CHAPTER 3

INTELLIGENT SPEED CONTROLLER BASED VSC DRIVE

3.1 INTRODUCTION

Fuzzy Logic Controller (FLC) is a type of nonconventional control system; it is a knowledge-based approach. Fuzzy logic is a rule-based decision-making method, used to control a process that a human usually handles with expertise gained from experience. FLC is seen as an alternative to conventional control strategies in automatic control systems. Fuzzy control theory affords linear and nonlinear controllers. The design of FLC does not need exact value of parameters of the system and also good knowledge about the working of the system need not be known. (Lotfi A. Zadeh, 1965) Lotfi A. Zadeh introduced fuzzy theory as an extension of the conventional control theory. The fuzzy inference is framed with degrees of truth, of inputs and outputs. The classical fuzzy set includes error and change in error as input. The integration of Fuzzy logic controller with the conventional or unconventional controller improves its performance. In this thesis, the integration FLC with the PI controller is proposed to improve the performance of variable structure controlled induction motor drive. The FLC with the PI controller is named as Fuzzy Gain Scheduling (FGS) PI controller since fuzzy logic controller tunes the controller gains of the proportional and integral controller. The sensorless model reference adaptive system provides simple
control for adjustable speed drives. It is preferred by many researchers for its simplicity. In this research VSC induction motor drive is proposed with FGS.

In this chapter, the background study of fuzzy systems, the basic components, the membership functions, IF-Then rules and the proposed fuzzy controller system are presented. The proposed fuzzy logic controller, fuzzy gain scheduling, and MRAS controlled VSC based induction motor drives are simulated using Matlab / Simulink. The results of the simulated system are validated for various speeds and loads. These results are presented in a tabular form.

3.2 BACKGROUND STUDY OF INTELLIGENT SYSTEMS

Agamy et al. (2004) analyzed the performance of Fuzzy logic controller in variable structure control for induction motor. Authors analyzed the performance of the drive in the aspects of speed tracking error and flux tracking error. The analysis was not attempted for speeds above rated speed.

Arun Kumar R & Febin Daya J (2013) analyzed the performance of fuzzy-tuned PID controller for induction motor drive. Authors analyzed the performance of the drive at various speeds. The performance of fuzzy-tuned PID controller is compared with fuzzy logic controller and PI controller based drive.

Colin Schauder (1992) analyzed the performance of induction motor drive by the model reference adaptive system (MRAS) to measure induction motor speed from measured terminal voltages and currents. It provides tacholess control of induction motor. It provides good performance at high speeds.
Suman K & Aditya V (2011) analyzed the performance of sensorless control of induction motor drive. The authors analyzed the performance in the aspects of speed ripple and torque ripple. In this paper, performance of the machine is analyzed with constant torque.

3.3 GENERAL THEORY ON FUZZIFICATION TECHNIQUE

The process of converting the crisp data of the control inputs into fuzzy values is called fuzzification. The typical function of a crisp set value moreover 1 or 0 in the universal set, thus discerning non-members and members of the crisp set under consideration. When the elements value assigned falls within the specific range, it assigns membership grade (Satyendra Nath Mandal et al. 2008). Bigger values indicate higher degrees of set membership. This function is named as membership function and the set defined by it is a fuzzy set. The various types of membership functions are pointed as follows,

- Gaussian Membership Function
- Triangular Membership Function
- Trapezoidal Membership Function
- S–Shaped Built-In Membership Function
- L-Shaped Membership Function
- Bell Membership Function

3.3.1 GAUSSIAN MEMBERSHIP FUNCTION

Equation (3.1) shows the Gaussian type membership function.

\[ G(u; c, \sigma) = \exp\left[-\left\{(u - c) / \sqrt{2\sigma}\right\}^2\right] \] (3.1)
Where $\sigma$ and $c$ are factors control width and the center of the membership function as shown in Figure 3.1.

![Gaussian Membership Function](image)

**Figure 3.1 Gaussian Membership Function**

### 3.3.2 Triangular membership function

The straight lines are used to form the Triangular membership function, and it is defined as in Equation (3.2).

\[
\Lambda(v; v_1, v_2, v_3) =
\begin{cases} 
0, & v < v_1 \\
(v - v_1)/(v_2 - v_3), & v_1 \leq v \leq v_2 \\
(v_1 - v)/(v_2 - v_1), & v_2 \leq v \leq v_3 \\
0, & v > v_3 
\end{cases}
\]

(3.2)
Figure 3.2 shows characteristic plot of triangular membership function.

![Triangular Membership Function](image)

**Figure 3.2 Triangular Membership Function**

3.3.3 Trapezoidal membership function

The mathematical model of the trapezoidal function is presented in equation (3.3).

\[
F(x, m, n, o, p) = \begin{cases} 
0 & \text{when } x < m \text{ and } x > p \\
(x - m)/(n - m), & \text{when } m \leq x \leq n \\
1, & \text{when } n \leq x \leq o \\
-(p - x)/(p - o) & \text{when } o \leq x \leq p 
\end{cases}
\]  

(3.3)

![Trapezoidal Membership Function](image)

**Figure 3.3 Trapezoidal Membership Function**
3.3.4 S–Shaped Built-in Membership Function

Equation (3.4) expresses the ‘S’ shaped built-in membership function and its classical model is shown in Figure 3.4.

\[
S((a; a_1, a_2, a_3)) = \begin{cases} 
0, & a < a_1 \\
2[(a - a_1)/(a_3 - a_1)]^2, & a_1 < a \leq a_2 \\
1 - 2[(a - a_3)/(a_3 - a_1)]^2, & a_2 < a \leq a_3 \\
1, & a > a_3
\end{cases}
\] (3.4)

![Figure 3.4 S-shaped Membership Function](image)

3.3.5 L-Shaped Membership Function

L shaped membership function is mathematically expressed in Equation (3.5).

\[
L(a; a_1, a_2) = \begin{cases} 
1, & a < a_1 \\
(a_1 - a)/(a_2 - a_1), & a_1 \leq a \leq a_3 \\
0, & a > a_2
\end{cases}
\] (3.5)
Figure 3.5 shows the typical form of the L-function.

![L-shaped Membership Function](image_url)

**3.3.6 Bell membership function**

The typical Bell function depends on three parameters such as $u_1$, $u_2$ and $u_3$ as given by Equation (3.6).

$$F(x, u_1, u_2, u_3) = \frac{1}{1 + (x - u_3)/u_1^2} u_2$$  \hspace{1cm} (3.6)

Where the parameter ‘$u_2$’ is usually positive. The parameter $u_3$ locates the center of the curve as shown in Figure 3.6.
3.3.7 Comparison of Different Membership Functions

Residuals for various types of membership functions are derived as follows.

Absolute Residual \[ = |\text{Calculated Value} - \text{Actual Value}| \]

Maximum Residual \[ = \text{Maximum (Absolute Residual)} \]

Mean Absolute Residual \[ = \text{Absolute Residual} / \text{Actual Value} \]

Mean of Mean Absolute Residual \[ = (\text{Mean Absolute Residual}) / N \]

Medium Absolute Residual \[ = \text{Middle Value of Absolute Residual} \]

The various residuals such as AR, Max AR, Mean AR, Mean of mean AR, Medium of AR and standard deviation are listed in Table 3.1.
Table 3.1  Residual Analysis of Membership Functions

<table>
<thead>
<tr>
<th>Membership Functions</th>
<th>AR</th>
<th>Max AR</th>
<th>Mean of AR</th>
<th>Mean of Mean AR</th>
<th>Medium of AR</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian</td>
<td>2.33</td>
<td>5.0</td>
<td>0.054</td>
<td>0.004</td>
<td>5.0</td>
<td>13.54</td>
</tr>
<tr>
<td>Bell Shaped</td>
<td>2.67</td>
<td>5.0</td>
<td>0.06</td>
<td>0.005</td>
<td>4</td>
<td>13.55</td>
</tr>
<tr>
<td>S-Shaped</td>
<td>1.50</td>
<td>4.0</td>
<td>0.035</td>
<td>0.002</td>
<td>0.0</td>
<td>13.55</td>
</tr>
<tr>
<td>L-Shaped</td>
<td>2.83</td>
<td>6.0</td>
<td>0.068</td>
<td>0.0056</td>
<td>5.0</td>
<td>11.35</td>
</tr>
<tr>
<td>Triangulated</td>
<td>2.83</td>
<td>6.0</td>
<td>0.071</td>
<td>0.0059</td>
<td>1.0</td>
<td>11.10</td>
</tr>
<tr>
<td>Trapezoidal</td>
<td>4.66</td>
<td>14.0</td>
<td>0.1075</td>
<td>0.0089</td>
<td>5.0</td>
<td>11.61</td>
</tr>
</tbody>
</table>

AR-Absolute Residual  SD-Standard Deviation

From Table 3.1 it is noted that the SD of the triangular shaped function is minimum compared to all other functions. Therefore, the triangular shape function is used for fuzzification (Satyendra Nath Mandal et al. 2008).

3.4  SELECTION OF BEST DEFUZZIFICATION TECHNIQUE

The process of converting fuzzy values into crisp values, which is mandatory for further sequences is stated as defuzzification. The defuzzification techniques are analyzed and formulated in two different ways based on frequency. They are discrete form (using $\sum$) and continuous form (using $\int$) (Pujar & Kodad 2009). Let us assume ‘X’ as Input variable for the discrete form of defuzzification. After the fuzzification process the input is expressed as fuzzy set $A^1$ on the basis of input values. Fuzzy logic rule base development is shown in Figure 3.7. ‘AND’ and ‘OR’ are the two operators used in fuzzy controller. The fuzzy set $A_i$ signifies a number of rules. It is
allocated as the universe of discourse of the input variable. Various types of defuzzification techniques are depicted below.

**Figure 3.7 Fuzzy if then Rule Bases**

### 3.4.1 First of maxima

The range of all possible values for an input to a fuzzy system is called universe of discourse. The first of maxima (FOM) consists of a universe of discourse with the highest degree of membership fuzzy set. In case of motor speed control, the universe of discourse is all possible ranges of speed. This method is convenient for fuzzy expert systems. FOPM is expressed as in Equation (3.7).

\[ Y_0 = \text{fom}(B^1) \tag{3.7} \]

Where,

- \( B^1 \) output fuzzy set

Three different types of maxima are available, and they are,

- Middle of Maxima (MOM)
- Last of Maxima (LOM)
- Random choice of Maxima (RCOM)
3.4.2 Area Defuzzification Techniques

De-Fuzzification value is determined using the area under the membership function named as Area defuzzification techniques. The Equation (3.8) illustrates center-of-area technique, (COA).

\[ y_0 = \text{COA}(B') \]  

(3.8)

COA consists only simple operations so is a fast method of defuzzification, it produces a continual change of De-Fuzzification value; hence it is convenient to be used in fuzzy controllers.

3.4.3 Distribution Techniques

In this method of defuzzification distribution function is treated in output fuzzy set membership function, for which the average value is evaluated. This heuristic approach leads to continuous and smooth output. Output changes for the change of values of an input variable in the universe of discourse. Center of gravity technique (COG) is the basic technique of this group. Discrete form of COG expression is shown in Equation (3.9).

\[
y_0 = \text{defuzzification}(B^1) = \frac{\sum_{(i=1)}^{\lambda(p,q)} [B^{s,1} (y_i)y_{i,j}]}{\sum_{(i=1)}^{\lambda(p,q)} [B^{s,1} (y_{i,j})]} = \text{cog}(B^{s,1}) \]  

(3.9)

The number of quantizing samples in \( y_i \) is \( P_q \). During this operation, it requires \((3P_q - 1)\) operations and involves more arithmetic operations such as large multiplications and division. More multiplication and division operations is less convenient for Hardware implementation, since it requires a more number of multipliers, as well as it requires passing through the whole universe of discourse of the output variable (Saade & Diab 2004).
However, due to permanence and, often, smoothness of changes of DeFuzzified values, this technique is used with fuzzy controllers.

### Table 3.2 Design Consideration of Defuzzification Techniques

<table>
<thead>
<tr>
<th>Design Specifications</th>
<th>COG</th>
<th>FOM</th>
<th>COA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Operations</td>
<td>3Pq-1</td>
<td>2 Pq</td>
<td>4Pq</td>
</tr>
<tr>
<td>Design suitability</td>
<td>No</td>
<td>No</td>
<td>Medium</td>
</tr>
<tr>
<td>Domain of Applicability</td>
<td>Fuzzy Controllers</td>
<td>Fuzzy Expert systems</td>
<td>Fuzzy Controllers</td>
</tr>
</tbody>
</table>

From Table 3.2 it suggests the center-of-gravity and center of area Defuzzification techniques for use in fuzzy controllers. Fuzzy decision making systems and Fuzzy expert systems use the maxima techniques. In this thesis COG method of defuzzification is proposed.

#### 3.5 SIMULATION OF FLC BASED VARIABLE STRUCTURE CONTROLLED INDUCTION MOTOR DRIVE

![Simulation model of FLC-based VSC of Induction motor drive](image)

**Figure 3.8 Simulation model of FLC-based VSC of Induction motor drive**
Fuzzy inference system is the name of an entire system that uses fuzzy reasoning to map an input space to an output space. There are several ways to define the result of a rule; this research implies max-min method of inference. In this analysis, two fuzzy controllers of Mamdani type are implemented. Each has two inputs such as speed error (e) and change in error (ec). FLC 1 produces k as output and FLC 2 produce β as output.

\[ E = w^* - w \]  \hspace{1cm} (3.10)

Where, \( E \) is the error in speed

\( w^* \) is the reference speed

\( w \) is the actual speed

Both inputs and outputs have five triangular membership functions such as NB-negative big, NS-negative small, Z-zero, PS-Positive Small, and PB-Positive Big (Tripura, P. and Y. Srinivasa Kishore Babu, 2011). Defuzzification is the mathematical procedure to convert fuzzy values into crisp values. Among the various methods of defuzzification, in this study centroid method of defuzzification is selected. Table 3.3 shows the fuzzy rules. Figure 3.9, Figure 3.10 & Figure 3.11 shows the input membership functions, Output membership functions of k and beta respectively (Zadeh, L.A, 1965).

Figure 3.9  Membership functions of input “e & ec”
Table 3.3 and 3.4 shows the range of fuzzy sets proposed in k and β fuzzy.

**Table 3.3 The range of fuzzy sets proposed in k fuzzy controller**

<table>
<thead>
<tr>
<th>Fuzzy set</th>
<th>Range of e</th>
<th>Range of ec</th>
<th>Range of u</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>[-3 -3 -1.2]</td>
<td>[-3 -3 -1.2]</td>
<td>[-3 -3 -0.2]</td>
</tr>
<tr>
<td>NS</td>
<td>[-2.8 -1 -0.2]</td>
<td>[-2.8 -1 1.2]</td>
<td>[-2.8 -1.2 -0.2]</td>
</tr>
<tr>
<td>Z</td>
<td>[-2 0 2]</td>
<td>[-1.8 0 1.8]</td>
<td>[-1.8 0 1.8]</td>
</tr>
<tr>
<td>PS</td>
<td>[0.2 1 2.8]</td>
<td>[0.2 1 2.8]</td>
<td>[1.2 2 2.8]</td>
</tr>
<tr>
<td>PB</td>
<td>[1.2 3 3]</td>
<td>[1.2 3 3]</td>
<td>[1.2 3 3]</td>
</tr>
</tbody>
</table>

Figure 3.10 Output membership functions of “k”

Figure 3.11 Output membership functions of "β."
Table 3.4 The range of fuzzy sets proposed in β fuzzy controller

<table>
<thead>
<tr>
<th>Fuzzy set</th>
<th>Range of e</th>
<th>Range of ec</th>
<th>Range of u</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>[-100, -100, -40]</td>
<td>[-100, -100, -40]</td>
<td>[-0.3, -0.3, -0.06]</td>
</tr>
<tr>
<td>NS</td>
<td>[-93.33, -33.33, -6.667]</td>
<td>[-93.33, -33.33, 40]</td>
<td>[-0.2733, -0.06, 0.0733]</td>
</tr>
<tr>
<td>Z</td>
<td>[-66.67, 0, 66.67]</td>
<td>[-60, 0, 60]</td>
<td>[-0.14, 0.1, 0.34]</td>
</tr>
<tr>
<td>PS</td>
<td>[6.667, 33.33, 93.33]</td>
<td>[7.73, 34.4, 94.4]</td>
<td>[0.26, 0.3667, 0.4733]</td>
</tr>
<tr>
<td>PB</td>
<td>[40, 100, 100]</td>
<td>[40, 100, 100]</td>
<td>[0.26, 0.5, 0.5]</td>
</tr>
</tbody>
</table>

Table 3.5 Fuzzy Rules of k and beta

<table>
<thead>
<tr>
<th>Change in error</th>
<th>NB</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NS</td>
<td>NS</td>
<td>Z</td>
<td>PS</td>
</tr>
<tr>
<td>NS</td>
<td>NB</td>
<td>NS</td>
<td>NS</td>
<td>PS</td>
<td>PB</td>
</tr>
<tr>
<td>Z</td>
<td>NB</td>
<td>NS</td>
<td>Z</td>
<td>PS</td>
<td>PB</td>
</tr>
<tr>
<td>PS</td>
<td>NB</td>
<td>NS</td>
<td>PS</td>
<td>PS</td>
<td>PB</td>
</tr>
<tr>
<td>PB</td>
<td>NS</td>
<td>Z</td>
<td>PS</td>
<td>PS</td>
<td>PB</td>
</tr>
</tbody>
</table>

Figure 3.12 Speed performance of FLC-based VSC control with no load
Figure 3.13 Speed performance of FLC-based VSC control with change in load

The performance of VSC based IM drive using Fuzzy controller with various speed and load is shown in Table 3.6

Table 3.6 Performance of Fuzzy controlled VSC based IM drive for various speeds

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Peak Overshoot (%)</th>
<th>Steady state error (%)</th>
<th>Rise time (sec.)</th>
<th>Peak time (sec.)</th>
<th>Settling time (sec.)</th>
<th>Speed drop during load change (%)</th>
<th>Restoration time (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>16</td>
<td>3.8</td>
<td>0.0208</td>
<td>0.031</td>
<td>0.12</td>
<td>1.5</td>
<td>0.176</td>
</tr>
<tr>
<td>1000</td>
<td>15</td>
<td>3.6</td>
<td>0.0225</td>
<td>0.037</td>
<td>0.125</td>
<td>1.8</td>
<td>0.17</td>
</tr>
<tr>
<td>1200</td>
<td>12.5</td>
<td>1.8</td>
<td>0.0271</td>
<td>0.0389</td>
<td>0.13</td>
<td>1.7</td>
<td>0.16</td>
</tr>
<tr>
<td>1430</td>
<td>8.0</td>
<td>1.3</td>
<td>0.0489</td>
<td>0.061</td>
<td>0.14</td>
<td>1.6</td>
<td>0.15</td>
</tr>
<tr>
<td>1800</td>
<td>2.2</td>
<td>1.2</td>
<td>0.0746</td>
<td>0.089</td>
<td>0.145</td>
<td>1.5</td>
<td>0.145</td>
</tr>
<tr>
<td>2000</td>
<td>1.7</td>
<td>0.9</td>
<td>0.1037</td>
<td>0.116</td>
<td>0.18</td>
<td>1.4</td>
<td>0.14</td>
</tr>
</tbody>
</table>

The Figure 3.14 shows the performance of FLC controlled VSC based IM drive with various parameters such as peak overshoot, steady state
error, rise time, peak time, settling time, speed drop during load change and restoration time.

Figure 3.14 Continued

a: Peak Overshoot Vs Speed

b: Peak Time Vs Speed

Figure 3.14 Continued
c: Rise Time Vs Speed

d: Settling Time Vs Speed

Figure 3.14 Continued
e. Steady State Error Vs Speed

f. Speed Drop During Load Change Vs Speed

Figure 3.14 Continued
3.6 INFERENCES

The performance graphs of the Fuzzy logic controller show its control on VSC based IM drive. The performance of IM drive is analyzed by using the features, rise time, peak time, settling time, peak overshoot, speed drop during a change in load and the restoration time. The performance is analyzed at various speeds and various loads. To analyze the parameters of speed drop and restoration time during change in load, the load is increased during run time.

Peak overshoot in speed is reduced by 30% compared to the conventional controller. Steady state error and speed drop during the change in load are reduced by 80% at rated speed compared to the conventional controller. Rise time, peak time are improved using Fuzzy logic controller compared to the conventional controller.
3.7 PROBLEMS ASSOCIATED WITH IMPLEMENTATION OF FUZZY LOGIC CONTROLLERS

The overshoot in speed of the motor is yet to be reduced. The settling time of the motor in some cases is worse than a conventional controller. It necessitates a controller to overcome the aforesaid problems.

3.8 SUMMARY

The fuzzy logic controller has been proposed for the control of VSC based IM drive. In this chapter the design of the proposed system, its working principle and performance characteristics of the scheme for various load values have been presented. The proposed scheme was simulated using MATLAB/ Simulink. The FLC-based VSC controlled drive improves performance of the motor in the aspects of steady state error and speed drop during the change in load. It performs well when the motor runs, at and above rated speed.

3.9 VSC USING FUZZY GAIN SCHEDULING CONTROLLER

Fixed value of $k_p$ and $k_i$ in a PI controller produces the high overshoot, settling time and speed drop during the change in load. Online controlling of $k_p$ and $k_i$ in a PI controller can conquer this problem. It necessitates the Fuzzy gain scheduling PI controller for online tuning of $k_p$ and $k_i$.

In a Fuzzy Gain Scheduling Controller, the Fuzzy logic module is considered as an auto tuning module for parameters $k_p$ and $k_i$ in PI controller. The Fuzzy Gain Scheduling controller is considered as the major contribution to this research. The fuzzy inference of FGS controller is based on the fuzzy
associative matrices. The computational speed of controller is very fast, which can satisfy the need for rapid control of the system. The block diagram of the control system is shown in Figure 3.15 shows the control system block diagram.

![Block Diagram of Fuzzy Gain Scheduling PI Controller](image)

**Figure 3.15 Fuzzy gain scheduling PI controller block diagram**

The control algorithm of traditional PI controller can be described as

\[ u(t) = k_p e(t) + k_i \int e(t) \]  

(3.11)

Where, \( k_p \) is the proportional constant, \( k_i \) is the integral constant and \( e(k) \) is the speed error. The design algorithm of Fuzzy gain scheduling controller in this work is to adjust the \( k_p \) and \( k_i \) parameters online through fuzzy inference based on the current ‘e’ and ‘ec’ to make the control object achieve the good dynamic and static performances. This analysis proposes two Mamdani FGS controllers for tuning \( k \) and \( \beta \).

Speed error ‘e’ and error change rate ‘ec’ are used as fuzzy input and the proportional factor \( k_p \) the integral factor \( k_i \) are the fuzzy outputs. The membership functions (MF) of E and EC are configured as 5 MFs, all defined as \{NB, NS, ZO, PS, PB\}, where NB, NS, ZO, PS, and PB represent negative big, negative small, zero, positive small and positive big respectively.
The degree of truth of $k_p$ and $k_i$ are configured for 4 degrees, are defined as \{Z, S, M, B\}, where Z, S, M, and B represent zero, small, medium and big. The triangular distribution functions are proposed as membership functions of $E$, $EC$, $k_p$ and $k_i$. The membership functions for each variable are shown in Figure 3.16, Figure 3.17 and Figure 3.18 respectively.

**Figure 3.16**  Fuzzy membership functions of $E$ and $EC$

**Figure 3.17**  Fuzzy membership functions of $k_p$

**Figure 3.18**  Fuzzy membership functions of $k_i$

The principle of designing fuzzy rules is that the output of the controller can make the system output response dynamic and static performances optimal. The fuzzy rules are generalized in Table 3.5 and Table
3.6 according to the expert real time analysis in IM drive system and simulation analysis of the system. The Mamdani type of fuzzy is used as the fuzzy inference mode. The rules can be stated as "IF E is NS AND EC is PS THEN K_p is S, K_i is M." K_p and K_i are framed with 25 fuzzy condition statements. The MIN - MAX method of fuzzification is applied. The centroid method is adopted for defuzzification.

**Table 3.7**  The range of fuzzy sets of input variables in proposed β fuzzy controller

<table>
<thead>
<tr>
<th>Fuzzy set</th>
<th>Range of E</th>
<th>Range of EC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>[-6.75 -5 -3.25]</td>
<td>[-6.75 -5 -3.25]</td>
</tr>
<tr>
<td>NS</td>
<td>[-5 -3.25 -1.5]</td>
<td>[-5 -3.25 -1.5]</td>
</tr>
<tr>
<td>ZO</td>
<td>[-3.25 -1.5 0.25]</td>
<td>[-3.25 -1.5 0.25]</td>
</tr>
<tr>
<td>PS</td>
<td>[-1.5 0.25 2]</td>
<td>[-1.5 0.25 2]</td>
</tr>
<tr>
<td>PB</td>
<td>[0.25 2 3.75]</td>
<td>[0.25 2 3.75]</td>
</tr>
</tbody>
</table>

**Table 3.8**  The range of fuzzy sets of output variables in proposed β fuzzy controller

<table>
<thead>
<tr>
<th>Fuzzy set</th>
<th>Range of k_p</th>
<th>Range of k_i</th>
</tr>
</thead>
<tbody>
<tr>
<td>VS</td>
<td>[-0.005082 9.406e-020 0.005082]</td>
<td>[-0.0003333 6.17e-021 0.0003333]</td>
</tr>
<tr>
<td>S</td>
<td>[0 0.005082 0.01017]</td>
<td>[0 0.0003333 0.0006667]</td>
</tr>
<tr>
<td>M</td>
<td>[0.005082 0.01017 0.01525]</td>
<td>[0.0003333 0.0006667 0.001]</td>
</tr>
<tr>
<td>B</td>
<td>[0.01017 0.01525 0.02033]</td>
<td>[0.0006667 0.001 0.001333]</td>
</tr>
</tbody>
</table>
Table 3.9 The range of fuzzy sets of input variables in proposed \( k \) fuzzy controller

<table>
<thead>
<tr>
<th>Fuzzy set</th>
<th>Range of E</th>
<th>Range of EC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>[-6.75 -5 -3.25]</td>
<td>[-6.75 -5 -3.25]</td>
</tr>
<tr>
<td>NS</td>
<td>[-5 -3.25 -1.5]</td>
<td>[-5 -3.25 -1.5]</td>
</tr>
<tr>
<td>ZO</td>
<td>[-3.25 -1.5 0.25]</td>
<td>[-3.25 -1.5 0.25]</td>
</tr>
<tr>
<td>PS</td>
<td>[-1.5 0.25 2]</td>
<td>[-1.5 0.25 2]</td>
</tr>
<tr>
<td>PB</td>
<td>[0.25 2 3.75]</td>
<td>[0.25 2 3.75]</td>
</tr>
</tbody>
</table>

Table 3.10 The range of fuzzy sets of output variables in proposed \( k \) fuzzy controller

<table>
<thead>
<tr>
<th>Fuzzy set</th>
<th>Range of ( k_p )</th>
<th>Range of ( k_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>VS</td>
<td>[-0.005082 9.406e-020 0.005082]</td>
<td>[-0.0003333 6.17e-021 0.0003333]</td>
</tr>
<tr>
<td>S</td>
<td>[0 0.005082 0.01017]</td>
<td>[0 0.0003333 0.0006667]</td>
</tr>
<tr>
<td>M</td>
<td>[0.005082 0.01017 0.01525]</td>
<td>[0.0003333 0.0006667 0.001]</td>
</tr>
<tr>
<td>B</td>
<td>[0.01017 0.01525 0.02033]</td>
<td>[0.0006667 0.001 0.001333]</td>
</tr>
</tbody>
</table>

Table 3.11 The Control Rules for \( k_p \)

<table>
<thead>
<tr>
<th>( Ec )</th>
<th>NB</th>
<th>NS</th>
<th>ZO</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>NS</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>ZO</td>
<td>B</td>
<td>B</td>
<td>Z</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>PS</td>
<td>S</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>PB</td>
<td>Z</td>
<td>S</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
</tbody>
</table>
Table 3.12  The Control Rules for $k_i$

<table>
<thead>
<tr>
<th>ec</th>
<th>NB</th>
<th>NS</th>
<th>ZO</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>M</td>
</tr>
<tr>
<td>NS</td>
<td>M</td>
<td>B</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>ZO</td>
<td>M</td>
<td>B</td>
<td>Z</td>
<td>S</td>
<td>B</td>
</tr>
<tr>
<td>PS</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>PB</td>
<td>M</td>
<td>B</td>
<td>B</td>
<td>M</td>
<td>B</td>
</tr>
</tbody>
</table>

Fuzzy Gain Scheduling PI controller reduces the overshoot, settling time and drop in speed during load change by adjusting the values of $k_p$ and $k_i$ based on the error and change in error as shown in Figures (3.19 - 3.21).

![Fuzzy rule output](image)

Figure 3.19 Fuzzy rule output for E and EC are Negative Big in β FGS
Figure 3.20 Fuzzy rule output for E and EC are zero in $\beta$ FGS

Figure 3.21 Fuzzy rule output for E and EC are Positive Big in $\beta$ FGS
The performance of VSC based IM drive using FGS controller at various speed and load is shown in Table 3.13.
Table 3.13  Performance of FGS controlled VSC based IM drive for various speeds

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Peak Overshoot (%)</th>
<th>Steady state error (%)</th>
<th>Rise time (sec.)</th>
<th>Peak time (sec.)</th>
<th>Settling time (sec.)</th>
<th>Speed drop during load change (%)</th>
<th>Restoration time (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>15</td>
<td>3</td>
<td>0.0194</td>
<td>0.029</td>
<td>0.118</td>
<td>3.5</td>
<td>0.172</td>
</tr>
<tr>
<td>1000</td>
<td>12</td>
<td>2.6</td>
<td>0.0212</td>
<td>0.0345</td>
<td>0.125</td>
<td>1.7</td>
<td>0.159</td>
</tr>
<tr>
<td>1200</td>
<td>9</td>
<td>1.7</td>
<td>0.0248</td>
<td>0.0374</td>
<td>0.112</td>
<td>1.6</td>
<td>0.1614</td>
</tr>
<tr>
<td>1430</td>
<td>5.5</td>
<td>1.2</td>
<td>0.044</td>
<td>0.06</td>
<td>0.135</td>
<td>1.3</td>
<td>0.15</td>
</tr>
<tr>
<td>1800</td>
<td>1.8</td>
<td>1.1</td>
<td>0.0716</td>
<td>0.082</td>
<td>0.141</td>
<td>1.2</td>
<td>0.135</td>
</tr>
<tr>
<td>2000</td>
<td>1.4</td>
<td>0.1</td>
<td>0.0977</td>
<td>0.112</td>
<td>0.175</td>
<td>1.05</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Figure 3.24 shows the performance of FGS controlled VSC based IM drive with various parameters such as peak overshoot, steady state error, rise time, peak time, settling time, speed drop during load change and the restoration time.

**Figure 3.24 continued**

**a: Peak Overshoot Vs Speed**
Figure 3.24 Continued

b: Peak Time Vs Speed

c: Rise Time Vs Speed

Figure 3.24 Continued
d. Settling Time Vs Speed

![Graph of Settling Time Vs Speed](image)

**Figure 3.24 Continued**

---

e. Steady State Error Vs Speed

![Graph of Steady State Error Vs Speed](image)

**Figure 3.24 Continued**
f. Speed Drop During Load Change Vs Speed

g. Restoration Time Vs Speed

Figure 3.24 Performance of the FGS controlled VSC based IM drive
3.10 INFERENCES

The performance graphs of the Fuzzy gain scheduling controller confirm its control efficiency on VSC based IM drive. The performance of IM drive is analyzed concerning the features, rise time, peak time, settling time, peak overshoot, speed drop during the change in load and the restoration time. The performance is analyzed at various speeds and various loads. To analyze the parameters of speed drop during a change in load and restoration time, the load is increased during run time.

Steady state error and speed drop during the change in load are reduced by around 88% at rated speed compared to the conventional controller. Rise time, peak time and settling time are reduced by about 50% using Fuzzy gain scheduling controller compared to the conventional controller.

3.11 PROBLEMS ASSOCIATED WITH IMPLEMENTATION OF FUZZY GAIN SCHEDULING CONTROLLERS

Peak Overshoot has not decreased compared to the conventional controller. In some speeds, peak overshoot is higher than the conventional controller.

3.12 SUMMARY

Fuzzy gain scheduling controller has been proposed for the control of VSC based IM drive. In this chapter, the design of the proposed system, its working principle and performance characteristics of the scheme for various load values have been presented. The proposed system has been simulated using MATLAB/ Simulink. The FGS-based VSC controlled drive
improves performance of the motor in the aspects of steady state error and speed drop during the change in load. It performs well when the motor runs at and above rated speed.

### 3.13 MODEL REFERENCE ADAPTIVE SCHEME FOR SPEED ESTIMATION IN VSC

The adaptive scheme is applied to estimate the speed of induction motor without the use of speed sensor. MRAS based VSC for vector controlled induction motor drive is shown in Figure 3.25.

![Figure 3.25 MRAS based VSC for vector controlled induction motor drive](image)

Model reference based adaptive system of speed estimation block (Pankaj Swarnkar, et al. 2010) is shown in Figure 3.26.
Figure 3.26 Model reference based speed observer

Consider the Lyapunov function candidate:

\[ V = V_1 - V_2 \]  \hspace{1cm} (3.12)

\[ V_1 = e^T e \quad V_2 = \frac{(e_\omega)^2}{\lambda} \]  \hspace{1cm} (3.13)

With \((\lambda > 0)\), is the positive constant ensuring the positive definiteness of \(V_2\) and which will be tuned in (3.13) to improve observer dynamics. \(e_\omega = \omega_r - \omega_\hat{r}\) and \(e^T = [i_{sd} - \hat{i}_{sd} \quad i_{sq} - \hat{i}_{sq} \quad 0 \quad 0]\) since it is assumed that \(\varnothing_r = \varnothing_\hat{r}\).

The derivatives of this lyapunov candidate function in thus:

\[ \frac{dV}{dt} = e^T [(A - GC)^T + (A - GC)] \]

\[ - 2(\omega_r - \omega_\hat{r}) \left[ K(e_{isd} \varnothing_{rq} - e_{isq} \varnothing_{rd}) - \frac{1}{\lambda} \frac{d}{dt} \omega_\hat{r} \right] \]  \hspace{1cm} (3.14)

\[ e^T [(A - GC)^T + (A - GC)] e < -Q \]  \hspace{1cm} (3.15)

With \(Q = \varepsilon l_n\) and \(\varepsilon > 0\).
The stability of adaptive observer has proved if it respects two conditions as follows:

The eigenvalue of the observer is selected to have negative real parts so that the states of the observer will converge to the desired states of the observed system. The term in a factor of \((\omega_r - \hat{\omega}_r)\) in the equation (3.14) must be zero. The expression of the derivative of estimated speed becomes then:

\[
K(e_{lsd} \hat{\Theta}_{rq} - e_{isq} \hat{\Theta}_{rd}) - \frac{1}{\lambda} \frac{d}{dt} \hat{\omega}_r = 0
\]  

However this adaptive law of the speed

\[
\hat{\omega}_r = K_i \int_0^t (e_{lsd} \hat{\Theta}_{rq} - e_{isq} \hat{\Theta}_{rd}) dt
\]  

has been obtained for the stator torque frame, the dynamic adjusted by \(K_i\) (finite positive constant). For augmenting the dynamic of this observer during the transitory phase of rotor speed, the esteemed speed by the large PI regulator; we added a supplementary term proportional to the error. Then

\[
\hat{\omega}_r = K_p (e_{lsd} \hat{\Theta}_{rq} - e_{isq} \hat{\Theta}_{rd}) + K_i \int_0^t (e_{lsd} \hat{\Theta}_{rq} - e_{isq} \hat{\Theta}_{rd}) dt
\]  

Where SZ and S' are adaptive gains for speed estimator. An identification system for speed is shown in Figure 3.26, which is constructed from a linear time-invariant forward block and a nonlinear time-varying feedback block.
3.14 SIMULATION ANALYSIS OF MRAS BASED VSC

The simulation model for MRAS based VSC is developed using MATLAB. It is varied from above discussed VSC methods in the aspect of speed sensor. In the MRAS method speed is not measured by any speed sensors and speed is estimated by MRAS method and the simulation model of entire system is shown in Figure 3.27.

![Simulation model of MRAS based VSC](image)

**Figure 3.27 Simulation model of MRAS based VSC of induction motor drive**

The VSC using MRAS and MRAS based speed estimator is shown in Figure 3.28 and 3.29.
Figure 3.28 Model of VSC using MRAS

Figure 3.29 Model of MRAS based speed estimator

Figure 3.30 and 3.31 shows speed performance of MRAS based VSC control with the no load and change in load.

Figure 3.30 Speed performance of MRAS based VSC control with no load
The performance of VSC based IM drive using MRAS controller with various speed and load is shown in Table 3.14.

**Table 3.14  Performance of MRAS controlled VSC based IM drive for various speeds**

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Peak Overshoot (%)</th>
<th>Steady state error (%)</th>
<th>Rise time (sec.)</th>
<th>Peak time (sec.)</th>
<th>Settling time (sec.)</th>
<th>Speed drop during load change (%)</th>
<th>Restoration time (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>2.9</td>
<td>1.5</td>
<td>0.0193</td>
<td>0.026</td>
<td>0.1</td>
<td>1.625</td>
<td>0.15</td>
</tr>
<tr>
<td>1000</td>
<td>2.3</td>
<td>1.3</td>
<td>0.0209</td>
<td>0.033</td>
<td>0.11</td>
<td>1.58</td>
<td>0.142</td>
</tr>
<tr>
<td>1200</td>
<td>1.7</td>
<td>1.2</td>
<td>0.024</td>
<td>0.035</td>
<td>0.12</td>
<td>1.2</td>
<td>0.1387</td>
</tr>
<tr>
<td>1430</td>
<td>1.4</td>
<td>1</td>
<td>0.0391</td>
<td>0.0536</td>
<td>0.13</td>
<td>1</td>
<td>0.12</td>
</tr>
<tr>
<td>1800</td>
<td>1.2</td>
<td>0.89</td>
<td>0.0579</td>
<td>0.082</td>
<td>0.14</td>
<td>0.95</td>
<td>0.115</td>
</tr>
<tr>
<td>2000</td>
<td>1.05</td>
<td>0.2</td>
<td>0.0912</td>
<td>0.103</td>
<td>0.15</td>
<td>0.8</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The Figure 3.32(a-g) shows the performance of MRAS controlled VSC based IM drive with various parameters such as peak...
overshoot, steady state error, rise time, peak time, settling time, speed drop during load change and restoration time.

Figure 3.32 Continued

a: Peak Overshoot Vs Speed

b: Peak Time Vs Speed

Figure 3.32 Continued
c: Rise Time Vs Speed

d: Settling Time Vs Speed

Figure 3.32  Continued
e: Steady State Error Vs Speed

f: Speed Drop During Load Change Vs Speed

Figure 3.32 Continued
3.15 INFERENCES

The performance graphs of the MRAS controller confirm its control on VSC based IM drive. The performance of IM drive is analyzed in the features of Rise time, Peak time, settling time, Peak overshoot, speed drop during the change in load and restoration time. The performance is analyzed with various speeds and various loads. To analyze the parameters of speed drop during the change in load and restoration time, the load is increased during run time.

Peak Overshoot in speed is reduced by 27% compared to the conventional controller. Steady state error is reduced by 81% and speed drop while change in load is reduced by 87% at rated speed compared to the conventional controller. Rise time, peak time and settling time are reduced about 94%. It performs well only in and above the rated speed.
3.16 SUMMARY

MRAS controller has been proposed for the control of VSC based IM drive. In this chapter the design of the proposed system, its working principle and performance characteristics of the scheme for various load values have been presented. The proposed system has been simulated using MATLAB/Simulink. The MRAS based VSC controlled drive improves performance of the motor in all aspects. It performs well when the motor is operated at and above rated speed.