6.1 INTRODUCTION

In position control system, the high accuracy, quick response, high stiffness, and smoothness of movement, high robustness, low cost, and limited maintenance are desirable. Generally, dc servo motors have been widely used for various industrial applications such as robots, manipulators, and numerically controlled machine tools due to their flexibility and increased productivity. Today’s servos include either dc motors or permanent-magnet motors [1-5]. Permanent magnet motors are generally more expensive than induction machine due to the high cost of their magnets but have higher efficiency and reduced size. For this, alternative motors are often highly desirable. The induction motors offer many attractive features, such as ruggedness, low cost, and high efficiency [6-7]. So, the induction motor can be used in place of dc servo motors provided these are able to give the desired performance under all operating conditions. The author has investigated the application of induction motor in position control.

In this chapter, the block diagram of the proposed position control scheme using conventional direct self control as well as using fuzzy direct self control of induction motor drive is presented. The mathematical model of the proposed schemes has been developed. The algorithms of digital simulation for position control of induction motor using conventional and fuzzy direct self control are discussed. The simulation results with respect to a typical system are also given. The comparative study of position
control of induction motor using conventional direct self control and fuzzy direct self control have been carried out.

6.2 POSITION CONTROL OF INDUCTION MOTOR USING CONVENTIONAL DIRECT SELF CONTROL

The mathematical model of proposed position control system, simulation algorithm and simulation results with respect to sample system are discussed in the following paragraph.

6.2.1 Mathematical Model of The Proposed Position Control Scheme

The schematic diagram of the position control system using conventional direct self controlled induction motor drive system under study is shown in Fig.6.1. It consists essentially of power circuit and control circuit. The power circuit of the induction motor drive consists of space vector modulated voltage source inverter, whereas the control circuit consists of flux estimator, torque estimator, speed controller and position controller as its essential components. The d-axis and q-axis currents are obtained from phase currents by using co-ordinate transformation. The d-axis and q-axis voltages are derived from dc voltage and the switching functions of inverter. The stator flux can be estimated by means of d-axis and q-axis currents and voltages and the torque can be measured by means of stator flux components and d-axis and q-axis components of current. The position controller and speed controller are used to estimate the reference torque. Then the reference values for the stator flux and the torque are compared with the estimated values of flux and torque in flux and torque comparators respectively. The output of comparators and the position of the stator flux are used as inputs to the selection table to generate switching functions for the inverter. The position of the stator flux is divided into twelve regions. In accordance with the Fig. 6.1, the state of the inverter is selected based on the torque error, stator flux error, and stator flux position as discussed in chapter four. The flux estimator, torque estimator, output voltage of space vector modulated inverter and modeling of induction motor are explain in previous chapters.
Fig. 6.1 Block diagram of position control system using conventional direct self control induction motor drive.
In position control the mathematical model of induction motor, position controller, and speed controller are explained below:

6.2.1.1 Induction Motor Model

To develop a general mathematical model of induction motor for the study of the dynamic behavior of the motor in position control, the following simplifying assumptions are made: resistances, $r$, $r'$, and inductances $L_s$, $L'_s$, and $L_{ms}$, are assumed constant and the air-gap flux distribution is considered sinusoidal. Furthermore, the absence of saturation, iron losses, eddy currents, capacitive effects, slot and end effects, and thermal phenomena is also assumed.

The equations of the induction motor governing its dynamic response expressed in the stationary reference frame are explained in article 4.2.4. These equations except the torque balance equation are used in position control. In position control applications the torque balance equation takes into account the torque caused by the rotating mass. As shown in Fig.6.2, the torque gives a positive or negative contribution, depending on its agreement with the actual position and the rotating direction.

The torque balance equation of the induction motor is given by [6]

$$J_m \frac{d\omega_r}{dt} + B_m \omega_r + T_s \sin \theta_r = T_r \tag{6.1}$$

![Fig.6.2 Schematic diagram of the induction motor with load](image-url)
6.2.1.2 Position Controller

The dynamic performance of the proposed position control system is primarily determined by the position controller. The position sensor is used to sense the rotor position \( \theta_r \). In this scheme the position is estimated by the equation (6.2). Then the reference position, \( \theta_{\text{ref}} \) is compared with rotor position, \( \theta_r \). The error in position, \( e\theta_r \), is obtained as the difference of \( \theta_{\text{ref}} \) and \( \theta_r \) and can be expressed by the equation (6.3). The error in position is then processed by position controller to provide the reference speed. Consequently, the reference speed is time varying and depends on the error in position.

\[
\theta_r (n + 1) = \int \omega_r \, dt + \theta_r(n) \quad (6.2)
\]

\[
e\theta_r = \theta_{\text{ref}} - \theta_r \quad (6.3)
\]

In the position controller, the maximum reference speed is denoted by \( \omega_{\text{max}} \). If error in position, \( e\theta_r \) is greater than \( e\theta_{\max} \), the reference speed, \( \omega_{\text{ref}} \) is equal to \( \omega_{\text{max}} \) and if the error is less than \( e\theta_{\max} \), then it will be reduced proportionately. So, when the error in position becomes zero, the reference speed, \( \omega_{\text{ref}} \) and rotor speed, \( \omega_r \) become zero. This may be expressed by the following equations:

\[
\text{if } e\theta_r \geq e\theta_{\max} \text{, then } \omega_{\text{ref}} = \omega_{\text{max}}. \quad (6.4)
\]

and

\[
\text{if } e\theta_r < e\theta_{\max} \text{, then } \omega_{\text{ref}} = \frac{e\theta_r}{e\theta_{\max}} \omega_{\text{max}}. \quad (6.5)
\]

6.2.1.3 Speed Controller

The speed control loop is the second important component in the present position control algorithm. It is used to reduce the effects of dry friction torque and also take care of load torque. A proportional integral type speed controller is used in this case.

The rotor speed is determined from the position signal of the encoder. The speed controller computes the error in speed, \( e\omega_r \), by comparing with the reference speed and rotor speed.
Then speed controller is used to determine the reference torque $T_{\text{ref}}$. $T_{\text{ref}}$ is determined by the load torque $T_i$ along with the error in speed. The $T_{\text{ref}}$ is calculated by the expression

$$T_{\text{ref}}(n+1) = K_p e\omega_r(n) + K_i e\omega_r(n)\Delta T + T_{\text{ref}}(n)$$  \hspace{1cm} (6.6)

where,

- $K_p$ = proportional gain constant
- $K_i$ = integral gain constant
- $\Delta T$ = sampling time, 400\,\mu s
- $T_{\text{ref}}$ = reference torque
- $e\omega_r = \omega_{\text{ref}} - \omega_r$ = error in speed error
- $\omega_{\text{ref}}$ = reference speed
- $\omega_r$ = actual speed
- $n$ = current interval

### 6.2.2 Simulation Algorithm for Position Control of Induction Motor Using Conventional Direct Self Control

The necessary algorithm for digital computer simulation for position control of induction motor using direct self control is described below:

i. Select $V_{ac}$, $\psi_{\text{ref}}$ and $\theta_{\text{ref}}$.

ii. Initialize $i_{d0(0)}$, $i_{q0(0)}$, $i_{d0(0)}$, $i_{q0(0)}$, $V_{d0(0)}$, $V_{q0(0)}$, $V_{\text{ref}(0)}$, $\theta_{\text{ref}(0)}$, and $\omega_{\text{ref}(0)}$ with a given value.

iii. Estimate position error from the difference between the reference position and actual rotor position using the equation (6.3).

iv. Position controller computes the reference speed from equation (6.4) and (6.5).

v. The rotor speed, $\omega_r$ is computed and compared with reference speed to
estimate error in speed. Then error in speed is used to compute the reference torque from equation (6.6).

vi. Compute torque error $eT_e$ and flux error $e\psi_f$. These parameters along with stator flux angle are fed to the selection table to compute the switching functions SA, SB and SC.

vii. Calculate the $V_d(k)$, $V_q(k)$ using equation (4.2.9) and the switching functions SA, SB, and SC.

viii. The matrix equation (4.2.15) is solved to compute $k+1$ iteration currents $i_{dq(k+1)}$, $i'_{dq(k+1)}$ and $i''_{dq(k+1)}$ by using $k$th currents $i_{dq(k)}$, $i'_{dq(k)}$, $i''_{dq(k)}$ and $\Delta i_{dq(k)}$, $\Delta i'_{dq(k)}$, $\Delta i''_{dq(k)}$ respectively.

ix. Compute $\psi_{dq(k+1)}$ and $\psi_{dq(k+1)}$ with the help of equation (4.2.1) and (4.2.2) respectively.

x. Estimate the stator flux $\psi_{st}(k+1)$ using the expression $\sqrt{\psi_{dq(k+1)}^2 + \psi_{dq(k+1)}^2}$ and stator flux angle using equation (4.2.4)

xi. Compute torque $T_e(k+1)$ using equation (4.2.6).

xii. Estimate rotor speed $\omega_r(k+1)$ using equation (6.1).

xiii. Estimate rotor position $\theta_r(k+1)$ using equation (6.3).

xiv. The procedure is used iteratively from step (iii) to step (xiii) to obtain the dynamic response for position control of the induction motor till the response reaches a steady value.

6.2.3 Simulation Results for Position Control of Induction Motor Using Conventional Direct Self Control

The digital computer program has been developed with the help of simulation algorithm given above to simulate the position control of induction motor using MATLAB. The dynamic performance of the position control using conventional direct self control induction motor drive has been investigated with respect to two representative changes in the position command as follows:
(i) fractional rotation subjected to partial load as well as to full load,
(ii) multi-turn rotation subjected to partial load as well as to full load.

The simulation study has been done to verify the ability of the system under different applications such as robotic arm and multi-turn applications such as conveyors, cranes, elevators, and so forth. The investigation has been done on the sample system which is already used in previous chapters [8]. All the simulations carried out in this chapter have been done using the terminal conditions are as given in table 6.2.1

<table>
<thead>
<tr>
<th>Table 6.2.1 Initial conditions for position control investigations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage to inverter</td>
</tr>
<tr>
<td>Flux command</td>
</tr>
<tr>
<td>Maximum speed for fractional rotation, ( \omega_{\text{max}} )</td>
</tr>
<tr>
<td>Maximum speed for multi-turn rotation, ( \omega_{\text{max}} )</td>
</tr>
</tbody>
</table>

The sampling period of position and speed has been taken as 400\( \mu \)s.

The dynamic performance of the position control using conventional direct self control of induction motor drive has been obtained and presented in the following paragraphs. The fractional rotation and multi-turn rotation have been considered for investigations under half the full load and full load operating conditions. The simulation results for these cases are given below.

### 6.2.3.1 Position Control Performance of Induction Motor Subjected to Step Change in Position Command \(-\frac{\pi}{2}\) Radian with Half The Full Load

The response of the system variables indicating the dynamic performance of position control of induction motor for this case are illustrated in Fig. 6.2.3.1.1 to Fig. 6.2.3.1.12.

The position response of induction motor for a step change in position reference, a fraction of the revolution \((\frac{\pi}{2}\) radian) with half the full load, is shown
Fig. 6.2.3.1.1. The delay time, $t_d$ is the time required for the response to reach half the final value the very fast time. The rise time, $t_r$ is the time required for the response to rise from 10 to 90% of its final value. The settling time, $t_s$ is the time required for the response curve to reach and stay within a range about the final value of size specified by absolute percentage of the final value (usually 2%) [9]. In this case the delay time, $t_d$ and rise time, $t_r$ of position response are about 97 ms and 206 ms respectively. The settling time of position response is about 358 ms. The variation of position error with time is shown in Fig. 6.2.3.1.2. At steady state, the position error is negative of the order of 1.08%.

Fig. 6.2.3.1.3 shows the speed response of the motor. Initially the motor runs at stand still. As the electromagnetic torque is developed in the machine, the induction motor is accelerated and speed rises up to the maximum speed of 10 rad/s in about 36 ms. Then the speed is maintained constant for 38 ms. After that the induction motor is decelerated from 10 rad/s to zero in about 458 ms. The phase plane trajectory for speed - position is depicted in Fig. 6.2.3.1.4.

Torque response of the motor is shown in Fig. 6.2.3.1.5. Initially the reference torque is 20 N-m. So, the electromagnetic torque rises to 20 N-m. After that the reference torque is estimated by the speed controller and electromagnetic torque follows the reference torque. At steady state operating condition, the average value of electromagnetic torque equals the holding torque.

Fig. 6.2.3.1.6 and Fig. 6.2.3.1.7 show the corresponding variation in q-axis and d-axis components of stator current. The locus of stator current vector is also shown in Fig. 6.2.3.1.8. Similarly, Fig. 6.2.3.1.9 and Fig. 6.2.3.1.10 show the variation of d-axis and q-axis components of stator flux vector. It may be noticed that the nature of stator flux vector is non-sinusoidal. The trajectory of stator flux vector is shown in Fig. 6.2.3.1.11 and the variation in position of stator flux vector is illustrated in Fig. 6.2.3.1.12.

To investigate the stability of position control using conventional direct self control induction motor drive subjected to step change in position command $\frac{\pi}{2}$
Fig. 6.2.3.1.1 Position response for sudden position variation \( \left( \frac{\pi}{2} \text{ radian} \right) \) with half the full load.

Fig. 6.2.3.1.2 The response of position error for sudden position variation \( \left( \frac{\pi}{2} \text{ radian} \right) \) with half the full load.
Fig.6.2.3.1.3 Speed response for sudden position variation ($\frac{\pi}{2}$ radian) with half the full load.

Fig.6.2.3.1.4 Phase plane trajectory for sudden position variation ($\frac{\pi}{2}$ radian) with half the full load.
Fig. 6.2.3.1.5 Torque response for sudden position variation \( (\pi/2 \text{ radian}) \) with half the full load.

Fig. 6.2.3.1.6 q-axis stator current for sudden position variation \( (\pi/2 \text{ radian}) \) with half the full load.
Fig. 6.2.3.1.7 d-axis stator current for sudden position variation ($\frac{\pi}{2}$ radian) with half the full load.

Fig. 6.2.3.1.8 Locus of stator current vector for sudden position variation ($\frac{\pi}{2}$ radian) with half the full load.
Fig. 6.2.3.1.9  $d$-axis stator flux for sudden position variation $(\frac{\pi}{2} \text{ radian})$ with half the full load.

Fig. 6.2.3.1.10  $q$-axis stator flux for sudden position variation $(\frac{\pi}{2} \text{ radian})$ with half the full load.
Fig. 6.2.3.1.11 Locus of stator flux vector for sudden position \( \frac{\pi}{2} \) (radian) with half the full load.

Fig. 6.2.3.1.12 Stator flux position for sudden position variation \( \frac{\pi}{2} \) (radian) with half the full load.
Fig.6.2.3.1.13 Phase-plane portrait of error in position and change in error in position for position control of induction motor using conventional DSC subjected to step change in position command $\frac{\pi}{2}$ radian with half the full load.
radian with half the full load, the author has used the phase plane analysis of the nonlinear control system. The Fig. 6.2.3.1.13 shows the phase-plane plot of error in position and change in error in position. The phase-plane trajectory start from point $A_1$, \((\frac{\pi}{2}, 0)\) and tends to converge to the stable focus $A_2$, \((-0.017, 0)\). As the trajectory approaches the singular point, $A_2$, the position control using conventional direct self control induction motor drive is stable.

6.2.3.2 Position Control Performance of Induction Motor Subjected to Step Change in Position Command -- $\frac{\pi}{2}$ Radian with Full Load

The variation of the system variables indicating the dynamic performance of position control of induction motor subjected to step change in position command, $\frac{\pi}{2}$ radian with full load is illustrated in Fig. 6.2.3.2.1 to Fig. 6.2.3.2.12.

Fig. 6.2.3.2.1 shows the position response of induction motor. It may be noticed that the delay time and rise time of the position response are about 97 ms and 206 ms respectively. The settling time of this response is about 347 ms. The response of position error is shown in Fig. 6.2.3.2.2. The steady state position error is negative of the order of 1.05%.

The speed response of the motor is illustrated in Fig. 6.2.3.2.3. Before applying the position command, the motor is at stand still. When the position command is given, the motor speed rises up to 10 rad/s. Thereafter the position control system retain this speed for 36 ms. Then the machine speed decrease and it reaches to zero in about 435 ms. Fig. 6.2.3.2.4 shows the phase plane trajectory.

Fig. 6.2.3.2.5 shows the torque response of the motor. After the application of step change in position reference, the reference torque becomes 20 N-m. Therefore the electromagnetic torque rises to 20 N-m and the motor speed increases. While the motor speed is 10 rad/s, the reference torque is estimated by the speed controller and
Fig.6.2.3.2.1 Position response for sudden position variation ($\frac{\pi}{2}$ radian) with full load.

Fig.6.2.3.2.2 The response of position error for sudden position variation ($\frac{\pi}{2}$ radian) with full load.
Fig.6.2.3.2.3 Speed response for sudden position variation 
\(\frac{\pi}{2}\) radian) with full load.

Fig.6.2.3.2.4 Phase plane trajectory for sudden position variation 
\(\frac{\pi}{2}\) radian) with full load.
Fig.6.2.3.2.5 Torque response for sudden position variation 
\((\frac{\pi}{2} \text{ radian})\) with full load.

Fig.6.2.3.2.6 q-axis stator current for sudden position 
variation \((\frac{\pi}{2} \text{ radian})\) with full load.
Fig. 6.2.3.2.7 d-axis stator current for sudden position variation (radian) with full load

Fig. 6.2.3.2.8 Locus of stator current vector for sudden position variation (radian) with full load
Fig. 6.2.3.2.9 d-axis stator flux for sudden position variation ($\frac{\pi}{2}$ radian) with full load

Fig. 6.2.3.2.10 q-axis stator flux for sudden position variation ($\frac{\pi}{2}$ radian) with full load
Fig. 6.2.3.2.11 Locus of stator flux vector for sudden variation ($\frac{\pi}{2}$ radian) with full load.

Fig. 6.2.3.2.12 Stator flux position for sudden position variation ($\frac{\pi}{2}$ radian) with full load.
Fig. 6.2.3.2.13 Phase-plane portrait of error in position and change in error in position for position control of induction motor using conventional DSC subjected to step change in position command $\frac{\pi}{2}$ radian with full load.
electromagnetic torque follows the reference torque. The average value of electromagnetic torque equals the holding torque at steady state condition.

The variations in $q$-axis and $d$-axis components of stator current are illustrated in Fig. 6.2.3.2.6 and Fig.6.2.3.2.7 respectively. The locus of stator current vector is shown in Fig.6.2.3.2.8. In the same way, Fig.6.2.3.2.9 and Fig.6.2.3.2.10 show the $d$-axis and $q$-axis stator flux vectors variation. It is observed that nature of stator flux vector is non-sinusoidal. Fig. 6.2.3.2.11 shows the trajectory of stator flux and the position response of stator flux vector is depicted in Fig. 6.2.3.2.12.

The phase-plane trajectory of error in position and change in error in position for position control using conventional direct self control induction motor drive subjected to step change in position command $\frac{\pi}{2}$ radian with full load is shown in Fig.6.2.3.2.13. The trajectory start from point $A_3$, $(\frac{\pi}{2}, 0)$ and tends to converge to the singular point $A_4$, (-0.0165, 0). Consequently, the position control using conventional direct self control induction motor drive is stable.

6.2.3.3 Position Control Performance of Induction Motor Subjected to Step Change in Position Command -- $5\pi$ Radian with Half The Full Load

The time response of the system variables indicating the dynamic performance of position control of induction motor for step change in multi-turn revolution, $5\pi$ radian with half the full load (10 N-m) are illustrated in Fig. 6.2.3.3.1 to Fig.6.2.3.3.12.

The variation of position of induction motor is depicted in Fig.6.2.3.3.1 when the machine is subjected to step change in position as indicated above. In this position response, it is observed that the delay time is about 556 ms and rise time is about 842 ms. The settling time is about 1070 ms. Fig.6.2.3.3.2 shows the time response of
Fig. 6.2.3.3.1 Position response for sudden position variation ($5\pi$ radian) with half the full load.

Fig. 6.2.3.3.2 The response of position error for sudden position variation ($5\pi$ radian) with half the full load.
Fig. 6.2.3.3.3 Speed response for sudden position variation (5\pi radian) with half the full load.

Fig. 6.2.3.3.4 Phase plane trajectory for sudden position variation (5\pi radian) with half the full load.
Fig. 6.2.3.5 Torque response for sudden position variation ($5\pi$ radian) with half the full load.

Fig. 6.2.3.6 $q$-axis stator current for sudden position variation ($5\pi$ radian) with half the full load.
Fig.6.2.3.7 \textbf{d-axis stator current for sudden position variation (5\pi \text{ radian}) with half the full load.}

Fig.6.2.3.8 \textbf{Locus of stator current vector for sudden position variation (5\pi \text{ radian}) with half the full load.}
Fig.6.2.3.9 d-axis stator flux for sudden position variation (5π radian) with half the full load.

Fig.6.2.3.10 q-axis stator flux for sudden position variation (5π radian) with half the full load.
Fig. 6.2.3.3.11 Locus of stator flux vector for sudden position variation (5π radian) with half the full load.

Fig. 6.2.3.3.12 Stator flux position for sudden position variation (5π radian) with half the full load.
position error. The steady state error of position error is negative and it is about 0.0125 radian.

Fig. 6.2.3.3.3 shows the speed response of induction motor. Initially the motor speed rises from zero to the maximum speed of 15 rad/s and maintained this speed for 932 ms. Then the motor decelerate from 15 rad/s to zero in about 1240 ms. The phase plane trajectory (plot of speed vs position) is illustrated in Fig. 6.2.3.3.4.

The time response of the electromagnetic torque is illustrated in Fig 6.2.3.3.5. Due to step change in position command, the electromagnetic torque of induction motor raises to about 20 N-m and the motor speed increases. When the machine speed is 15 rad/s, the electromagnetic torque decreases to 10 Nm. It may be observed from the response that the electromagnetic torque is maintained constant for 942 ms to retain the constant speed. At about 1002 ms the electromagnetic torque is reduced to decelerate the machine and speed decreases. At steady state operating condition, the holding torque equals the average electromagnetic torque.

Fig. 6.2.3.3.6 and Fig.6.2.3.3.7 show the variation of q-axis and d-axis components of stator current vector respectively. The locus of stator current vector is shown in Fig.6.2.3.3.8. Similarly, Fig.6.2.3.3.9 and Fig.6.2.3.3.10 show the response of d-axis and q-axis components of stator flux vector. It is depicted that nature of stator flux vector is non-sinusoidal. Fig. 6.2.3.3.11 shows the trajectory of stator flux vector and the variation in position of stator flux vector is illustrated in Fig. 6.2.3.3.12.

6.2.3.4 Position Control Performance of Induction Motor Subjected to Step Change in Position Command -- $5\pi$ Radian with Full Load

The dynamic response of position control of induction motor subjected to step change in position reference as indicated above is illustrated in Fig. 6.2.3.4.1 to Fig.6.2.3.4.12.

The position response of induction motor for a step change in multi turn revolution ($5\pi$ radian) is shown Fig.6.2.3.4.1. It is depicted in this figure that the delay
Fig. 6.2.3.4.1 Position response for sudden position variation (5π radian) with full load.

Fig. 6.2.3.4.2 The response of position error for sudden position variation (5π radian) with full load.
Fig. 6.2.3.4.3 Speed response for sudden position variation (5\pi radian) with full load.

Fig. 6.2.3.4.4 Phase plane trajectory for sudden position variation (5\pi radian) with full load.
Fig. 6.2.3.4.5 Torque response for sudden position variation ($5\pi$ radian) with full load.

Fig. 6.2.3.4.6 q-axis stator current for sudden position variation ($5\pi$ radian) with full load.
Fig. 6.2.3.4.7 d-axis stator current for sudden position variation ($5\pi$ radian) with full load.

Fig. 6.2.3.4.8 Locus of stator current vector for sudden position variation ($5\pi$ radian) with full load.
Fig. 6.2.3.4.9 d-axis stator flux for sudden position variation (5π radian) with full load.

Fig. 6.2.3.4.10 q-axis stator flux for sudden position variation (5π radian) with full load.
Fig. 6.2.3.4.11 Locus of stator flux vector for sudden position variation ($5\pi$ radian) with full load.

Fig. 6.2.3.4.12 Stator flux position for sudden position variation ($5\pi$ radian) with full load.
time and rise time are 560 ms and 832 ms respectively. The response reaches steady state position in about 1081 ms. Fig.6.2.3.4.2 shows the variation of position error. The steady state position error is negative and it is 0.012 rad.

Fig.6.2.3.4.3 shows the speed response of the motor. Initially the motor speed rises to the maximum speed of 15 rad/s and maintained this speed for 922 ms. Then the motor is decelerated from 15 rad/s to zero in about 1255 ms. The phase plane trajectory is depicted in Fig.6.2.3.4.4.

Torque response of the motor is shown in Fig.6.2.3.4.5. Initially the reference torque is 30 N-m. So, the electromagnetic torque rises to 30 N-m and speed increases. When the motor speed is 15 rad/s, the reference torque is estimated by the speed controller and electromagnetic torque follows the reference torque. At steady state condition the electromagnetic torque equals the holding torque.

The response of q-axis and d-axis components of stator current vector is shown in Fig.6.2.3.4.6 and Fig.6.2.3.4.7 respectively. The nature of stator current vector is non-sinusoidal as depicted in Fig.6.2.3.4.8. Fig.6.2.3.4.9 and Fig.6.2.3.4.10 show the d-axis and q-axis stator flux vectors variation. The nature of stator flux vector is also non-sinusoidal as indicated in Fig.6.2.3.4.11 and the position variation of stator flux with time is given in Fig.6.2.3.4.12.

6.3 POSITION CONTROL OF INDUCTION MOTOR USING FUZZY DIRECT SELF CONTROL

The modeling of position control of induction motor using fuzzy direct self control, simulation algorithm and simulation results with respect to typical system are explained below.
6.3.1 Mathematical Model of the Proposed Position Control Scheme

The schematic diagram for position control of induction motor using fuzzy direct self control is shown in Fig. 6.3. This block diagram is similar to the one given in Fig. 6.1 with some differences. In place of selection table of Fig. 6.1, the fuzzy controller is used to generate switching functions for the space vector modulated inverter. In addition, fuzzy position controller and fuzzy speed controller are used in place of conventional position and speed controller. The error in position and change in position error are used as input parameters of fuzzy position controller. Then fuzzy position controller determines the reference speed. The error in speed and change in error in speed are obtained and fed to the fuzzy speed controller. Thereafter the reference torque is provided by the fuzzy speed controller. The flux estimator and torque estimator are used to estimate stator flux and electromagnetic torque. Then the estimated values of flux and torque are compared with the reference values of the stator flux and the torque to estimate stator flux error and torque error. The torque error, stator flux error, and stator flux vector position are used as inputs to the fuzzy controller to select space voltage vector of the inverter. The modeling of flux estimator and torque estimator has been discussed in chapter 4. The mathematical model of induction motor, fuzzy speed controller and fuzzy position controller for position control of induction motor using fuzzy direct self control are explained in the following paragraphs.

6.3.1.1 Induction Motor Model

The mathematical model of induction motor in the stationary reference frame is explained in chapter 4 and the torque balance equation is given in article 6.2.1. These equations of induction motor are used to develop a mathematical model of the position control of induction motor using fuzzy direct self control.

6.3.1.2 Fuzzy Position Controller

The fuzzy position control system is first important block of the position control system. In the fuzzy position controller, the input parameters are error in position and change in error in position and the control action of position controller is reference.

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Fig. 6.3 Block diagram of position control system using fuzzy direct self control induction motor drive.
speed. The rotor position, \( \theta_r \), is measured by the position sensor and the reference position is commanded by \( \theta_{ref} \). The error in position \( e\theta_r \) is obtained as the difference of \( \theta_{ref} \) and \( \theta_r \), and the change in position error, \( ce\theta_r \), is estimated from the difference between two successive position errors. The error in position and change in error position are determined by the equation (6.3.1) and (6.3.2).

\[
e\theta_r(n) = \theta_{ref}(n) - \theta_r(n)
\]
\[
ce\theta_r(n) = e\theta_r(n) - e\theta_r(n-1)
\]

where, \( e\theta_r(n) \) = position error
\( ce\theta_r(n) \) = change in position error
\( \theta_{ref} \) = reference position
\( \theta_r \) = actual rotor position
\( n \) = sampling interval

The reference speed is time varying and depends on error in rotor position and the change in position error. The following basic steps involved in the design of proposed fuzzy position controller are discussed below:

**Step 1 Fuzzification:** The fuzzifier takes crisp values of position error and change in position error, and calculates the membership values for all the fuzzy sets defined for these two inputs [10]. A singleton fuzzifier is used with triangular membership functions to obtain the fuzzified values of position error and change in position error. The fuzzy membership functions for position error and change in position error are shown in Fig.6.4(a) and Fig.6.4(b) respectively, where the fuzzy set names stand for linguistic fuzzy variables Positive Big (PB), Positive Medium (PM), Positive Small (PS), Zero (ZE), Negative Small (NS), Negative Medium (NM), and Negative Big (NB). Correspondingly, output of fuzzy position controller, the reference speed, is also fuzzified as shown in Fig.6.4(c). The fuzzy linguistic variables of reference speed are Positive Big (PB), Positive Medium (PM), Positive Small (PS), Zero (ZE), Negative Small (NS), Negative Medium (NM), and Negative Big (NB).
Fig. 6.4(a) Fuzzification of position error

Fig. 6.4(b) Fuzzification of change in position error

Fig. 6.4(c) Fuzzification of reference speed
**Step 2 Fuzzy Rule Base:** In this step, the knowledge pertaining to the fuzzy position controller is formulated in terms of a set of fuzzy inference rules [11]. The set of rules are represented in Table 6.3.1. Each entry in a Table 6.3.1 is a rule base and there are 49 rules. The structure of a general rule can be given as

$$\text{IF } e\theta_r(n) \text{ is PB AND } ce\theta_r(n) \text{ is ZE THEN } \omega_{ref}(n) \text{ is PB.}$$

**Step 3 Inference Engine:** When a set of input variables namely position error and change in position error is applied to fuzzy position controller, four rules are fired with any degree of truth in its premise. If position error, $e\theta_r$ is 0.56 rad and change in position error, $ce\theta_r$ is 0.0024, the following four rules of Table 6.3.1 are fired:

- If $e\theta_r(n)$ is PS AND $ce\theta_r(n)$ is ZE THEN $\omega_{ref}(n)$ is PS
- If $e\theta_r(n)$ is PS AND $ce\theta_r(n)$ is PS THEN $\omega_{ref}(n)$ is PS
- If $e\theta_r(n)$ is PM AND $ce\theta_r(n)$ is ZE THEN $\omega_{ref}(n)$ is PM
- If $e\theta_r(n)$ is PM AND $ce\theta_r(n)$ is PS THEN $\omega_{ref}(n)$ is PM.

**Step 4 Defuzzification:** The fuzzy set representing the controller output in linguistic labels has to be converted into crisp reference speed by defuzzification. Then the crisp reference speed can be used to control the system.

<table>
<thead>
<tr>
<th>Table 6.3.1 Rule base for position controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\theta_r$ $ce\theta_r$ NB NM NS ZE PS PM PB</td>
</tr>
<tr>
<td>NB NB NM NS NS PS PM PB</td>
</tr>
<tr>
<td>NM NB NM NS NS PS PM PB</td>
</tr>
<tr>
<td>NS NB NM NS NS PS PM PB</td>
</tr>
<tr>
<td>ZE NB NM NS ZE PS PM PB</td>
</tr>
<tr>
<td>PS NB NM NS PS PS PM PB</td>
</tr>
<tr>
<td>PM NB NM NS PS PS PM PB</td>
</tr>
<tr>
<td>PB NB NM NS PS PS PM PB</td>
</tr>
</tbody>
</table>

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6.3.1.3 Fuzzy Speed Controller

The fuzzy speed controller is the second important component in the present control algorithm. In this scheme fuzzy speed controller is applied in place of the conventional PI controller, to improve transient response. The design steps of fuzzy speed controller are already discussed in previous chapter and the same fuzzy speed controller is used in the position control of induction motor using fuzzy direct self control.

6.3.2 Simulation Algorithm for Position Control of Induction Motor Using Fuzzy Direct Self Control

The necessary algorithm for digital computer simulation of fuzzy direct self control induction motor drive is described below:

i. Select $V_{dc}$, $\psi_{ref}$ and $\theta_{ref}$.

ii. Initialize $i_{ds}(0)$, $i_{qs}(0)$, $i_{dr}(0)$, $i_{qr}(0)$, $\psi_{ds}(0)$, $\psi_{qs}(0)$, $T_{e}(0)$, $\theta(0)$ and $\omega(0)$ for the sample system.

iii. Estimate position error from the difference between the reference position and actual rotor position using the equation (6.3.1). The change in position error is computed from the difference between two successive position errors.

iv. The controller computes the reference speed using knowledge base, as position error and change in position error are input to the fuzzy position controller.

v. The rotor speed, $\omega_r$ is compared with the reference speed to calculate error in speed. The change in error in speed is determined from the difference between two successive error in speed. Both error in speed and change in error in speed are used as inputs to fuzzy speed controller to compute the reference torque.

vi. Compute torque error $eT_e$ and flux error $e\psi_s$. Compute switching functions $S_A$, $S_B$ and $S_C$ using torque error, flux error and stator flux angle.
vii. \( V_{\text{d}}(k), V_{\text{q}}(k) \) are calculated using equation (4.2.9) with known switching functions \( S_A, S_B, \) and \( S_C. \)

equation (4.2.15) is solved to compute \( k+1 \) iteration currents \( i_{\text{d}}(k+1), i_{\text{q}}(k+1), \) and \( i'_{\text{d}}(k+1) \) by using \( k \) iteration currents \( i_{\text{d}}(k), i_{\text{q}}(k), \)
\( i'_{\text{d}}(k), i'_{\text{q}}(k) \) and \( \Delta i_{\text{d}}(k), \Delta i_{\text{q}}(k), \Delta i'_{\text{d}}(k), \Delta i'_{\text{q}}(k) \) respectively.

ix. Compute \( \psi_{\text{d}}(k+1) \), and \( \psi_{\text{q}}(k+1) \) using equation (4.2.1) and (4.2.2).

x. Estimate the stator flux \( \psi_{\text{d}}(k+1) \) with the help of the expression
\[ \sqrt{\psi_{\text{q}}(k+1)^2 + \psi_{\text{d}}(k+1)^2} \]
and stator flux angle using equation (4.2.4).

xi. Compute electromagnetic torque \( T_e(k+1) \) using equation (4.2.6).

xii. Estimate rotor speed \( \omega_r(k+1) \) using equation (6.1).

xiii. Estimate rotor position using equation (6.2).

xiv. The procedure is used iteratively from step (iii) to step (xiii) to obtain the time response for position control of the induction motor till the response reaches a steady value.

6.3.3 Simulation Results for Position Control of Induction Motor Using Fuzzy Direct Self Control

Using the simulation algorithm given above the author has developed digital computer programs to investigate the position control of induction motor using MATLAB. The dynamic performance of the position control using fuzzy direct self control induction motor drive has been simulated with respect to two representative changes in the position reference namely: a fraction of revolution subjected to half the full load as well as to full load, and multi revolutions subjected to half the full load as well as to full load. The investigation has been done for a sample system which is already used for previous investigations [8]. All the simulations carried out in this chapter have been done using the terminal conditions as given in Table 6.3.2. The sampling period of position and speed has been taken as 400\( \mu \)s. The dynamic performance of the position control of induction motor using fuzzy direct self control has been obtained and presented in the following paragraphs.

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Table 6.3.2 Initial conditions for position control investigations

<table>
<thead>
<tr>
<th>Input voltage to inverter</th>
<th>200V dc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux command</td>
<td>0.611wb</td>
</tr>
<tr>
<td>Maximum speed for fractional rotation, $\omega_{\text{max}}$</td>
<td>10 rad/s</td>
</tr>
<tr>
<td>Maximum speed for multi-turn rotation, $\omega_{\text{max}}$</td>
<td>15 rad/s</td>
</tr>
</tbody>
</table>

6.3.3.1 Position Control Performance of Induction Motor Subjected to Step Change in Position Command $- \frac{\pi}{2}$ Radian with Half The Full Load

The dynamic response of the position control of induction motor using fuzzy direct self control due to step change in position reference, $- \frac{\pi}{2}$ radian with half the full load is illustrated in Fig. 6.3.3.1.1 to Fig. 6.3.3.1.12.

Fig.6.3.3.1.1 shows the position response of induction motor for this case. It is observed that the delay time and rise time of position response are about 94 ms and 144 ms respectively. The response reaches steady state position in about 310 ms. The variation of position error with time is shown in Fig.6.3.3.1.2. The position error is negligible at steady state condition and it is positive of the order of 0.25%.

The variation of speed of the motor with time is shown in Fig.6.3.3.1.3. After the application of the position command, the motor speed rises from zero to the maximum speed 10 rad/s in about 35 ms and it is maintained constant for 85 ms. Then the machine has decelerated from 10 rad/s to zero in about 370 ms. The phase plane trajectory is illustrated in Fig. 6.3.3.1.4.

Torque response of the motor is shown in Fig.6.3.3.1.5. Initially the electromagnetic torque rises to 20 N-m and speed increases. While the motor speed is 10 rad/s, the electromagnetic torque follows the reference torque which is estimated by the fuzzy speed controller. When the motor reaches steady state position, the electromagnetic torque developed by the machine equals the holding torque.

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Fig. 6.3.3.1.1 Position response for sudden position variation $(\frac{\pi}{2} \text{ radian})$ with half the full load.

Fig. 6.3.3.1.2 The response of position error for sudden position variation $(\frac{\pi}{2} \text{ radian})$ with half the full load.
Fig. 6.3.3.1.3 Speed response for sudden position variation ($\frac{\pi}{2}$ radian) with half the full load.

Fig. 6.3.3.1.4 Phase plane trajectory for sudden position variation ($\frac{\pi}{2}$ radian) with half the full load.
Fig. 6.3.3.1.5 Torque response for sudden position variation $(\frac{\pi}{2} \text{ radian})$ with half the full load.

Fig. 6.3.3.1.6 q-axis stator current for sudden position variation $(\frac{\pi}{2} \text{ radian})$ with half the full load.
Fig. 6.3.3.1.7 d-axis stator current for sudden position variation ($\frac{\pi}{2}$ radian) with half the full load.

Fig. 6.3.3.1.8 Locus of stator current vector for sudden position variation ($\frac{\pi}{2}$ radian) with half the full load.
Fig. 6.3.3.1.9 d-axis stator flux for sudden position variation $(\frac{\pi}{2} \text{ radian})$ with half the full load.

Fig. 6.3.3.1.10 q-axis stator flux for sudden position variation $(\frac{\pi}{2} \text{ radian})$ with half the full load.
Fig. 6.3.3.1.11 Locus of stator flux vector for sudden position variation ($\frac{\pi}{2}$ radian) with half the full load.

Fig. 6.3.3.1.12 Stator flux position for sudden position variation ($\frac{\pi}{2}$ radian) with half the full load.
Fig. 6.3.3.1.13 Phase-plane portrait of error in position and change in error in position for position control of induction motor using fuzzy DSC subjected to step change in position command $\frac{\pi}{2}$ radian with half the full load.
q-axis and d-axis components of stator current vector are shown in Fig. 6.3.3.1.6 and Fig.6.3.3.1.7. The locus of stator current vector is given in Fig.6.3.3.1.8. It may be noticed that the nature of stator current vector is approximately sinusoidal. In the same way, Fig.6.3.3.1.9 and Fig.6.3.3.1.10 show the variation of d-axis and q-axis stator flux vectors variation respectively. The nature of stator flux vector is sinusoidal. The trajectory of stator flux vector is almost circle as shown in Fig.6.3.3.1.11 and the variation in position of stator flux vector is illustrated in Fig.6.3.3.1.12.

In the investigation of stability of position control using fuzzy direct self control induction motor drive subjected to step change in reference position $\frac{\pi}{2}$ radian with half the full load, the phase-plane plot of error in position and change in error in position is depicted in Fig. 6.3.3.1.13. The phase-plane trajectory starts at point $F_1$, $(\frac{\pi}{2}, 0)$ and tends to converge to the stable focus $F_2$, (0.0039, 0). At steady state operating condition the magnitude of the steady state error is equal to about 0.0039 radian. As the trajectory tends to towards a stable focus $F_2$, the position control using fuzzy direct self control induction motor drive is stable.

6.3.3.2 Position Control Performance of Induction Motor Subjected to Step Change in Position Command $-\frac{\pi}{2}$ Radian with Full Load

The time response of the system variables indicating the dynamic performance of position control of induction motor subjected to sudden variation of position reference, $\frac{\pi}{2}$ radian with full load is illustrated in Fig.6.3.3.2.1 to Fig.6.3.3.2.12. The variation of position is depicted in Fig.6.3.3.2.1. The delay time and rise time of position response are about 94 ms and 145 ms. It may be noticed that the settling time of position response is in about 320 ms. Fig.6.3.3.2.2 shows the response of position error. The steady state error of position is positive of the order of 0.59%.
The speed response of the motor is illustrated in Fig.6.3.3.2.3. Before applying the position command, the motor is at stand still. After the application of the position command, the motor speed rises up to 10 rad/s. Thereafter the position control system has maintained this speed for 84 ms. Then the machine speed decreases and it reaches to zero in about 360 ms. Fig.6.3.3.2.4 shows the phase plane trajectory.

Fig.6.3.3.2.5 shows the torque response of the motor. Initially the reference torque is 20 N-m. Therefore the electromagnetic torque rises to 20 N-m and the motor speed increases. While the motor speed is 10 rad/s, the reference torque is estimated by the fuzzy speed controller and electromagnetic torque tracks the reference torque. The electromagnetic torque equals the holding torque at steady state condition.

The variation in q-axis and d-axis components of stator current is illustrated in Fig.6.3.3.2.6 and Fig.6.3.3.2.7 respectively. Fig.6.3.3.2.8 shows the locus of stator current vector. It is evident from Fig.6.3.3.2.6 to Fig.6.3.3.2.8 that the nature of stator current is closer to sinusoidal. In the same way, Fig.6.3.3.2.9 and Fig.6.3.3.2.10 show the d-axis and q-axis stator flux vectors variation. It is observed that nature of stator flux vector is sinusoidal. Fig.6.3.3.2.11 shows the trajectory of stator flux vector. The time response of position of stator flux vector is illustrated in Fig.6.3.3.2.12.

Fig. 6.3.3.2.13 shows the phase-plane plot of error in position and change in error in position for the position control of induction motor using fuzzy direct self control. The locus starts at point F3, (\frac{\pi}{2}, 0) and tends to converge to the stable focus F4 (0.0093, 0). As the trajectory tends to towards a stable focus F4, the position control using fuzzy direct self control induction motor drive subjected to step change in position command \frac{\pi}{2} radian with full load is stable.
Fig. 6.3.3.2.1 Position response for sudden position variation ($\frac{\pi}{2}$ radian) with full load.

Fig. 6.3.3.2.2 The response of position error for sudden position variation ($\frac{\pi}{2}$ radian) with full load.
Fig.6.3.3.2.3 Speed response for sudden position variation ($\frac{\pi}{2}$ radian) with full load.

Fig.6.3.3.2.4 Phase plane trajectory for sudden position variation ($\frac{\pi}{2}$ radian) with full load.
Fig. 6.3.3.2.5 Torque response for sudden position variation ($\frac{\pi}{2}$ radian) with full load.

Fig. 6.3.3.2.6 q-axis stator current for sudden position variation ($\frac{\pi}{2}$ radian) with full load.
Fig. 6.3.3.2.7 d-axis stator current for sudden position variation (\(\frac{\pi}{2}\) radian) with full load.

Fig. 6.3.3.2.8 Locus of stator current vector for sudden position variation (\(\frac{\pi}{2}\) radian) with full load.
Fig. 6.3.3.2.9 d-axis stator flux for sudden position variation ($\frac{\pi}{2}$ radian) with full load.

Fig. 6.3.3.2.10 q-axis stator flux for sudden position variation ($\frac{\pi}{2}$ radian) with full load.
Fig. 6.3.3.2.11 Locus of stator flux vector for sudden position variation ($\frac{\pi}{2}$ radian) with full load.

Fig. 6.3.3.2.12 Stator flux position for sudden position variation ($\frac{\pi}{2}$ radian) with full load.
Fig. 6.3.2.13 Phase-plane portrait of error in position and change in error in position for position control of induction motor using fuzzy DSC subjected to step change in position command \( \frac{\pi}{2} \) radian with full load.
The dynamic response of the position control of induction motor for step change in position command, \(5\pi\) radian with half the full load (10 N-m) is depicted in Fig. 6.3.3.3.1 to 6.3.3.3.12.

Fig.6.3.3.3.1 shows the variation of position of induction motor when the machine is subjected to step change in position as indicated above. It is evident from the response that the delay time and rise time of position response are about 554 ms and 840 ms. The settling time of position response is in about 1061 ms. Fig.6.3.3.3.2 shows the time response of position error. The steady state error of position is positive and its value is 0.005 radian.

Fig. 6.3.3.3.3 shows the speed response of induction motor. Initially the motor speed rises up to the maximum speed of 15 rad/s and maintained this speed for 952 ms. After that speed decreases and reaches to zero in about 1245 ms. The phase plane trajectory of speed - position is given in Fig. 6.3.3.3.4.

Transient response of the electromagnetic torque is illustrated in Fig 6.3.3.3.5. Initially the electromagnetic torque of induction motor reaches to the peak value of 20 N-m and then decreases to 10 N-m. It may be observed from the response that the electromagnetic torque is maintained constant for 964 ms to retain the constant speed. At about 1018 ms the electromagnetic torque has decreased to decelerate the machine. At steady state operating condition, the holding torque is developed in the motor.

Fig. 6.3.3.3.6 and Fig.6.3.3.3.7 show the corresponding variation in q -axis and d-axis components of stator current vector. The locus of stator current vector is shown in Fig.6.3.3.3.8. Similarly, the response of d-axis and q-axis components of stator flux is given in Fig.6.3.3.3.9 and Fig.6.3.3.3.10 respectively. It is observed that nature of stator flux vector is sinusoidal. Fig. 6.3.3.3.11 shows the trajectory of stator flux. The time response of position of stator flux vector is illustrated in Fig. 6.3.3.12.
Fig. 6.3.3.1 Position response for sudden position variation ($5\pi$ radian) with half the full load.

Fig. 6.3.3.2 The response of position error for sudden position variation ($5\pi$ radian) with half the full load.
Fig. 6.3.3.3.3 Speed response for sudden position variation (5\pi radian) with half the full load.

Fig. 6.3.3.3.4 Phase plane trajectory for sudden position variation (5\pi radian) with half the full load.
Fig. 6.3.3.3.5 Torque response for sudden position variation (5π radian) with half the full load.

Fig. 6.3.3.3.6 q-axis stator current for sudden position variation (5π radian) with half the full load.
Fig.6.3.3.3.7 d-axis stator current for sudden position variation ($5\pi$ radian) with half the full load.

Fig.6.3.3.3.8 Locus of stator current vector for sudden position variation ($5\pi$ radian) with half the full load.
Fig. 6.3.3.3.9 d-axis stator flux for sudden position variation (5π radian) with half the full load.

Fig. 6.3.3.3.10 q-axis stator flux for sudden position variation (5π radian) with half the full load.
Fig. 6.3.3.3.11 Locus of stator flux vector for sudden position variation (5π radian) with half the full load.

Fig. 6.3.3.3.12 Stator flux position for sudden position variation (5π radian) with half the full load.
6.3.3.4 Position Control Performance of Induction Motor Subjected to Step Change in Position Command — $5\pi$ Radian with Full Load

The time responses of the system variables indicating the dynamic response of position control of induction motor subjected to step change in position reference as indicated above are illustrated in Fig.6.3.3.4.1 to Fig.6.3.3.4.12.

The position response of induction motor for this case is shown Fig.6.3.3.4.1. The delay time and rise time are 557 ms and 829 ms respectively. The settling time of the position response is about 1067 ms. Fig.6.2.3.4.2 shows the variation of position error. The steady state position error is 0.01 radian.

The variation of speed with time is illustrated in Fig.6.3.3.4.3. Initially the motor speed rises to the maximum speed of 15 rad/s in about 85 ms and maintained this speed for 935 ms. After that the motor is decelerated from 15 rad/s to zero in about 1260 ms. The phase plane trajectory of speed-position is given in Fig.6.3.3.4.4.

Fig.6.3.3.4.5 shows the torque response of the motor. Initially the electromagnetic torque rises to 30 N-m and speed increases. When the motor speed is 15 rad/s, the developed electromagnetic torque in the machine maintain the constant speed. At steady state operating condition the electromagnetic torque equals the holding torque.

The response of q-axis and d-axis components of stator current vector is shown in Fig.6.3.3.4.6 and Fig.6.3.3.4.7 respectively. The nature of stator current vector is approximately sinusoidal as depicted in Fig.6.3.3.4.8. Fig.6.3.3.4.9 and Fig.6.3.3.4.10 show the variation of d-axis and q-axis components of stator flux vector respectively. The nature of stator flux vector is sinusoidal as indicated in Fig.6.3.3.4.11 and the position variation of stator flux with time is given in Fig.6.3.3.4.12.
Fig. 6.3.3.4.1 Position response for sudden position variation (5π radian) with full load.

Fig. 6.3.3.4.2 The response of position error for sudden position variation (5π radian) with full load.
Fig. 6.3.3.4.3 Speed response for sudden position variation ($5\pi$ radian) with full load.

Fig. 6.3.3.4.4 Phase plane trajectory for sudden position variation ($5\pi$ radian) with full load.
Fig.6.3.3.4.5 Torque response for sudden position variation (5\pi radian) with full load.

Fig.6.3.3.4.6 \(q\)-axis stator current for sudden position variation (5\pi radian) with full load.
Fig. 6.3.3.4.7 d-axis stator current for sudden position variation (5\pi radian) with full load.

Fig. 6.3.3.4.8 Locus of stator current vector for sudden position variation (5\pi radian) with full load.
Fig 6.3.3.4.9 d-axis stator flux for sudden position variation (5\pi radian) with full load.

Fig 6.3.3.4.10 q-axis stator flux for sudden position variation (5\pi radian) with full load.
Fig. 6.3.3.4.11 Locus of stator flux vector for sudden position variation ($5\pi$ radian) with full load.

Fig. 6.3.3.4.12 Stator flux position for sudden position variation ($5\pi$ radian) with full load.
6.4 POSITION CONTROL PERFORMANCE COMPARISON OF INDUCTION MOTOR USING CONVENTIONAL AND FUZZY DIRECT SELF CONTROL

The simulation results of position control using conventional direct self control of induction motor drive as well as fuzzy direct self control of induction motor drive with respect to a typical system has been discussed in article 6.2 and 6.3 of this chapter. The dynamic performance of both of these cases is compared in the following paragraphs.

6.4.1 Induction Motor Subjected to Step Change in Position Command -- \( \frac{\pi}{2} \) Radian with Half The Full Load

The position response of the motor with conventional DSC and fuzzy DSC due to step change in position command \( \frac{\pi}{2} \) radian with half the full load is shown in Fig.6.2.3.1.1 and Fig.6.3.3.1.1 respectively. In conventional DSC method, the delay time and rise time of position response are 97 ms and 206 ms. The settling time of position response is 358 ms. When the fuzzy DSC is used in position control of induction motor, the delay time and rise time of position response are reduced to 94 ms and 144 ms. The time required by the induction motor to achieve the steady state is 310 ms for fuzzy DSC. It may be inferred that the machine position reaches its steady state value faster in case of the position control with the help of fuzzy DSC drive. Therefore, the fast position response is achieved by the proposed fuzzy DSC scheme. Fig.6.2.3.1.2 and Fig.6.3.3.1.2 show the corresponding variation of position error for conventional and fuzzy direct self control. The steady state position error is negative of the order of 1.08% with the conventional direct self control strategy, whereas it is 0.25% for fuzzy direct self control. Consequently, the position control using fuzzy DSC provides less steady state error than the conventional DSC method.

Fig.6.2.3.1.8 shows the locus of stator current vector for position control using conventional DSC. The trajectory even though six sided polygon for this case, but
it has oscillatory nature during the transition from one set of switching function involving real flux vectors to another set of switching function using pseudo-flux vectors. The nature of stator current vector is non-sinusoidal as shown in Fig.6.2.3.1.6 and Fig.6.2.3.1.7. When fuzzy direct self control is used in position control, the trajectory of stator current vector is nearly a circle as shown in Fig.6.3.3.1.8. The nature of stator current vector locus is almost sinusoidal as given in Fig.6.3.3.1.6. Therefore it may be inferred that fuzzy DSC provides better stator current waveform with respect to conventional DSC in position control.

Fig 6.2.3.1.11 shows the stator flux vector locus. It is evident that the trajectory of stator flux vector is concavo-convex type polygon. The nature of stator flux vector is non-sinusoidal as given in Fig.6.2.3.1.9 and Fig.6.2.3.1.10. Fig.6.3.3.1.11 shows the locus of stator flux vector using fuzzy logic controller which is a smooth circle. The nature of stator flux vector locus is almost sinusoidal as shown in Fig.6.3.3.1.9 and Fig.6.3.3.1.10. So, it is clear from Fig 6.2.3.1.11 and Fig.6.3.3.1.11 that the position control by fuzzy DSC drive is able to provide a smooth stator flux vector trajectory as compared to conventional direct self-controlled strategy.

Table 6.4.1 shows the comparative performance of position control of induction motor using conventional and fuzzy direct self control in a tabular form. It is evident from this investigation that a much better response is achieved by the fuzzy DSC.

### 6.4.2 Induction Motor Subjected to Step Change in Position Command -- 

\[ \frac{\pi}{2} \] Radian with Full Load

The variation of position of the motor with conventional DSC and fuzzy DSC due to step change in position reference, \( \frac{\pi}{2} \) radian with full load is shown in Fig.6.2.3.2.1 and Fig.6.3.3.2.1 respectively. In position control using conventional DSC, the delay time and rise time of position response are 97 ms and 206 ms whereas in position control with fuzzy DSC, the delay time and rise time of position response are
94 ms and 145 ms. The settling time of position response is 347 ms for conventional DSC and 320 ms for fuzzy DSC. Therefore the machine position reaches to steady state value faster in case of fuzzy direct self control based drive. Accordingly the fast position response is achieved by the fuzzy DSC drive. Fig.6.2.2.2 and Fig.6.3.3.2.2 show the response of position error for conventional and fuzzy direct self control respectively. At steady state condition position error is negative of the order of 1.05% with the conventional direct self control strategy and it is 0.59% for fuzzy direct self control. As a result, the better response is achieved by the fuzzy DSC method.

Table 6.4.1 Comparative performance of induction motor subjected to step change in position command $\pm \frac{\pi}{2}$ radian with half the full load.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Conventional Direct Self Control</th>
<th>Fuzzy Direct Self Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay Time of Position Response</td>
<td>97 ms</td>
<td>94 ms</td>
</tr>
<tr>
<td>Rise Time of Position Response</td>
<td>206 ms</td>
<td>144 ms</td>
</tr>
<tr>
<td>Settling Time of Position Response</td>
<td>358 ms</td>
<td>310 ms</td>
</tr>
<tr>
<td>Steady State Position Error</td>
<td>1.08% positive</td>
<td>0.25% negative</td>
</tr>
<tr>
<td>Locus of Stator Current Vector</td>
<td>Stator current vector follows the wavy 6-sided polygon. So, its nature is non sinusoidal.</td>
<td>The trajectory of stator current vector follows a circle and its nature is approximately sinusoidal.</td>
</tr>
<tr>
<td>Locus of Stator Flux Vector</td>
<td>Stator flux vector follows the 12-sided polygon. It is concavo-convex type. Its nature is non sinusoidal.</td>
<td>The trajectory of stator flux vector follows a smooth circle. Its nature is approximately sinusoidal.</td>
</tr>
</tbody>
</table>
The nature of stator current vector locus and stator flux vector trajectories is identical to the previous case. The comparative performance of position control of induction motor using conventional and fuzzy direct self control is shown in Table 6.4.2 for the time response parameters.

Table 6.4.2 Comparative performance of induction motor subjected to step change in position command $-\frac{\pi}{2}$ radian with full load

<table>
<thead>
<tr>
<th>Specification</th>
<th>Conventional Direct Self Control</th>
<th>Fuzzy Direct Self Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay Time of Position Response</td>
<td>97 ms</td>
<td>94 ms</td>
</tr>
<tr>
<td>Rise Time of Position Response</td>
<td>206 ms</td>
<td>145 ms</td>
</tr>
<tr>
<td>Settling Time of Position Response</td>
<td>347 ms</td>
<td>320 ms</td>
</tr>
<tr>
<td>Steady State Position Error</td>
<td>1.05% positive</td>
<td>0.59% negative</td>
</tr>
</tbody>
</table>

6.4.3 Induction Motor Subjected to Step Change in Position Command -- $5\pi$ Radian with Half The Full Load

When the machine is subjected to step change in reference position as indicated above, the variation of position of the motor with conventional DSC and fuzzy DSC is shown in Fig.6.2.3.3.1 and Fig.6.3.3.3.1. In position control using conventional DSC method, the delay time and rise time of position response are 556 ms and 842 ms. In fuzzy DSC scheme, the delay time and rise time of position response are 554 ms and 840 ms. The machine position reaches to steady state position response at 1070 ms for conventional DSC and 1061 ms for fuzzy DSC. Therefore the fast position response is achieved by the fuzzy DSC drive. Fig.6.2.3.3.2 and Fig.6.3.3.3.2 show the response of position error for conventional and fuzzy direct self control respectively. At steady state
condition position error is negative and it is 0.0125 rad with the conventional direct self control strategy and it is 0.005 rad for fuzzy direct self control. So, the better response is achieved by the fuzzy DSC method.

The nature of stator current vector locus and stator flux vector trajectories is identical to those of the fractional rotation cases discussed in the previous paragraphs.

Table 6.4.3 shows the comparative performance of position control of induction motor using conventional and fuzzy direct self control for this case.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Conventional Direct Self Control</th>
<th>Fuzzy Direct Self Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay Time of Position Response</td>
<td>556 ms</td>
<td>554 ms</td>
</tr>
<tr>
<td>Rise Time of Position Response</td>
<td>842 ms</td>
<td>840 ms</td>
</tr>
<tr>
<td>Settling Time of Position Response</td>
<td>1070 ms</td>
<td>1061 ms</td>
</tr>
<tr>
<td>Steady State Position Error</td>
<td>0.0125 rad positive</td>
<td>0.005 rad negative</td>
</tr>
</tbody>
</table>

### 6.4.4 Induction Motor Subjected to Step Change in Position Command -- $5\pi$ Radian with Full Load

The variation of position of the motor with conventional DSC and fuzzy DSC due to step change in position reference, $5\pi$ radian with full load is shown in Fig. 6.2.3.4.1 and Fig. 6.3.3.4.1 respectively. In conventional DSC method the delay time and rise time of position response are 560 ms and 832 ms whereas in fuzzy DSC the delay time and rise time of position response are 557 ms and 829 ms. The settling time of position response is 1081 ms for conventional DSC and 1067 ms for fuzzy DSC. Therefore the machine position reaches to steady state value faster in case of fuzzy direct self control based drive. Therefore the fast position response is achieved by the fuzzy
DSC drive. Fig.6.2.3.4.2 and Fig.6.3.3.4.2 show the response of position error for conventional and fuzzy direct self control respectively. At steady state condition, position error is negative and it is 0.012 rad with the conventional direct self control strategy and it is 0.01 rad for fuzzy controller. Hence, the better response is achieved by the fuzzy DSC method.

The nature of stator current vector locus and stator flux vector trajectories is identical to the previous case. The comparative performance of position control of induction motor using conventional direct self control as well as fuzzy direct self control is shown in Table 6.4.4.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Conventional Direct Self Control</th>
<th>Fuzzy Direct Self Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay Time of Position Response</td>
<td>560 ms</td>
<td>557 ms</td>
</tr>
<tr>
<td>Rise Time of Position Response</td>
<td>832 ms</td>
<td>829 ms</td>
</tr>
<tr>
<td>Settling Time of Position Response</td>
<td>1081 ms</td>
<td>1067 ms</td>
</tr>
<tr>
<td>Steady State Position Error</td>
<td>0.012 rad positive</td>
<td>0.01 rad negative</td>
</tr>
</tbody>
</table>

CONCLUSIONS

In this chapter, the block diagram of position control of induction motor using conventional direct self control as well as fuzzy direct self control has been brought out. The complete mathematical model of both the position control schemes for simulation has also been developed. The author has designed the proposed fuzzy position controller for fuzzy direct self control and has presented the design process for this
scheme. The fuzzy speed controller which is discussed in previous chapters has also been used in this control system. The simulation algorithm for the proposed schemes has been discussed. These algorithms have been used to develop computer programs to study the position control performance of induction motor drive.

These digital computer programs have been used to investigate the application of conventional and fuzzy direct self control induction motor drive in position control. The dynamic performance of the position control using conventional direct self control as well as fuzzy direct self control induction motor drive has been investigated with respect to two representative changes in the position command namely fractional rotation subjected to half the load as well as to full load, and multi-turn rotation subjected to half the full load as well as to full load. In fractional rotation the step change in reference position is $\frac{\pi}{2}$ radian and in multi-turn rotation position command is $5\pi$ radian.

Feasibility of the proposed position control of induction motor using conventional and fuzzy direct self control induction motor drive is verified by simulation study. The simulation results for above cases have been discussed. These simulation results of position control by fuzzy direct self control have been compared with the results obtained by conventional direct self control. The comparison of dynamic performance of induction motor drive in position control using conventional and fuzzy direct self control has been presented in this chapter. It may be concluded that the position control system using fuzzy direct self control is able to provide better response with respect to the position control with the help of direct self control induction motor drive.
REFERENCES


