Modeling and Performance Analysis of Current Source Inverter Fed Induction Motor Drive

P. Satish Kumar and K. Satyanarayana

Abstract: **A dynamic model for current controlled induction motor drive is developed, and a time response approach for analyzing transient behavior is formulated by means of d-q variables in the synchronously rotating reference frame. A well damped closed loop response is possible if slip frequency and current magnitude control are imposed by proper tuning of control elements of PI controller.**

Key words: **Induction motor modeling, closed loop CSI, tuning of PI controller.**

I. Nomenclature

In general, subscripts have the following meaning

O	Steady state quantity as in I_{dro}^{1e}, d or q equivalent 2-phase transformed variable as in i_{ds}^{e} ,
b	base quantity as in ω_b
e	electrical quantity as in ω_e
F	smoothing choke parameter as in R_F^1
I	inverter quantity as in $V_{1,}$
M	mutual value as in x_m
l	leakage quantity,
r	rotor quantity as in x_r,
R	rectifier quantity as in V_R
s	stator quantity as in x_s,
sl	slip quantity as in $\omega_{sl.}$

Superscripts have the following meaning

*	command value as in ω_r * ,
,	rotor quantity referred to the stator or as noted in text,
e	quantities in synchronously rotating reference frame

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Variables have the following meaning

Δ	perturbation variable,
T	voltage regulator zero location,
ω	angular velocity,
V	dc voltage,
J	system inertia,
K_{sp}	speed regulator gain,
K_{sl}	slip channel gain,
K_C	compensator gain,
p	differential operator d/dt
P	machine poles,
Q	output of integral controller.

II. Introduction

A v/f controlled induction motor drive can exhibit self-sustained oscillations about a steady-state point[1]. These oscillations are actual instantaneous rotor speed changed caused by variations in out torque, motor current and input power. This paper presents an analytical design technique for finding the better performance by tuning the PI controller. The CSI is a very rugged supply capable of recovery from short circuits or commutation faults. It offers inherent over current protection when current feedback is used. It is a simple circuit when current feedback is used. It is a simple circuit which does not require fast turnoff thyristors. The CSI is capable of full regeneration with 12 SCR's and 6 diodes. While it produces a square wave current supply, the motor voltage and hence flux is quasi sinusoidal. These numerous advantages have results in increasing use of the CSI for motor drives[2].

III. D-Q Model for CSI Fed I.M. Drive

When supplied from a current-controlled inverter the motor phase currents are not sinusoidal but are rectangular in nature and flow for only 120^0 of each half-cycle(neglecting commutation effects). If I_R is the magnitude of the current in the dc link, these stepped currents exciting the three stator phases can be represented by the Fourier series expansion given by

$$i_{as}=\frac{2\sqrt{3}}{\pi}I_R\left[\cos\omega_e t-\frac{1}{5}\cos 5\omega_e t+\frac{1}{7}\cos 7\omega_e t-\frac{1}{11}\cos 11\omega_e t+\ldots\ldots\right] \quad \ldots.(1)$$

$$i_{bs}=\frac{2\sqrt{3}}{\pi}I_R\left[\cos(\omega_e t-\frac{2\pi}{3})-\frac{1}{5}\cos(5\omega_e t+\frac{2\pi}{3})+\frac{1}{7}\cos(7\omega_e t-\frac{2\pi}{3})\ldots\ldots\right] \quad \ldots.(2)$$

$$i_{as}=\frac{2\sqrt{3}}{\pi}I_R\left[\cos(\omega_e t+\frac{2\pi}{3})-\frac{1}{5}\cos(5\omega_e t-\frac{2\pi}{3})+\frac{1}{7}\cos(7\omega_e t+\frac{2\pi}{3})......\right] \quad ...(3)$$

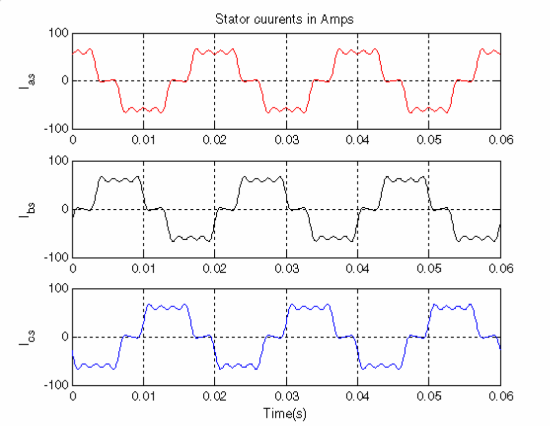

Fig (1)

When performing stability or transfer function analyses, it is convenient to view the system in a reference frame that rotates around the air gap in synchronism with the stator MMF at a speed corresponding to stator excitation frequency, Machine voltage, flux, and current variables become constant quantities during steady-state operation, These system equations represented in the synchronous rotating frame can thus be readily linear zed around a particular steady-state operating point. Using the notation of Krause and Thomas [4]

$$\begin{bmatrix} v_{qs}^{e} \\ v_{ds}^{e} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s+\frac{p}{\omega_b}\chi_s & \frac{\omega_e}{\omega_b}\chi_s & \frac{p}{\omega_b}\chi_m & \frac{\omega_e}{\omega_b}\chi_m & -\frac{\omega_e}{\omega_b}\chi_s \\ r_s+\frac{p}{\omega_b}\chi_s & -\frac{\omega_e}{\omega_b}\chi_m & \frac{p}{\omega_b}x_m & \frac{p}{\omega_b}\chi_m & \frac{\omega_{sl}}{\omega_b}\chi_m \\ r_r^{1}+\frac{p}{\omega_b}\chi_r^{1} & \frac{\omega_{sl}}{\omega_b}\chi_r^{1} & -\frac{\omega_{sl}}{\omega_b}\chi_m & \frac{p}{\omega_b}\chi_m & -\frac{\omega_{sl}}{\omega_b}\chi_r^{1} \quad r_r^{1}+\frac{p}{\omega_b}\chi_r^{1} \end{bmatrix} \begin{bmatrix} i_{qs}^{e} \\ i_{ds}^{e} \\ i_{qr}^{1e} \\ i_{dr}^{1e} \end{bmatrix} \quad ...(4)$$

In these equations, the superscript e is employed to denote that the d-q-axes are synchronously rotating. A p denotes the operator d/dt. All reactance values are referred to base frequency such that the operator p/ω_b always appears. Although six equations are generally required to completely define the machine response, the two zero-sequence equations have been omitted since the sum of stator as well as rotor currents are zero. Also, in (4), ω_b is the base electrical angular velocity used to obtain the per unit machine parameters, ω_r is the equivalent electrical angular velocity of the rotor and $\omega_{sl} = \omega_e - \omega_r$ is the slip angular frequency. The parameters r_s and r_r are stator, and referred rotor resistance referred to the stator. The quantities x_{sl} x_m and x_r^1 are the stator self, mutual, and rotor self-reactance referred to the stator, respectively.

Using (1)=(3) and applying the proper equations of transformation [4], the corresponding q-and d-axis currents in the synchronously rotating reference frame are

$$i_{as}^{e}=\frac{2\sqrt{3}}{\pi}I_R(1-\frac{2}{35}\cos 6\omega_e t-\frac{24}{143}\cos 12\omega_e t-.......) \quad .... (5)$$

$$i_{ds}^{e}=\frac{2\sqrt{3}}{\pi}I_R(1-\frac{12}{35}\sin 6\omega_e t-\frac{24}{143}\sin 12\omega_e t-.......) \quad .... (6)$$

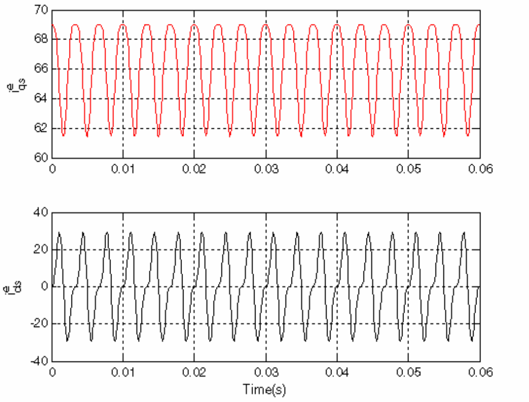

Fig (2)

In (5) and (6) the q and the as-axes are assumed aligned at time t=0. For convenience, these currents can be expressed as

$$i_{qs}^{e}=I_R^{1}g_{qs}^{e} \quad .... (7)$$

$$i_{ds}^{e}=I_R^{1}g_{qs}^{e}, \quad .... (8)$$

Where g_{qs}^e and g_{ds}^e are the switching or g functions defined as

$$g_{qs}^{e}=1-\frac{2}{35}\cos 6\omega_e t-\frac{2}{143}\cos 12\omega_e t-......(9)$$

$$g_{ds}^{e}=-\frac{12}{35}\sin 6\omega_e t-\frac{12}{143}\sin 12\omega_e t-...... \quad ....(10)$$

And

$$I_R^{1}=\frac{2\sqrt{3}}{\pi}I_R, \quad ....(11)$$

It is important to note that (7) and (8) are valid even if I_R is not constant

Assuming no power loss in the inverter, the power into and out of the inverter is identical, so that

$$v_I i_R = \frac{3}{2}(\upsilon_{qs}^{e} i_{qs}^{e}+\upsilon_{ds}^{e} i_{ds}^{e}) \quad ....(12)$$

The inverter voltage can be obtained by combining (7), (8), and (12) as

$$V_I = \frac{3\sqrt{3}}{\pi}(\upsilon_{qs}^{e} g_{qs}^{e}+\upsilon_{ds}^{e} g_{ds}^{e}) \quad ....(13)$$

Or simply

$$v^{1} = \upsilon_{qs}^{e} g_{qs}^{e}+\upsilon_{ds}^{e} g_{ds}^{e}, \quad ....(14)$$

Where

$$V_I^{1} = \frac{\pi}{3\sqrt{3}}V_I \quad ......(15)$$

Assuming continuous current in the smoothing reactor, the quantities I_R and V_I can be viewed as normalized dc link variables referred to the d-q-axes. The differential equation expressing the dc link variables can be expressed in terms of normalized quantities as.

$$V_R^1 = V_1^1 + (R_F^1 + \frac{p}{\omega_b} X_F^1) I_R \quad \text{……….(16)}$$

Where it has been convenient to define new normalized link parameters

$$R_F^1 = \frac{\pi^2}{18} R_F \quad \text{………………………(17)}$$

$$X_F^1 = \frac{\pi^2}{18} X_F \quad \text{………………………(18)}$$

$$V_R^1 = \frac{\pi}{3\sqrt{3}} V_R \quad \text{…………………………(19)}$$

Equations (4), (7),(8),(14), and (16) form the basic system equations in the synchronously rotating reference frame and can be used to form the system equivalent circuit and subsequently it is assumed that the time derivative operator is (p/ω_b).

Although the actual system operates with rectangular-wave excitation from a high equivalent impedance source, it is well-known that machine stability is determined primarily by the fundamental components of machine variables. If the effects of harmonics are ignored, the g functions become simply.

$$g_{qs}^e \cong 1.0 \quad \text{…….(20)}$$

$$g_{ds}^e \cong 0, \quad \text{………(21)}$$

Whereby, from (7) and (8)

$$i_{qs}^e = i_R^1 \quad \text{……….(22)}$$

$$i_{ds}^e = 0.1 \quad \text{………(23)}$$

Because of the normalization employed, the current in the stator q-axis, I_R^1, corresponds to the peak value of the fundamental component of motor phase current. The d-axis stator current is identically zero during both steady-state and transient conditions due to the positioning of the synchronously rotating reference frame axes. From (14), orientation of the d-q axes also results in the identity that

$$v_{qs}^e = V_1^1, \quad \text{…………………(24)}$$

With v_{ds}^e assuming the open-circuit value resulting from mutual coupling.

Neglecting harmonics, the detailed equivalent circuit Equations (7) and (8) can be combined with the equations of the induction machine in the synchronously rotating reference frame to yield the corresponding system equations, (22) and (23). Note that the ds equation in(23) has been omitted since i_{ds}^e is identically zero.

$$\begin{bmatrix} V_R^1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + R_F^1 + \frac{p}{\omega_b}(x_s + X_F^1) & \frac{p}{\omega_b} x_m & \frac{\omega_e}{\omega_b} x_m \\ \frac{p}{\omega_b} x_m r_r^1 + \frac{p}{\omega_b} x_r^1 \frac{\omega_{sl}}{\omega_b} x_r^1 & & \\ -\frac{\omega_{sl}}{\omega_b} x_m - \frac{\omega_{sl}}{\omega_b} x_r^1 r_r^1 + \frac{p}{\omega_b} x_r^1 & & \end{bmatrix} \times \begin{bmatrix} i_{qs}^e \\ i_{qr}^{1\,e} \\ i_{dr}^{1\,e} \end{bmatrix}$$

$$T_e = \frac{3P}{4\omega_b} x_m i_{qs}^e i_{dr}^{1\,e} = T_L + \frac{2J}{P} p\omega_r \quad \text{…………..(25)}$$

IV CLOSED-LOOP CONTROL

These system inputs are the rectifier voltage and the frequency command to the inverter. An elementary closed-loop control which results in stable operation for full motoring and regenerative operation is the independent current magnitude and slip frequency control shown in Fig.6.

With slip frequency control, incremental changes in rotor speed are related to incremental changes in electrical frequency by the constraint.

$$\Delta\omega_e = \Delta\omega_r + \Delta\omega_{sl} \quad \text{….. (26)}$$

Slip frequency control forces electrical frequency to change in response to rotor speed, which tends to maintain a constant angular displacement between rotor and stator MMF's during both steady-state and transient conditions. Although this type of control has a stabilizing effect, it is not capable of ensuring stable operation under all operating conditions. To obtain steady-state current control along with improved system transient response, the rectifier voltage must be constrained to respond to the error between a commanded value and the actual value of the dc link current. An integral plus proportional controller is used to give a satisfactory speed of response with zero steady-state error.

$$\frac{\Delta V_R^1}{(\Delta I_R^1 * - \Delta I_R^1)} = \frac{K_C(1+\tau p)}{p} \quad \text{………. (27)}$$

To include the compensator in the analysis, a fifth state variable must be defined. ΔQ is defined to be the output of the integral controller, that is

$$\Delta Q = \frac{K_C}{p}(\Delta I_R^1 * - \Delta I_R^1) \quad \text{…………….. (28)}$$

The rectifier voltage can then be expressed as

$$\Delta V_R^1 = \Delta Q(1+\tau p) \quad \text{…………….. (29)}$$

The system matrix equation including the slip frequency and current magnitude control is

$$\begin{bmatrix} r_s + R_F^1 + \frac{p}{\omega_b}(x_s + X_F^1) & \frac{p}{\omega_b}x_m & \frac{\omega_e}{\omega_b}x_m & -1-\tau p & x_m i_{dro}^{1e} \\ \frac{p}{\omega_b}x_m & r_r^1 + \frac{p}{\omega_b}x_r^1 & \frac{\omega_{sl}}{\omega_b}x_r^1 & 0 & 0 \\ -\frac{\omega_{sl}}{\omega_b}x_m & -\frac{\omega_{sl}}{\omega_b}x_r^1 & r_r^1 + \frac{p}{\omega_b}x_r^1 & 0 & 0 \\ K_C & 0 & 0 & p & 0 \\ \frac{3Px_m i_{dro}^{1e}}{4\omega_b} & 0 & \frac{3Px_m i_{qso}^{1e}}{4\omega_b} & 0 & \frac{2J\omega_b^2\left(\frac{p}{\omega_b}\right)}{P} \end{bmatrix} \begin{bmatrix} \Delta i_{qs}^{1e} \\ \Delta i_{qr}^{1e} \\ \Delta i_{dr}^{1e} \\ \Delta Q \\ \frac{\Delta\omega_r}{\omega_b} \end{bmatrix} \qquad \text{............ (30)}$$

$$= \begin{bmatrix} -x_m i_{dro}^{1e} \\ -x_r^1 i_{dro}^{1e} \\ (x_m i_{qso} + x_r^1 i_{qro}^{1e}) \\ 0 \\ 0 \end{bmatrix} \frac{\Delta\omega_{sl}}{\omega_b} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ K_C \\ 0 \end{bmatrix} \Delta I_R^{1*} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \Delta T_L \qquad \text{.................... (31)}$$

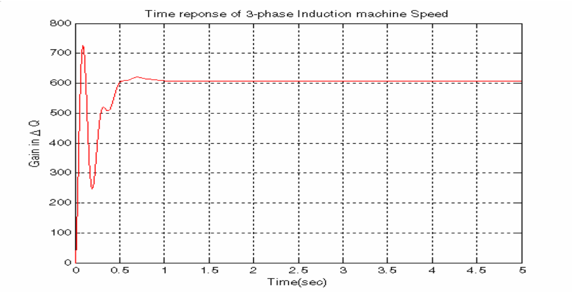

Fig (4)

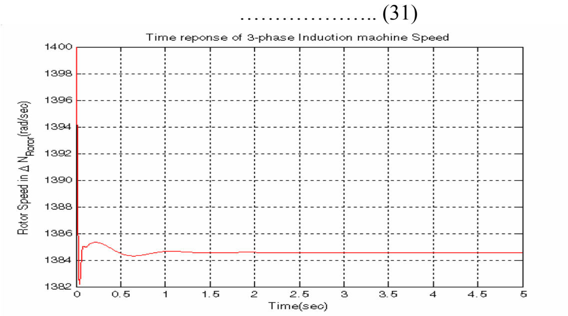

Fig (7)

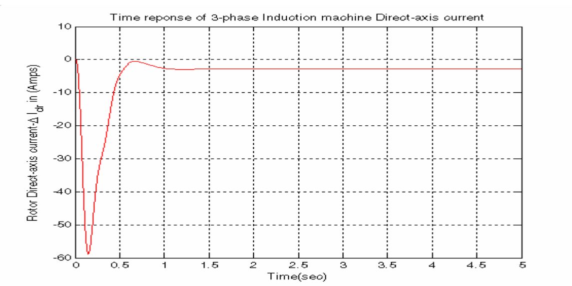

Fig (5)

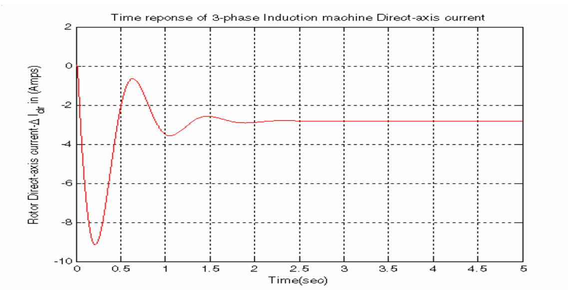

Fig (8)

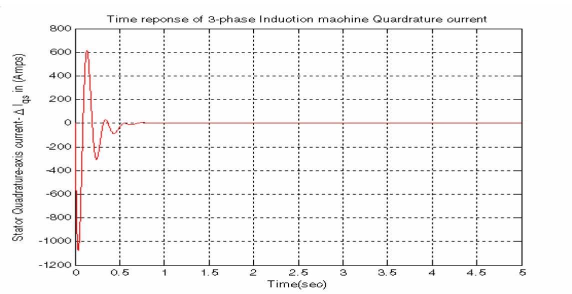

Fig (6)

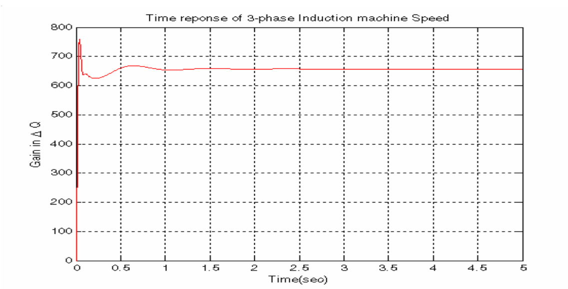

Fig (9)

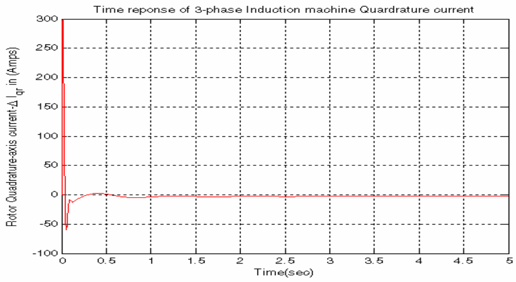

Fig (10)

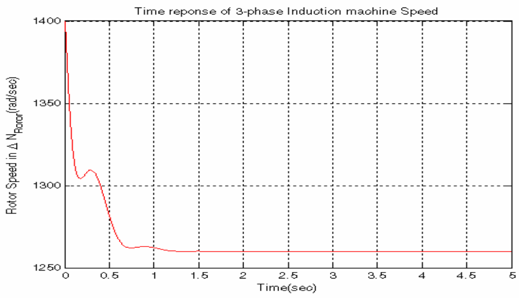

Fig (11)

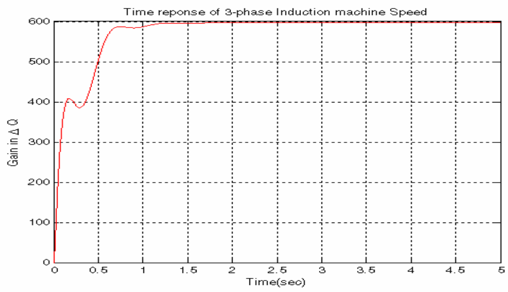

Fig (12)

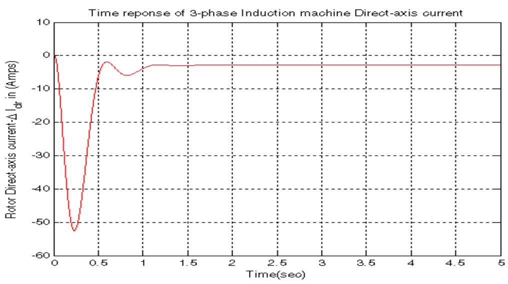

Fig (13)

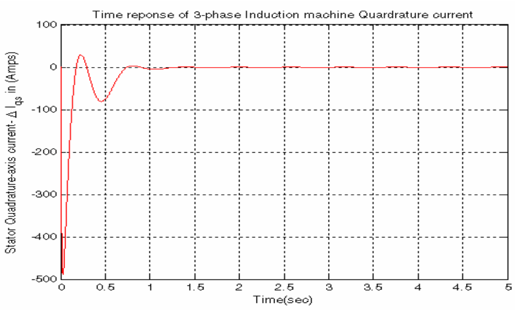

Fig (14)

V .TUNING OF CONTROLLER

Tuning methods are used to determine appropriate values of controller parameters. Since during the induction motor installing and commissioning do not have a ling time to tune the systems. Consequently, a number of systems use the default parameters may not be appropriate. Induction motor systems are non-linear and time varying. Thus, fixed-gain controllers may be properly tuned some of the time even if they were properly tuned when they were installed. Control loops in induction motor systems may require retuning during the year for the processes that have non-linear characteristics that are dependent upon the load. If a feedback control loop is not retuned, the control response may be poor. (The closed loop response for the controlled variable is oscillatory).

APPENDIX

Nameplate motor data	Motor and filter parameters
18.6kW	$r_S = 0.0788\Omega$
4-pole	$r_r = 0.0408\Omega$
3-phase Y-connected	$x_s = 5.7518\Omega$
$\omega_b = 377$ rad/sec	$x_r = 6.0028\Omega$
$J_{TOTAL} = 0.31$ Kg-m^2	$x_m = 5.54\Omega$
$V_{rated} = 230$ V rms	$X_F = 5.50\Omega$
$I_{rated} = 64$ A rms	$R_F = 0.091\Omega$

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