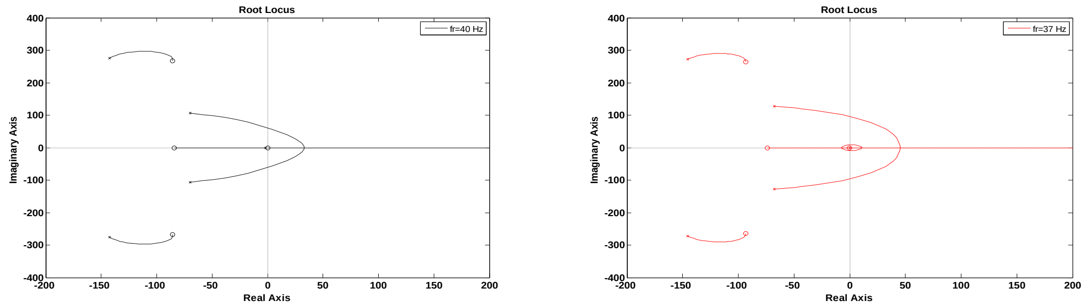

Fig 2 Root Locus diagram for the transfer function G(s) = $(\delta Te/\delta\omega_s)$

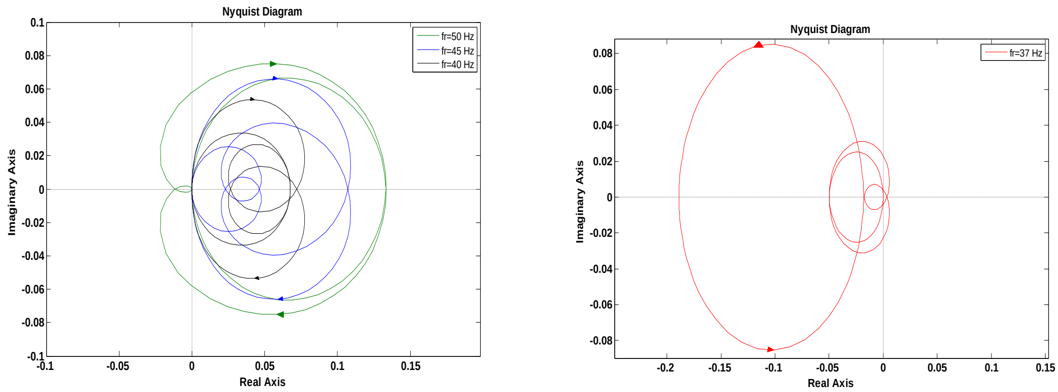

Fig 3 Nyquist diagram for the transfer function G(s) = $(\delta Te/\delta\omega_s)$

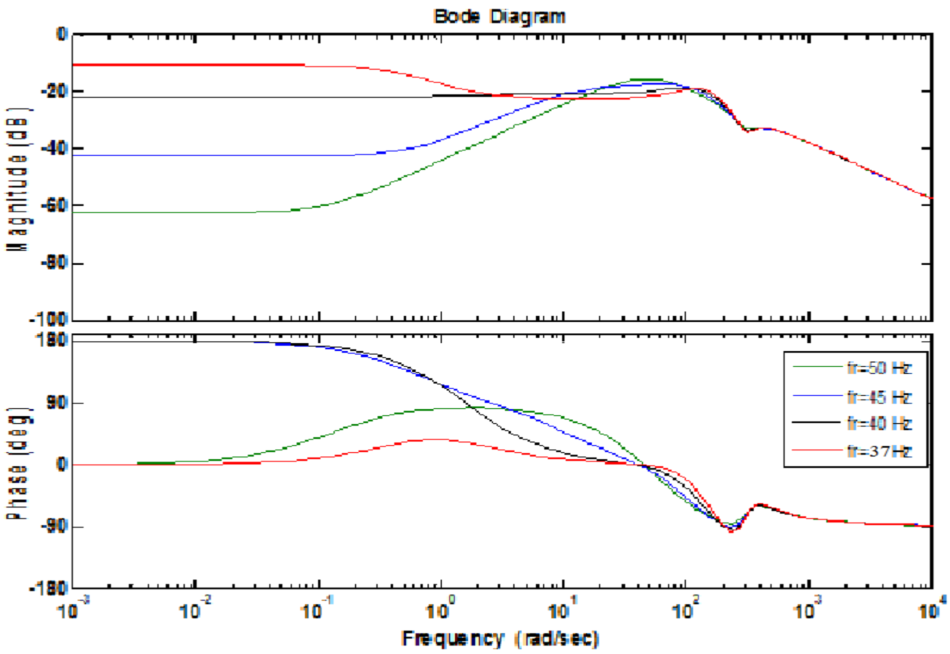

Fig 4 Bode diagram for the transfer function G(s) = $(\delta Te/\delta\omega_s)$

VI. DISCUSSION ON THE RESULTS

For f_r = 50 Hz

- **Step response-**this has been observed that observed that an incremental overshoot in electromagnetic torque has taken place. However, these responses settle to the original torque response.
- **Root locus diagram-**For all values of gain K, the roots lie to the L.H.S of s- plane so we can say that the machine is stable.

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- **Nyquist diagram-** In Nyquist plot at 40 Hz there is no pole in R.H.P. and no encirclement of (-1,0) so motor is closed loop stable.
- **Bode diagram-**Gain and phase margins are positive so machine is closed loop stable.

For f_r= 45 Hz

- **Step response-** In this case, the settling time is higher than the previous value and hence the relative stability decreases.
- **Root locus diagram-**For all values of gain K, the roots lie to the L.H.S of s- plane so we can say that the machine is stable.But the roots arerelatively to the right as compared to previous case ,so relative stability decreases.
- **Nyquist diagram-** P=0,N=0.So,Z=0.Hence there are no closed loop poles in the R.H.S. of s-plane.Therefore,machine is closed loop stable.But the separation between (-1,0) and the nyquist loop is more than previous case so gain margin decreases ,relative stability decreases.
- **Bode diagram-**Gain and phase margins are positive so machine is closed loop stable.But they are less as compared to previous case so relative stability decreases.

For f_r=40 Hz

Step response-for this value, the response first decreases and then moves to the original value response.However, this settling time is substainatially higher than the previous two cases and hence the relative stability decreases.

- **Root locus diagram-**For all values of gain K, the roots lie to the L.H.S of s- plane so we can say that the machine is stable.But the roots are relatively to the right as compared to previous two cases ,so relative stability decreases.
- **Nyquist diagram-** P=0,N=0.So,Z=0.Hence there are no closed loop poles in the R.H.S. of s-plane.Therefore,machine is closed loop stable.But the separation between (-1,0) and the nyquist loop is more than previous two cases so gain margin decreases,relative stability decreases.
- **Bode diagram-**Gain and phase margins are positive so machine is closed loop stable.

For f_r=37 Hz

- **Step response-**The electromagnetic torque abruptly decreases from its reference value i.e 0 and leads the system to **instability.**
- **Root locus diagram-**For all values of gain K, one root lies in the R.H.S of s- plane so we can say that the machine is **unstable..**
- **Nyquist diagram-** P=1,N=0 .So,Z=1.Hence there is a closed loop pole in the R.H.S. of s-plane.Therefore,motor is **not closed loop stable.**
- **Bode diagram-**Gain and phase margins are negative so machine is **not closed loop stable.**

VII. CONCLUSION

The discussion on the stability analysis of three phase induction motor drive is done in this paper. The mathematical equations obtained are non linear in nature. These equations are linearised using perturbation technique. The analysis is carried out using different stability criterion such as root locus, Nyquest plot and Bode plot. The Transfer function for between values of electromagnetic torque (proportional to rotor frequency and hence rotor speed) and stator speed is determined and the stability analysis is carried out. The rotor frequency is varied from 50 Hz to a value at which motor shows unstable operation. The response of the motor for different values is shown by the graphs shown in figure 1- 4. With this discussion it has been concluded that this drive shows stable operation for the rotor frequencies more than 37 Hz. The motor shows unstable operation for rotor frequency of 37 Hz. The results so reported are based on the voltage and flux linkage model of the motor drive.

APPENDIX

Rating and parameters of the three-phase induction motor	Ls	=	0.46H
Drive	Lr	=	0.46H
Three phase, 220 volts, 50 Hz, 4 pole	Lm	=	0.42H
Rs = 10 ohm	J	=	0.03kg-m^2
Rr = 6.3 ohm	B	=	0.0ms/rad

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