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Tuning of PI Controller for Current Source Inverter Fed Induction Motor Drive

Abstract— Direct torque control (DTC) of Induction motor is preferred as compared to vector control scheme due to its quick torque response, simplicity and robustness against rotor parameters variation. PID controllers are very common since they can offer a satisfactory performance over a wide range of operation. The main problem with this controller is the correct choice of the PID gains and the fact that by using fixed gains, the controller may not provide the required control performance, when there are variations in the plant parameters and operating conditions. Therefore, a tuning process must be performed to ensure that the controller can deal with the variations in the plant. The tuning of these controllers is governed by system nonlinearities and continuous parameter variations. In this paper, a complete and rigorous study is made for tuning of PI controller used in a speed control loop in a Direct Torque Control (DTC) scheme applied in a current source inverter (CSI) fed induction motor drive system. The controller value is adjusted by Ziegler and Nichols method. A comparative study is made between P and PI controller. It has been found that with P controller the transient time to reach the steady state value is small.

Keywords – Direct torque control, current source inverter, Ziegler and Nichols

Nomenclature

v_{as}, v_{bs}, v_{cs}	= Stator phase voltages
v_{qs}, v_{ds}	=Stator phase voltages in d-q reference frame
v_{qr}, v_{dr}	= Rotor phase voltages in d-q reference frame
i_a, i_b, i_c	= Inverter output currents
i_q, i_d	= Inverter output currents in d-q reference frame
i_{as}, i_{bs}, i_{cs}	= Stator currents
i_{qs}, i_{ds}	= Stator currents in d-q reference frame
i_{qr}, i_{dr}	= Rotor currents in d-q reference frame
i_{act}, i_{react}	= Active & reactive component of stator current
i_{ref}, i_c	= Reference current, Capacitor current
ω_e	= Electrical angular velocity of d-q axis
ω_r	= Electrical angular velocity of rotor
ω_{sl}	= Slip speed in rad/sec
ω_{slref}	= Slip speed command in rad/sec
T_e, T_l	= Electromagnetic torque and load torque
v_{dc}, i_{dc}	= Rectifier output voltage, DC link current
v_i	= Inverter input voltage
v_s, v_r	= Amplitude of stator & rotor voltage
r_s, r_r	= Stator & rotor resistance
l_s, l_r	= Stator & rotor self inductance
l_m	= Mutual inductance between stator and rotor
C	= Capacitance of each output capacitor
r_f, l_f	= DC link resistance & inductance
P	= Number of pole
J	= Moment of inertia of rotor 'Kg-m^2'
K_{ps}	= Proportional gain of speed controller
K_{pi}	= Proportional gain of current controller
K_1, K_2	= Slope of active & reactive component of slip regulator characteristics respectively

I. INTRODUCTION

The speed of an induction motor can be smoothly controlled over a desired speed range by varying the frequency of AC source. Due to inherent disadvantages in voltage source inverter [1], a slip regulated current source inverter (CSI) has been preferred for a wide range speed control [2, 3]. The current source inverter fed drive finds application in high power drives such as fan drives, where fast dynamic response is not needed. Also, since CSI drives employ fully controlled silicon-controlled rectifier (SCR) converter at the input. Under regeneration the polarity of the voltage at the converter terminals will reverse and the energy will be fed back to the utility. So regeneration is built in to the system and unlike VSI fed drives does not require any additional circuit [4]. In CSI drives the dc link reactor limits the rate of rise of current under short circuit conditions, so the drives can be easily protected under short circuit and thus results in improved reliability of the drive [5, 6].

The most common choice for the controller in CSI drive is the PID compensator due to its simple structure and satisfactory performance over a wide range of operation [7]. To tune a PI controller (usually in drives applications the derivative part of the controller is not used) [8] a lot of strategies have been proposed.. The technique [9] uses

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frequency response method to design and tune PI controller gains based on specified phase and gain margins as well as cross over frequency. Furthermore, root locus and pole assignment design techniques are also proposed in addition to transient response specifications. All these methods are considered as model based strategies and then the efficiency of the tuning law depends on the accuracy of the proposed model as well as the assumed conditions with respect to actual operating conditions [10, 11]. On the other hand the Ziegler-Nichols method does not require any system model and control parameters are designed only from the plant step response [12]. Tuning, using this method is characterized by a good disturbance rejection. This paper presents tuning of PI Controller for Current Source Inverter Fed Induction Motor Drive. In this study, the dynamic analysis of SCCSI fed induction motor system is done with proportional and integral controller in speed and current loops, the parameter of which are adjusted by Ziegler and Nichols method. Simulation studies are made at various motor speeds for different loading conditions. It has been shown that due to very small offset, P controller works satisfactorily as compared to PI controller for all loads.

II. CSI FED IM DRIVE SYSTEM

Fig. 1 shows a current controlled induction motor drive system. It consists of three phase power source, controlled rectifier bridge, a DC link smoothening reactor, a current source inverter and a three phase squirrel cage induction motor. The magnitude and polarity of the speed error are used to determine the slip speed reference. This maintains the air gap flux in the machine at a constant value and also used to determine the DC link current reference value. Rectifier output voltage is controlled by PI controller working on the DC link current error that decides the input current of CSI. The slip speed is added to the rotor speed in order to determine the synchronous speed, which then determines the inverter operating frequency.

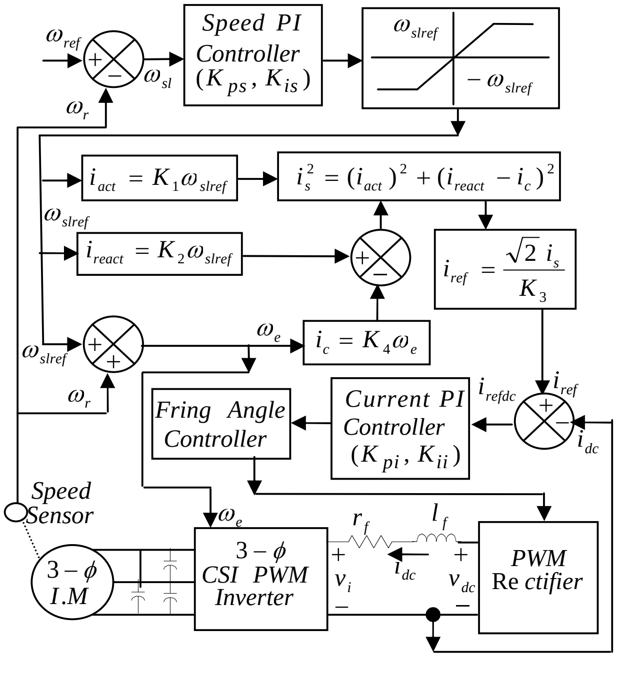

Fig. 1. Closed Loop Control of Induction Motor fed by CSI

III. MODELING OF CSI FED IM DRIVE SYSTEM

The composite inverter fed induction motor system has been modeled in different structures and cascaded together to obtain the overall performance of system.

A. Modeling of Induction Motor

The voltages and currents of the squirrel cage induction motor can be represented in a synchronously rotating d-q reference frame as follows [13]

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} r_s + pl_s & \omega_e l_s & pl_m & \omega_e l_m \\ -\omega_e l_s & r_s + pl_s & -\omega_e l_m & pl_m \\ pl_m & \omega_{sl} l_m & r_r + pl_r & \omega_{sl} l_r \\ -\omega_{sl} l_m & pl_m & -\omega_{sl} l_r & r_r + pl_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (1)$$

Solving (1), following model of induction motor is obtained

$$\begin{bmatrix} \dot{i}_{ds} \\ \dot{i}_{qs} \\ \dot{i}_{dr} \\ \dot{i}_{qr} \end{bmatrix} = \frac{1}{l_1} \begin{bmatrix} -r_s l_r & \omega_e l_1 + \omega_r l_m^2 & r_r l_m & \omega_r l_m l_r \\ -(\omega_e l_1 + \omega_r l_m^2) & -r_s l_r & -\omega_r l_m l_r & r_r l_m \\ r_s l_m & -\omega_r l_m l_s & -r_r l_s & \omega_e l_1 - \omega_r l_s l_r \\ \omega_r l_s l_m & r_s l_m & -(\omega_e l_1 - \omega_r l_s l_r) & -r_r l_s \end{bmatrix} \begin{bmatrix} \dot{i}_{ds} \\ \dot{i}_{qs} \\ \dot{i}_{dr} \\ \dot{i}_{qr} \end{bmatrix}$$

$$+ \frac{1}{l_1} \begin{bmatrix} l_r & 0 & 0 & 0 \\ 0 & l_r & 0 & 0 \\ -l_m & 0 & 0 & 0 \\ 0 & -l_m & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \\ 0 \\ 0 \end{bmatrix} \quad (2)$$

Where $l_1 = l_s l_r - l_m^2$ (3)

The machine and load torque are related as

$$Jp\omega_r = T_e - T_l \quad (4)$$

In equation (4), friction and windage losses are neglected. The electromagnetic torque, T_e and load torque, T_l is given by the following equations.

$$T_e = (3P/4) l_m \left(i_{qs} i_{dr} - i_{ds} i_{qr} \right) \quad (5)$$

$$T_l = T_L * (\omega_r / \omega_b) \quad (6)$$

The load torque in the present case is considered to be varying linearly with the speed.

B. Modeling of Capacitors

For the balanced condition, the equations related to the output capacitors can be expressed, in term of phase voltages as following:

$$i_a = 3Cpv_{as} + i_{as} \quad (7)$$

$$i_b = 3Cpv_{bs} + i_{bs} \quad (8)$$

$$i_c = 3Cpv_{cs} + i_{cs} \quad (9)$$

Transforming the inverter output currents i_a, i_b & i_c in a synchronously rotating d-q reference frame, following equations are obtained.

$$i_q = 3Cpv_{qs} + 3C\omega_e v_{ds} + i_{qs} \tag{10}$$

$$i_d = 3Cpv_{ds} - 3C\omega_e v_{qs} + i_{ds} \tag{11}$$

In CSI the inverter output current flows for 120° of each half cycle in the form of a rectangular wave. Their harmonic components are neglected on the assumptions that the drive system stability is primarily determined by the fundamental component of each variable. Thus, the inverter output currents, considering only the fundamental component, are obtained as below

$$i_q = (2\sqrt{3}/\pi)i_{dc}, \quad i_d = 0 \tag{12}$$

From equation (10) to (12) the derivative of stator phase voltage in dq reference frame are obtained

$$pv_{ds} = (1/3C)\left(-i_{ds} + 3C\omega_e v_{qs}\right) \tag{13}$$

$$pv_{qs} = (1/3C)\left((2\sqrt{2}/\pi)i_{dc} - 3C\omega_e v_{ds} - i_{qs}\right) \tag{14}$$

C. Modeling of DC Link

The dc link is expressed as

$$l_f pi_{dc} + r_f i_{dc} = v_{dc} - v_i \tag{15}$$

If inverter is assumed lossless, the inverter input voltage be

$$v_i = (3\sqrt{3}/\pi)v_{qs} \tag{16}$$

The relationship between the stator rms current and dc reference current is

$$i_{ref} = (\sqrt{2}/K_3)i_s \tag{17}$$

IV. STEADY STATE CHARACTERISTICS

Tuning a controller involves setting the proportional, integral, and derivative values to get the best possible control for a particular process. In order to obtain the adequate control the motor is tuned here using Ziegler Nichols Method.

The test machine used in the work is a 3-phase, 400/440V, 50 Hz, 4 poles, 7 Amps, induction motor. Different parameters of the motor are $r_s = r_r = 5.53$ Ω/ph, $l_s = l_r = 0.68$ H, l_m=0.6503 H, $l_f = 0.05H$, $r_f = 3\Omega$, C = 28.22 μF, K_1 = 0.0821 and K_2 0.2474.

The steady state equation (18) is obtained by substituting all the derivative terms equal to zero in the equations (1), (13) and (14) and assuming the DC link current i_{dc} as an input.

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{-2\sqrt{3}}{3\pi C}i_{dc} \\ 0 \end{bmatrix} = \begin{bmatrix} -l_r r_s & -(\omega_e l_1 + \omega_r l_m^2) & r_r l_m & -\omega_r l_r l_m & l_r & 0 \\ \omega_e l_1 + \omega_r l_m^2 & -r_s l_r & \omega_r l_m l_r & r_r l_m & 0 & l_r \\ l_m r_s & \omega_r l_m l_s & -l_s r_r & \omega_r l_s l_r - \omega_e l_1 & -l_m & 0 \\ -\omega_r l_s l_m & r_s l_m & \omega_e l_1 - \omega_r l_r l_s & -l_s r_r & 0 & -l_m \\ \frac{-l_1}{3C} & 0 & 0 & 0 & 0 & -l_1\omega_e \\ 0 & \frac{-l_1}{3C} & 0 & 0 & l_1\omega_e & 0 \end{bmatrix} \begin{bmatrix} i_{qso} \\ i_{dso} \\ i_{qro} \\ i_{dro} \\ v_{qso} \\ v_{dso} \end{bmatrix} \tag{18}$$

The subscript 'o' denotes the steady state value. Once the DC link current required for an arbitrary speed and a load torque is determined, all the motor currents and the developed electromagnetic torque can be obtained using equations (18) and (5) respectively. Fig. 2 shows the torque versus slip characteristics for different value of dc link current. Near the synchronous speed i.e. at low slips the torque is linear and is proportional to slip; beyond the maximum torque the torque is approximately inversely proportional to slip. Fig.3 shows the rotor current characteristic for different value of dc link current. It shows that at unity slip the current taken by the motor is large as expected.

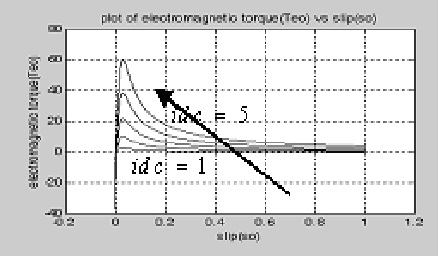

Fig. 2. Plot of electromagnetic torque (Te) vs slip(s)

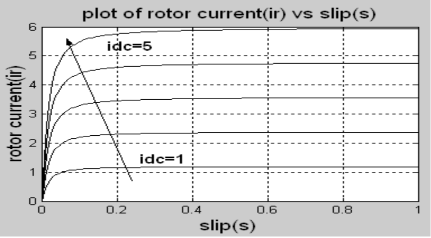

Fig. 3. Plot of rotor current (ir) vs slip(s*)*

V. DYNAMIC CHARACTERISTICS

To investigate the dynamic characteristics, the equations (1), (4), (5), (10), (11), (15) & (16) are linearzed about a steady state operating point. Then the resulting state equation can be expressed as

$$\dot{x} = Ax + Bu \tag{19}$$

Where

$$x = [\delta i_{qs}\ \delta i_{ds}\ \delta i_{qr}\ \delta i_{dr}\ \delta v_{qs}\ \delta v_{ds}\ \delta i_{dc}\ \delta\omega_r]^T \tag{20}$$

$$u = [\delta\omega_s\ \delta v_{dc}\ \delta T_l]^T \tag{21}$$

$$A=\frac{1}{l_1}\begin{bmatrix} -r_s l_r & l_m^2\omega_{slo}-l_s l_r\omega_{so} & r_r l_m & -\omega_{ro} l_m l_r & l_r & 0 & 0 & -(l_m^2 i_{dso}+l_m l_r i_{dro}) \\ l_r l_s\omega_{so}-l_m^2\omega_{slo} & -l_r l_s & l_r l_m\omega_{ro} & l_m l_r & 0 & l_r & 0 & (l_m^2 i_{qso}+l_m l_r i_{qro}) \\ r_s l_m & l_s l_m\omega_{ro} & -r_r l_s & l_m^2\omega_{so}-l_s l_r\omega_{slo} & -l_m & 0 & 0 & (l_m i_{dso}+l_r i_{dro})l_s \\ -l_s l_m\omega_{ro} & l_m r_s & -(l_m^2\omega_{so}-l_r l_s\omega_{slo}) & -r_r l_s & 0 & -l_m & 0 & -(l_m i_{qso}+l_r i_{qro})l_s \\ -\frac{l_1}{3C} & 0 & 0 & 0 & 0 & -l_1\omega_{so} & \frac{2l_1}{\pi C\sqrt{3}} & 0 \\ 0 & -\frac{l_1}{3C} & 0 & 0 & l_1\omega_{so} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{3\sqrt{3}l_1}{\pi l_f} & 0 & -\frac{r_f l_1}{l_f} & 0 \\ \frac{3P^2 l_m l_1}{8J}i_{dro} & -\frac{3P^2 l_m l_1}{8J}i_{qro} & -\frac{3P^2 l_m l_1}{8J}i_{dso} & \frac{3P^2 l_m l_1}{8J}i_{qso} & 0 & 0 & 0 & 0 \end{bmatrix} \tag{22}$$

$$B=\frac{1}{l_1}\begin{bmatrix} -l_1 i_{dso} & 0 & 0 \\ l_1 i_{qso} & 0 & 0 \\ -l_1 i_{dro} & 0 & 0 \\ l_1 i_{qro} & 0 & 0 \\ -l_1 v_{dso} & 0 & 0 \\ l_1 v_{qso} & 0 & 0 \\ 0 & \frac{l_1}{l_f} & 0 \\ 0 & 0 & -\frac{P}{2J} \end{bmatrix} \tag{23}$$

Software MATLAB is used to solve Equation (19) to investigate the starting transient of the drive. Initially, load torque is kept at very low value equal to 0.8 N-M. In order to obtain the steady state operating value corresponding to this load torque, the dC link current range has been obtained with the help of steady state characteristic shown in Fig.2. To obtain high efficiency it is preferred to operate near low slips. Now the controller gain is adjusted when speed was taken equal to $\omega_r = 150\ rad/\sec$.

The sustain oscillation are obtained at the gain value of K_{psmax} = 60 & K_{pimax} = 25 and ultimate period of P_u has been observed equal to 0.2 sec as shown in Fig. 4. Now the controller gain is adjusted by Ziegler Nichols method, first for P controller. The steady state condition is reached with K_{ps}= 30 & K_{pi}=12.5 as shown in Fig. 5. It is clear that time to reach steady state value is approximately 1.2 sec.

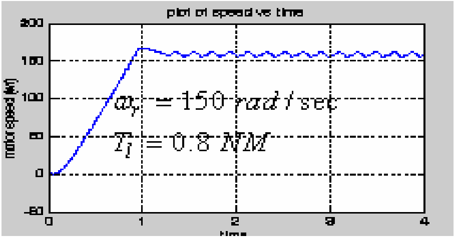

Fig. 4. Plot of rotor speed (ω_r) vs time (t)

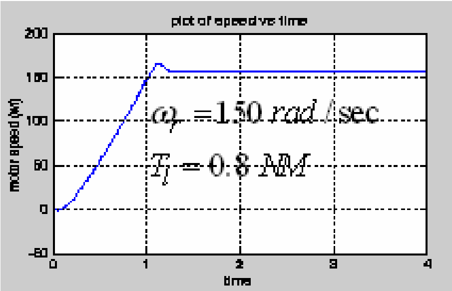

Fig. 5. Plot of rotor speed (ω_r) vs time (t) with P controller

Next the controller gain is adjusted for PI controller and in this case the steady state condition is reached with K_{ps} = 27 & K_{pi} = 11.25 as shown in Fig. 6. The time to reach steady state speed is approximately 1.3 sec in this case. Since with P controller there is no offset thus with PI controller system become sluggish as desired.

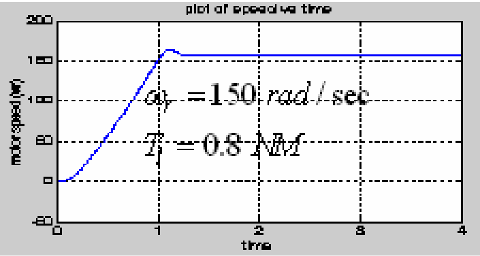

Fig. 6. Plot of rotor speed (ω_r) vs time (t) with PI controller

The load torque is now increased gradually and it has been observed that up to a value of 4 Nm same controller gain value works satisfactorily as shown in Fig. 7, Fig. 8 and Fig 9 for sustain oscillation, P controller, and PI controller respectively. It is observed that if the load torque is increased, the DC link current range increases to obtain the steady state operating value. This reduces the time to reach the steady state speed as shown in Fig. 8 and Fig. 9. The DC link current taken by the CSI inverter with T_l = 0.8 Nm is approximately 8 amps as shown in Fig. 10 and it reaches to 22 amps for a load torque of 4 Nm shown in Fig. 11.

These controller values work satisfactorily up to a torque of 18 Nm.

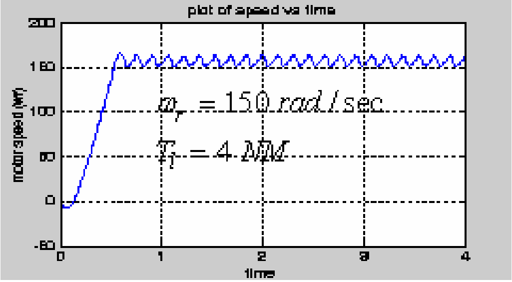

Fig. 7. Plot of rotor speed (ω_r) vs time (t)

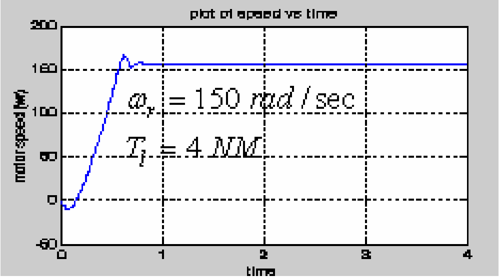

Fig. 8. Plot of rotor speed (ω_r) vs time (t) with P controller

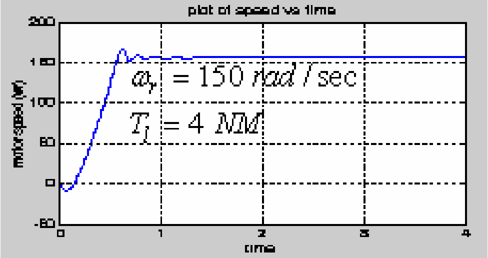

Fig. 9. Plot of rotor speed (ω_r) vs time (t) with PI controller

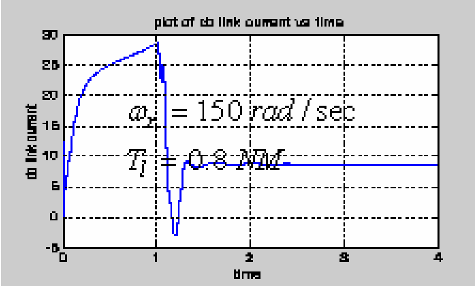

Fig. 10 Plot of dc link current (i_{dc}) vs time (t) with P controller

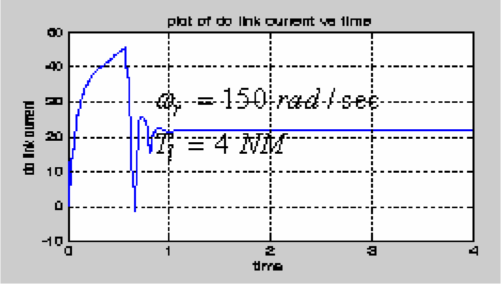

Fig. 11 Plot of dc link current (i_{dc}) vs time (t) with P controller

When the speed of the motor is reduced say, $\omega_r = 145\ rad/\sec$ then for the same initial load torque of T_l = 0.8 Nm the sustain oscillation are now obtained at the gain value of K_{psmax} = 38 and K_{pimax} = 20 and ultimate period of P_u = 0.203 sec as shown in Fig. 12. The speed transients for P controller and PI controller are shown in Fig. 13 and Fig. 14, respectively for this staring load torque. These gain values are constant if the load torque is increased up to a value of 4 Nm as shown in Fig. 15, Fig. 16 and Fig. 17 for sustain oscillations, P controller and PI controller respectively.

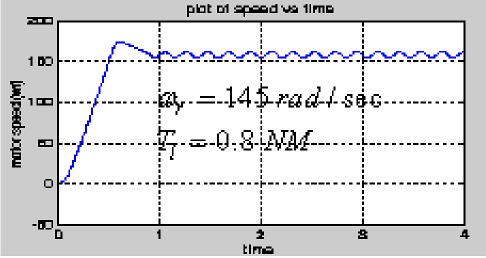

Fig. 12. Plot of rotor speed (ω_r) vs time (t)

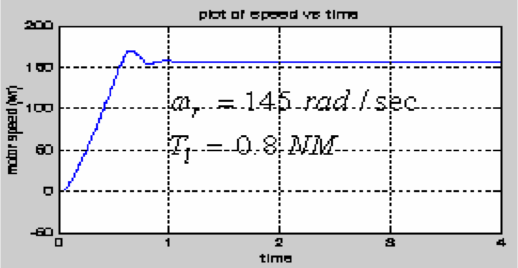

Fig. 13. Plot of rotor speed (ω_r) vs time (t) with P controller

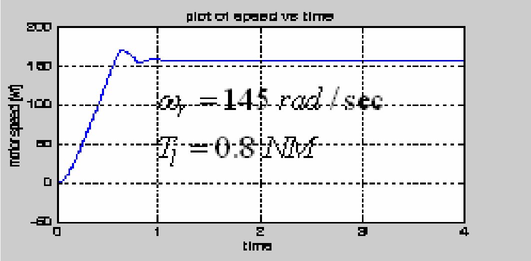

Fig. 14. Plot of rotor speed (ω_r) vs time (t) with PI controller

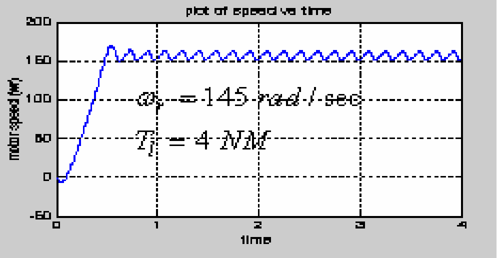

Fig. 15. Plot of rotor speed (ω_r) vs time (t)

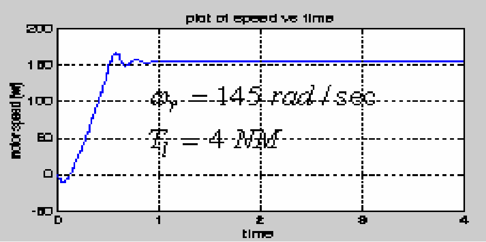

Fig.16. Plot of rotor speed (ω_r) vs time (t) with P controller

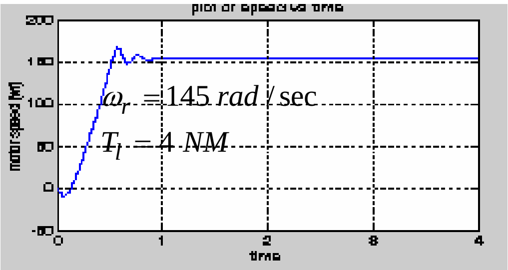

Fig. 17. Plot of rotor speed (ω_r) vs time (t) with PI controller

It has also been observed that with a reduction in speed the corresponding DC link current range is reduced. The DC link current taken by the CSI inverter with $\omega_r = 150\, rad / \sec$ and T_l = 0.8 Nm was approximately 8 amps (Fig. 10) but with increasing speed error and with same load torque DC link current has become approximately 6.8 amp as shown in Fig. 18. This reduction in DC link current reduces the transient time of the system which can be observed in Fig. 12 as compared to Fig. 5

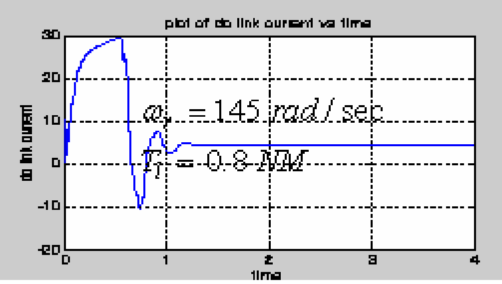

Fig. 18 Plot of dc link current (i_{dc}) vs time (t) with P controller

VI. CONCLUSIONS

Mathematical modeling of current source inverter (CSI) fed induction motor drive system has been done in synchronously rotating d-q reference frame using proportional and integral regulators in speed and current loops. Tuning of speed controller and current controller is performed using simulation in MATLAB in DTC approach. A capacitor bank is mounted on the terminal of drive for maintaining better power factor at each operating condition of the drive. The steady-state parameters and slip regulator characteristics of the drive are determined experimentally. Steady state and Transient performance are obtained by developing a computer program. A number of observations have been made to analyze various waveforms. Motor has been loaded with rated load. Optimum value of controller parameters is determined by Ziegler and Nichols method for different motor speed. It has been found that for low value of torque without any controller sustained oscillation are obtained and ultimate period of P_u has been observed equal to 0.2 sec. However, with P and PI controllers these oscillations are almost zero and the time to reach steady state value is approximately 1.2 sec for P controller and 1.3 sec for PI controller. Since with P controller there is no offset thus with PI controller system become sluggish as desired.

The controller constants remain same for increase of load torque but the DC current requirement increases which results the reduction in settling time.

The controller constants reduce with a decrease in speed and at the same time the DC link current requirement also decreases. This again increases the system stability.

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VIII. BIBLIOGRAPHIES

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