Design of Fuzzy PI Controller for CSI Fed Induction Motor Drive

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***Abstract*—In this paper the closed loop control of CSI fed induction motor is investigated using fuzzy logic controller. A slip control scheme has been used for the induction motor. The evaluation of the fuzzy logic controller behavior is made through computer simulation with MATLAB coding. The starting transient of the motor is investigated for different operating speeds with different load torque. It has been found that for fuzzy controller, once the parameters are selected for a specified load and speed it will work for all other load and speed whereas for conventional PI controller, the parameters have to be changed for each load and speed setting. The fuzzy controller reduces the over shoot value of speed by approximately 2 to 5 % while for dc link current it reduces around 4% as compared to conventional PI controller. This reduces the rating of the devices used in the drive system. It has also been found that the system shows some what slow response with less oscillation so that fuzzy controller can be used where smooth operation is required.**

Index Terms—: **Current source inverter, fuzzy logic, induction motor, mathematical model**

I. Introduction

IN lieu of the advances in power electronics and microprocessors, digitally controlled induction motor drives have become increasingly popular.

Manuscript received October 19, 2010.

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The use of variable speed drives is increasing in the industrial, utility and agricultural processes. Most of these variable speeds drives, employ electric motors and power converters, resulting in energy savings over other types of variables speed drives [1] such as motor generator sets and eddy current drives etc. The squirrel cage induction motor has been employed for variable speed drive applications because of the advantages like robust construction, less expensive, higher torque to weight ratio, running at higher speeds with reasonably higher efficiency etc. The current source inverter fed induction motor (CSI-IM) drive is very rugged, but is more complex than the voltage source inverter fed induction motor (VSI-IM) drive [2-3].

The PID controller is widely used in the induction motor drive application due its simplicity in structure, superior robustness, and familiarity to most field operators.

The key issue in designing PID controller, for the induction motor drive, is to settle the gains so that the controller works well in every condition [4]. Unfortunately it is very difficult to tune these controllers for satisfactory operations. In recent years, scientists and researchers have acquired significant development on various sorts of control theories and methods. Some of these new control schemes include fuzzy logic, sliding mode control, predictive control, neural networks, neuro fuzzy and other advanced control techniques [5-6]. Among these control technologies, fuzzy logic control is suitable for applications where the controlled system or some of its parameters are unknown [7-8]. Fuzzy logic makes the controlling complicated system, such as induction motor/variable speed drive combinations, much easier. In this paper fuzzy logic control is applied to obtain the gain parameters of PI controller for a CSI fed induction motor to obtain transient performance for different speed and different torques.

II. CSI FED INDUCTION MOTOR DRIVE SYSTEM

Fig. 1 shows a current source inverter fed induction motor drive system. The inverter uses switching devices with self extinguishable capability. It requires a three phase capacitor at its output to assist the commutation of the switching devices [9].

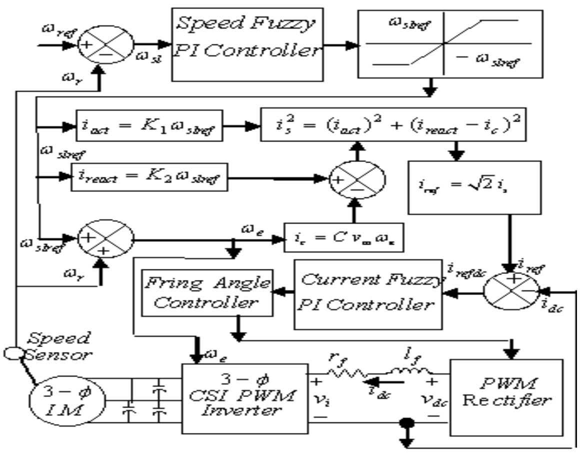

Fig. 1: Closed loop control of induction motor fed by CSI

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{-2\sqrt{3}}{3\pi C} i_{dc} \\ 0 \end{bmatrix} = \begin{bmatrix} -l_r r_s & -(\omega_e l_1 + \omega_r l_m^2) & r_r l_m & -\omega_r l_r l_m & l_r & 0 \\ \omega_e l_1 + \omega_r l_m^2 & -r_s l_r & \omega_r l_m l_r & r_r l_m & 0 & l_r \\ l_m r_s & \omega_r l_m l_s & -l_s r_r & \omega_r l_s l_r - \omega_e l_1 & -l_m & 0 \\ -\omega_r l_s l_m & r_s l_m & \omega_e l_1 - \omega_r l_r l_s & -l_s r_r & 0 & -l_m \\ \frac{-l_1}{3C} & 0 & 0 & 0 & 0 & -l_1 \omega_e \\ 0 & \frac{-l_1}{3C} & 0 & 0 & l_1 \omega_e & 0 \end{bmatrix} \begin{bmatrix} i_{qso} \\ i_{dso} \\ i_{qro} \\ i_{dro} \\ v_{qso} \\ v_{dso} \end{bmatrix} \quad (1)$$

The detailed mathematical modeling of the induction motor, current source inverter, and capacitor has been done in [10] using synchronously rotating d-q reference frame. The steady state performance of the motor is described by equation (1), which, relate different voltages and current in synchronously rotating d-q reference frame under steady state condition assuming the DC link current, i_{dc}, as an input parameter [11].

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 (1). The test machine used in this 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 = 0.05 H, r_f = 3Ω, C = 28.22 μF, K_1 =0.0821 and K_2 0.2474. K_1 and K_2 is the slope of slip regulator characteristic I_{act} versus ω_{sl} and I_{react} versus ω_{sl} for V/f control operation of the drive respectively.

Fig. 2 shows the torque versus slip characteristics while Fig. 3 shows the rotor current versus slip characteristic of the motor for different values of DC link current. It can be observed that both the torque developed as well as the current taken by the motor increases when the input DC link current is increased. 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.

The efficiency and power factor characteristic of the motor are shown in Fig. 4 and Fig. 5 respectively for different value of DC link current. It is observed that there is no change in efficiency and in power factor when input DC link current is changed. Both of these increase linearly for a slip, ranging from 0 to 0.06, which is the range of interest for variable speed drive or positive slope region of the torque versus slip characteristic in Fig. 2

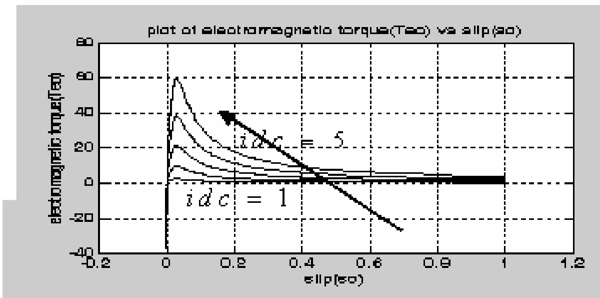

Fig.2: Plot of electromagnetic torque (Te) vs slip(s)

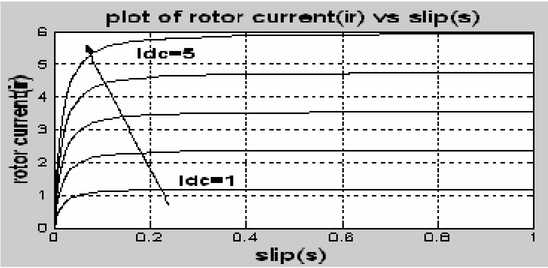

Fig.3: Plot of rotor current (ir) vs slip(s)

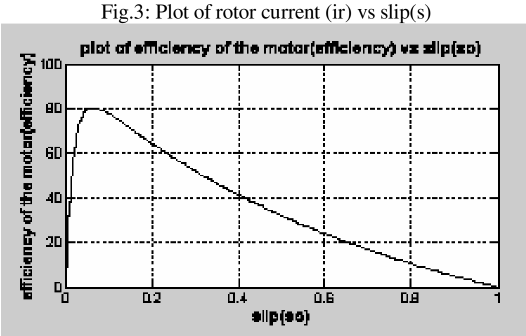

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Fig.4: Plot of motor efficiency vs slip(s)

Fig.5: Plot of power factor (p.f.) vs slip(s)

III. FUZZY CONTROLLER DESIGN

Fig. 6 shows the fuzzy controller for proposed CSI fed induction motor. A simple fuzzy proportional and integral speed control scheme has been implemented and used to assess the basic performance of the system. Two fuzzy controllers namely fuzzy speed controller and fuzzy current controller are placed in the proposed drive. Considering the fuzzy speed controller block, it is seen that the controller observes the pattern of the speed loop error signal and correspondingly updates the output slip speed ω_{ref} so that the actual speed ω_r matches the command speed ω_{ref}. There are two input signals to the fuzzy controller, the error $E = \omega_{ref} - \omega_r$ and change in error 'CE', which is related to the derivative dE/dt of error.

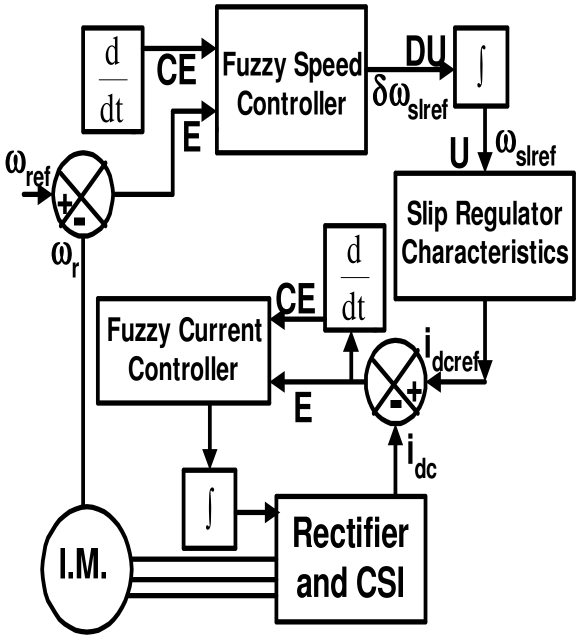

Fig. 6: Fuzzy controller for proposed drive

The general structure of a fuzzy feed back control system is shown in Fig. 7. The loop error E and change in error CE signals are converted to the respective per unit signals e and ce by dividing by the respective scale factors; i.e e = E/GE and ce = CE/GC. Similarly the output plant control signal U is derived by multiplying per unit by the scale factor GU that is DU=du ×GU and then summed to generate the U signal. The advantage of fuzzy control in terms of per unit variables is that the same control algorithm can be applied to all the plants of the same family [12]. Membership functions with values between 0 and 1 are used in the fuzzy logic control to deal with the control puzzle such as nonlinearity load disturbance and parameter disturbance.

For the proposed fuzzy controller, the universe of discourse is first partitioned in to nine linguistic variables.

LN = Large Negative
N = Negative
SN = Small Negative
Z = Zero

SP = Small Positive
P = Positive
LP = Large Positive
VSP = Very Small Positive
VSN = Very Small Negative

The triangular membership functions (MFs) are chosen to represent the linguistic variables [13]. For more precision, in the steady state, more crowding of MFs is used, near the origin. The membership function for input, output for fuzzy speed/current controller is as shown in Fig. 8, Fig. 9 and Fig. 10 respectively. The MAX-MIN inference method was used and the defuzzification was based on the centre of area method.

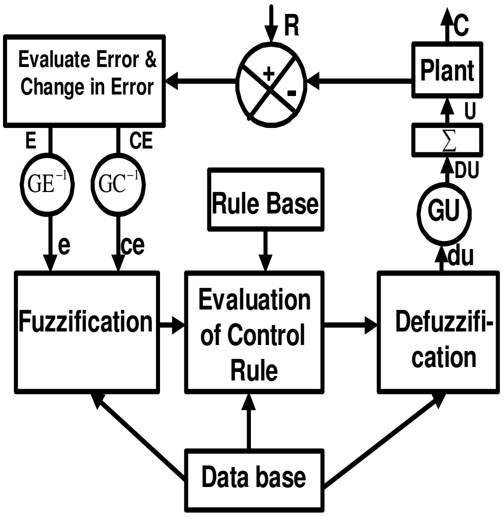

Fig. 7: Structure of fuzzy control in feedback system

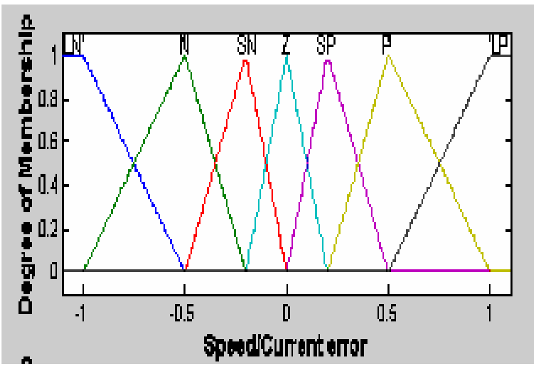

Fig. 8: Membership function of speed/current error

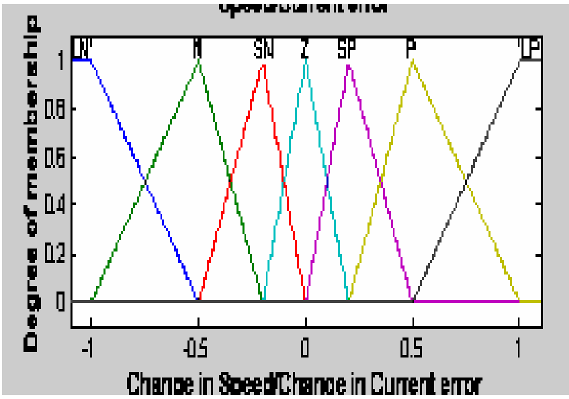

Fig. 9: Membership function of change in speed/current error

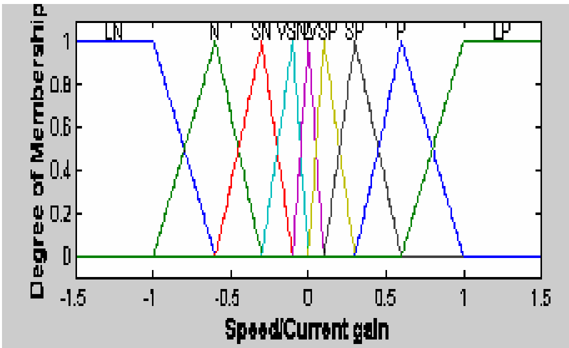

Fig. 10: Membership function of speed/current gain

The universe of discourse of all the variables, covering the whole region, is expressed in per unit values. All the MFs are asymmetrical because near the origin (steady state), the signals require more precision. There are seven MFs for e(pu) and ce(pu) signals, while there are nine MFs for the output. All the MFs are symmetrical for positive and negative values of the variables. Table 1 shows the corresponding rule table for speed/current controller.

TABLE 1
THE FUZZY CONTROL RULE

e(pu)\ ce(pu)	LN	N	SN	Z	SP	P	LP
LN	LN	LN	LN	SN	SN	SN	SN
N	LN	N	LN	VSN	VSN	VSN	VSN
SN	LN	LN	SN	Z	Z	Z	Z
Z	LN	SN	VSN	Z	VSP	SP	LP
SP	Z	Z	Z	Z	SP	LP	LP
P	VSP	VSP	VSP	VSP	LP	P	LP
LP	SP	SP	SP	SP	LP	LP	LP

IV. DYNAMIC ANALYSIS

The dynamic performance of the motor can be described by state equation (2)

$$\dot{x} = Ax + Bu \tag{2}$$

Where

$$x = [\delta i_{qs}\ \delta i_{ds}\ \delta i_{qr}\ \delta i_{dr}\ \delta v_{qs}\ \delta v_{ds}\ \delta i_{dc}\ \delta \omega_r]^T \tag{3}$$

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

$$u = [\delta\omega_s\ \delta v_{dc}\ \delta T_l]^T \tag{4}$$

$$l_1 = l_s l_r - l_m^2 \tag{5}$$

$$A = \frac{1}{l_1}\begin{bmatrix} -r_s l_r & l_m^2\omega_{slo} - l_s l_r \omega_{so} & r_r l_m & -\omega_{ro} l_m l_r & l_r & 0 & 0 & -(l_m^2 i_{dso} + l_m l_r i_{dro}) \\ l_r l_s \omega_{so} - l_m^2 \omega_{slo} & -l_r l_s & l_r l_m \omega_{ro} & l_m l_r & 0 & l_r & 0 & (l_m^2 i_{qso} + l_m l_r i_{qro}) \\ r_s l_m & l_s l_m \omega_{ro} & -r_r l_s & l_m^2 \omega_{so} - l_s l_r \omega_{slo} & -l_m & 0 & 0 & (l_m i_{dso} + l_r i_{dro}) l_s \\ -l_s l_m \omega_{ro} & l_m r_s & -(l_m^2 \omega_{so} - l_r l_s \omega_{slo}) & -r_r l_s & 0 & -l_m & 0 & -(l_m i_{qso} + l_r i_{qro}) l_s \\ -\frac{l_1}{3C} & 0 & 0 & 0 & 0 & -l_1 \omega_{so} & \frac{2 l_1}{\pi C \sqrt{3}} & 0 \\ 0 & -\frac{l_1}{3C} & 0 & 0 & l_1 \omega_{so} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{3\sqrt{3} l_1}{\pi l_f} & 0 & -\frac{r_f l_1}{l_f} & 0 \\ \frac{3P^2 l_m l_1}{8J} i_{dro} & -\frac{3P^2 l_m l_1}{8J} i_{qro} & -\frac{3P^2 l_m l_1}{8J} i_{dso} & \frac{3P^2 l_m l_1}{8J} i_{qso} & 0 & 0 & 0 & 0 \end{bmatrix} \tag{6}$$

Symbols v and i denote the voltage and current, subscripts r and s stand for rotor and stator, d and q denote direct and quadratic components of the vectors with respect to the synchronously rotating reference frame, l and r denote inductance and resistance, l_m denote the mutual inductance, ω_r ω_s ω_{sl} represents the rotor speed, synchronous speed and slip speed respectively. P is the no of pole, J is moment of inertia, and T_l is load torque,

V. RESULTS AND DISCUSSION

In order to investigate the starting transients of the system, equation (2) is solved using the software MATLAB. Results of simulation are reported for two values of load torque for two different values of operating speed.

A. Low Load Torque

Initially, the load torque is kept at a low value, equal to 0.8 Nm and operating speed of the motor is 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. 11.

Now the controller gain is adjusted by Ziegler Nichols method, first for PI controller [14]. The steady state condition is reached with K_{ps}= 27, K_{pi}= 11.25, T_{is}=0.167, and T_{ii}=0.167 as shown in Fig. 12. It is seen that the time to reach steady state conditions is approximately 1.25 sec. The peak value of dc link current is approximately 28.9 amps while the steady state value is 8.5 amps as shown in Fig. 13.

With same loading condition and same speed, the results are obtained with fuzzy controller. For this the error and change in error signal has been converted into per unit value by taking speed error factor SE = 150, speed change in error factor SC = 1, current error factor CE = 150, current change in error factor CC = 1. Fig. 14 shows the plot of rotor speed (ω_r) versus time (t) with fuzzy logic controller. In this case the peak over shoot of the speed is decreased but the settling time is now increased from 1.25 sec. to approximately 1.6 sec. The peak value of dc link current is slightly reduced to 26.8 amps as shown in Fig. 15. The steady state value is approximately the same as the conventional PI controller.

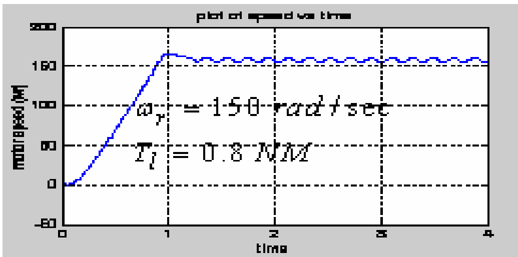

Fig. 11: Plot of rotor speed (ω_r) vs time (t)

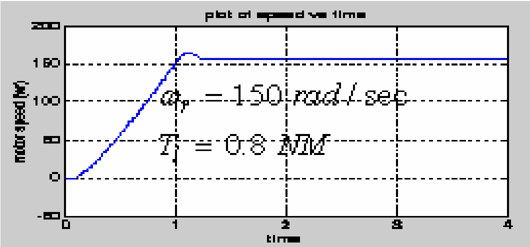

Fig. 12: Plot of rotor speed (ω_r) vs time (t) with PI controller

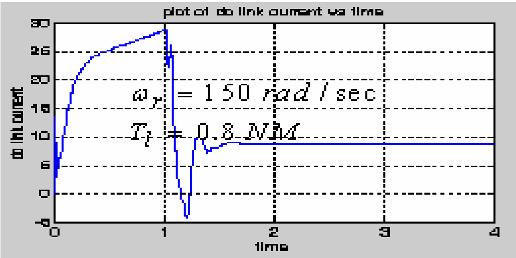

Fig. 13: Plot of DC link current (i_{dc}) vs time (t) with PI controller

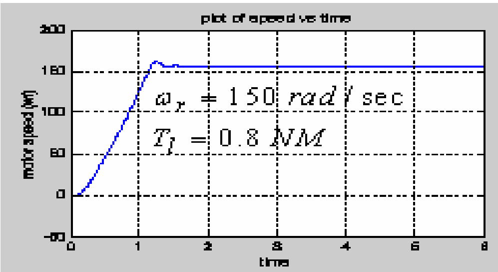

Fig. 14: Plot of rotor speed (ω_r) vs time (t) with fuzzy PI controller

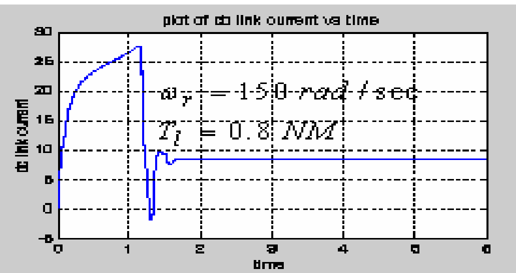

Fig. 15: Plot of DC link current (i_{dc}) vs time (t) with fuzzy PI controller

When the operating speed of the motor is decreased say now equal to 140 rad/sec and loading condition is same as 0.8 Nm, it is observed that with conventional PI controller, steady state conditions is reached at 1.6 sec by changing the controller gain value of K_{ps}=14.4, K_{pi}=8.1, and T_{is}= 0.208 as shown in Fig. 16. The peak value of dc link current is almost same as 28.5 amps while its steady value is now reduced from 8.5 amps to 4 amps as shown in Fig. 17.

In case of fuzzy controller no change is required in the controller parameters and same controller works well as shown in Fig. 18 & 19 for speed and dc link current respectively. The steady state speed is reached now at 2.2 sec. The peak overshoot value of dc link current is reduced from 26.8 amps to approximately 20 amps. The state value is also decreased from 8.5 to 7 amps as shown in Fig. 19.

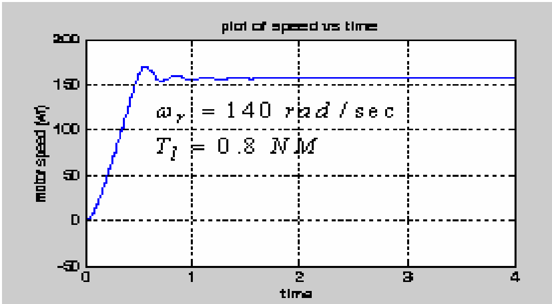

Fig. 16: Plot of rotor speed (ω_r) vs time (t) with PI controller

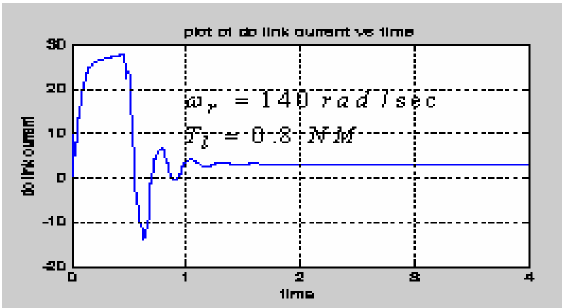

Fig. 17: Plot of DC link current (i_{dc}) vs time (t) with PI controller

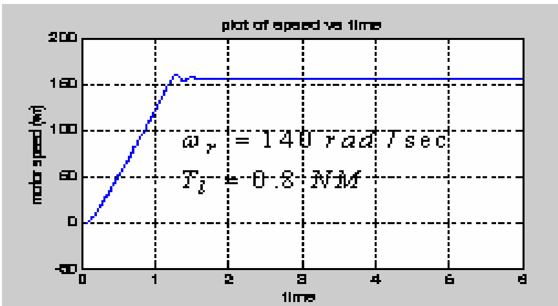

Fig. 18: Plot of rotor speed (ω_r) vs time (t) with fuzzy PI controller

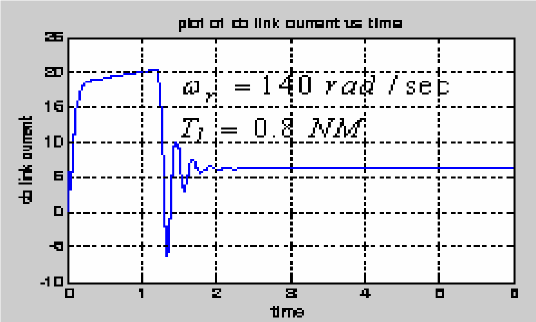

Fig. 19: Plot of DC link current (i_{dc}) vs time (t) with fuzzy P controller

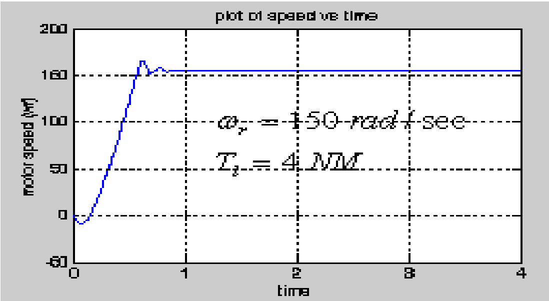

Fig. 20: Plot of rotor speed (ω_r) vs time (t) with PI controller

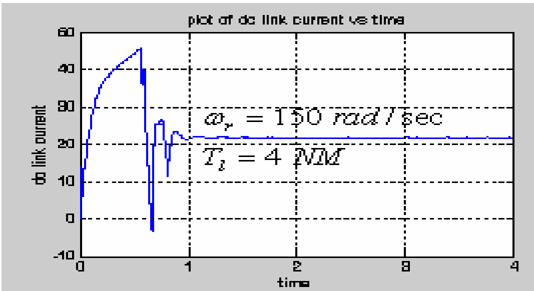

Fig. 21: Plot of DC link current (i_{dc}) vs time (t) with PI controller

With fuzzy logic controller, no adjustment is required for controller parameters. The controller designed earlier gives the required response as shown in Fig. 22 and Fig. 23 for rotor speed and dc link current respectively. Now, the peak value of DC link current is 45.4 amps and steady state value is same as 21 amps for conventional PI controller.

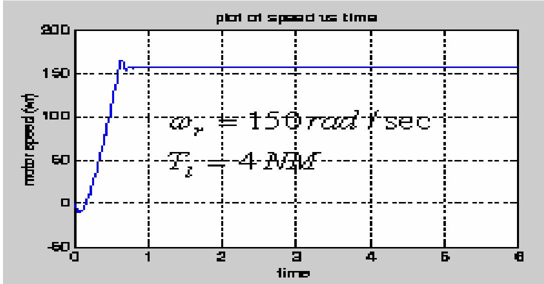

Fig. 22: Plot of rotor speed (ω_r) vs time (t) with fuzzy PI controller

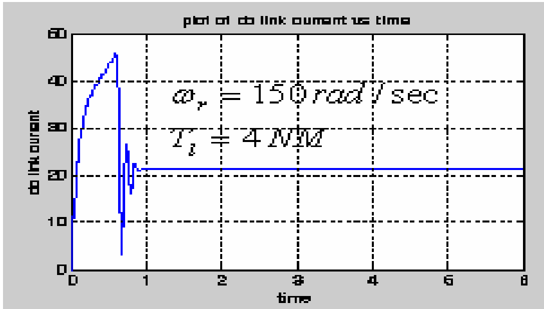

Fig. 23: Plot of DC link current (i_{dc}) vs time (t) with fuzzy PI controller

B. High Load Torque

Now the study has been made when the load torque is increased to 4 Nm and operating speed are same as 150 rad/sec. and 140 rad/sec. respectively. When rotor speed is $\omega_r = 150\ rad/\sec$, in case of conventional PI controller, the parameters are adjusted in order to obtain the steady state characteristics of the motor. The rotor speed now becomes stable at 0.9 sec with controller parameter of K_{ps} = 27, K_{pi} = 11.25 $T_{is} = 0.167$, $T_{ii} = 0.167$ as shown in Fig. 20. The peak value of dc link current is increased to 46.8 amps as shown in Fig. 21 while its steady state value is 21 amps.

With rotor speed of 140 rad/sec, for conventional PI controller the parameters are again have to change as $K_{ps} = 27$, $K_{pi} = 6.75$, & $T_{is} = 0.183$, $T_{ii} = 0.183$. In this case rotor speed becomes stable in 1.3 sec as shown in Fig. 24. The peak value of DC link current is now 36 amps and steady state value is reduced from 21 amps to 16 amps as shown in Fig. 25

For fuzzy logic controller again no adjustment is required and the same controller is used to obtain the transient characteristics. The rotor speed now becomes stable in 3.6 sec as shown in

Fig. 26. The peak value of DC link current is 30 amps while steady state value is 23 amps.

Thus, it may be stated that for fuzzy controller, once the parameters are selected for a specified load and speed it will work for all other load and speed. For conventional PI controller, the parameters have to be change for each load and speed setting, which is difficult task to achieve. The peak value of DC link current is also less in Fuzzy controller as compared to conventional PI controller, which reduces the rating of the devices used in the inverter, thus saves the cost.

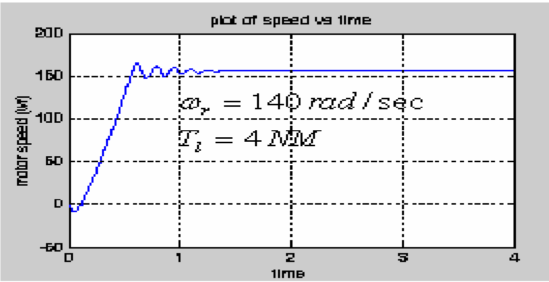

Fig. 24: Plot of rotor speed (ω_r) vs time (t) with PI controller

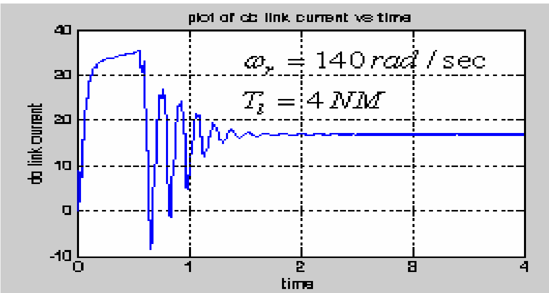

Fig. 25: Plot of DC link current (i_{dc}) vs time (t) with PI controller

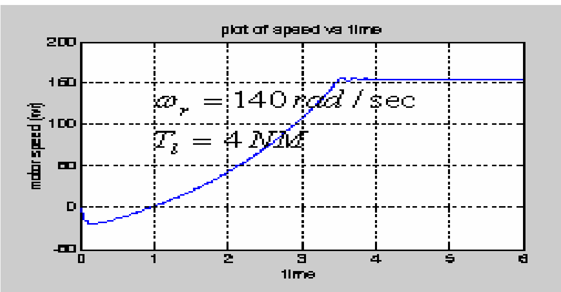

Fig. 26: Plot of rotor speed (ω_r) vs time (t) with fuzzy PI controller

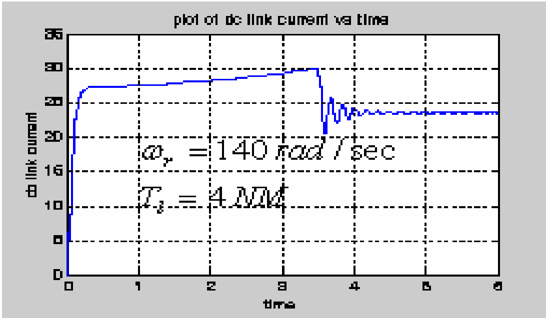

Fig. 27: Plot of DC link current (i_{dc}) vs time (t) with fuzzy PI controller

VI. Conclusions

A comparative study has been made for the starting transients of a current source inverter fed inverter motor drive system using conventional PI controller and fuzzy PI controller in speed and current loops by simulating the system with MATLAB coding. It has been found that with a fixed torque and speed the fuzzy controller reduces the over shoot value of speed by approximately 2 to 5%. It also reduces the peak over shoot value of DC link current around 4% that reduces the rating of the device used in the system. When the motor speed is changed the controller parameters value for conventional PI controller have to be changed manually for each speed while it is adjusted itself for Fuzzy logic controller. But at the same time, with fuzzy logic controller the system shows some what slow response with fewer oscillations. This implies that fuzzy controller can be used where smooth operation is required.

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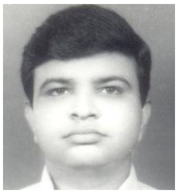

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