CHAPTER 4

FUZZY TUNED AWPI CONTROLLER BASED CHOPPER CONTROLLED DRIVE

4.1 INTRODUCTION

Fuzzy logic is a rule-based decision making method, used to control a process that a human can control with expertise gained from experience. Fuzzy Logic Controller (FLC) is a type of modern controller system, which is a knowledge based approach. FLC has progressed as a substitute for traditional control strategies in automatic control systems. Fuzzy control theory offers non-linear controllers that are capable of performing different complex non-linear control action. Their design doesn’t require precise knowledge of the system model such as the poles and zeros of the system transfer function. Lotfi Zadeh (1960) introduced fuzzy theory as an extension of traditional control theory. The fuzzy sets were formulated from elements which have degrees of membership and are framed based on the error and change in error of a system.

In this chapter, the background study of fuzzy systems, the basic components, the membership functions, IF-THEN rules and the proposed fuzzy tuned AWPI controller systems are presented. The proposed fuzzy tuned AWPI controller scheme is simulated using MATLAB / Simulink. The fuzzy tuning algorithm is attempted in back calculation AWPI scheme and the simulation results have been presented and analyzed.
4.2 BACKGROUND STUDY OF FUZZY SYSTEMS

A fuzzy system is based on fuzzy logic, which is a mathematical system that analyzes logical variables which operates on discrete values of either 1 or 0 i.e. true or false. Fuzzy logic employs the logic of approximate reasoning and continues to grow, as it provides an inexpensive solution for controlling ill-known systems. Fuzzy control algorithm is based on a linguistic control strategy, which is derived from expert knowledge. It doesn’t need any difficult mathematical calculations, but uses them to simulate expert knowledge and provides a good performance on a control system.

Fuzzy set theory (Lofti Zadeh 1960), differs from traditional Boolean set theory. It allows a partial membership in the set, whereas the traditional Boolean set is two-valued represented as 1 or 0. The partial membership or a degree of membership might be any value along the continuum of 0 to 1. Fuzzy set theory uses a linguistic term, which is defined quantitatively as a membership function. This membership function specifically defines the degrees of membership based on the property of the control variable such as speed or torque. With the membership functions defined for controller system inputs or outputs, the IF-THEN type conditional rules are formed. The rule base and corresponding membership functions are employed to analyze the controller inputs and determines the outputs by using fuzzy logic inference.

designed and proposed a fuzzy controller based chopper fed drive for DC motor. The speed and the deviation of change in speed are taken as inputs to the fuzzy controller of the chopper drive. The chopper drive with PI or PID controller can be self-tuned with the fuzzy controller Rajani Mudi & Nikhil Pal (1999); Tan et al (2003) suggested having dynamic input values in order to get an effective controlled output. Senthilkumar et al (2004 and 2007) designed and suggested a fuzzy controller for closed loop operation of chopper controlled DC motor drives. Muruganandam & Madheswaran (2009) analyzed the performance of chopper drive using fuzzy controller.


Girija Nambal & Hasle (2012) presented the triangular membership functions for the fuzzification process of the speed and change in speed error values whereas; the defuzzification process was carried out by the center of gravity method for the chopper drive of DC motors. Rambir Singh et al (2012) designed a fuzzy logic controller in order to provide a better dynamic as well as steady state response for speed control applications of DC drives. Atul Kumar Dewangan et al (2012) proposed a fuzzy tuning method for
conventional PID controller for a chopper controlled DC motor drive and demonstrated its performance using digital simulation.


The chopper control drive proposed in this chapter utilizes the speed error and the change in speed error as parameters to frame the fuzzy rules. The fuzzy inference system uses mamdani method for framing the fuzzy rules and the crisp values are fuzzified using min-max method. The center of gravity method of defuzzification has been adopted to obtain the controlled outputs of the fuzzy controller. A fuzzy logic controller using these crisp values has been used to control the chopper drive of the PMDC motor. The crisp values obtained as output of the fuzzy controller forms the gain values of the AWPI controller. In this manner, the proposed system acts as fuzzy tuned AWPI controller. The proposed drive has been simulated using MATLAB Simulink and the results have been presented and analyzed.

4.3 FUZZY LOGIC SYSTEM AND ITS COMPONENTS

The inherent approximation capability, high degree of tolerance, smooth operation, reduced effect of non-linearity and faster learning ability are the advantages of fuzzy logic system. These advantages make to use fuzzy logic in wide control applications. The block diagram of fuzzy logic based motor control system is shown in Figure 4.1. The system includes a fuzzifier, inference Engine, defuzzifier and rule base.
4.3.1 Fuzzy Set

Fuzzy sets were introduced by Lotfi A Zadeh (1965) and are sets whose elements have degrees of membership. The fuzzy sets are extension of classical sets. The membership of classical set theory is assessed in binary terms as 1 or 0. But the fuzzy set membership functions are valued in the interval [0, 1]. In fuzzy set theory, the classical sets are termed as crisp sets. The fuzzy sets are inexact defined classes, as they do not have sharply defined boundaries.

4.3.2 Degree of Membership

The degree of membership is the degree to which a crisp value belongs to a fuzzy set. It is expressed over a range as 0.0 to 1.0 or as percentage ranging from 0% to 100%.

4.3.3 Membership Functions

The membership function of fuzzy set is the representation of the degree of truth. It describes the degree of membership of an entity to a class
with inexact boundaries. It illustrates how completely a crisp value belongs to a fuzzy set. For any set \( X \), a membership function on \( X \) is any function \( X \) from to the real unit interval \([0, 1]\). The membership functions on \( X \) represent fuzzy subsets of \( X \). For a fuzzy set \( \tilde{A} \), the membership function is denoted by \( \mu_A \). For an element \( x \) of \( X \), the value \( \mu_A(x) \) is called the membership degree of \( x \) in the fuzzy set \( \tilde{A} \). The membership degree \( \mu_A(x) \) measures the rank of the membership element \( x \) to the fuzzy set \( \tilde{A} \). The value 0 means that \( x \) is not a member of the fuzzy set; the value 1 means \( x \) is fully a member of the fuzzy set. The values in the interval \([0, 1]\) illustrate fuzzy members, which belong to the fuzzy set only partially.

![Membership Function of Fuzzy Set](image)

(a) Membership Function of Fuzzy Set

Figure 4.2 (Continued)

The fuzzy membership functions are classified into four types based on the shapes. They are:

1. Trapezoidal Membership Functions
2. Triangular Membership Functions
3. Gaussian Membership Functions
4. Generalized Bell Membership Functions
The most popular shapes are triangular and trapezoidal membership functions as these shaped are easy to represent designer’s idea and also require low computation time.

(b) Triangular Membership Function

(c) Trapezoidal Membership Function

Figure 4.2 (Continued)
(d) Gaussian Membership Function

(e) Generalized Bell Membership Function

Figure 4.2 Fuzzy Membership Functions
4.3.4 Fuzzification

Fuzzification is the process of converting or transforming the measured inputs of the system called crisp value, into the fuzzy linguistic values, called the membership functions. This fuzzification takes place in the fuzzifier block.

4.3.5 Rule Base

The rule base is a collection of expert control rules which are needed to obtain the controlled output. The rule base is of IF-Then type. The If-Then statement is the one in which the words are characterized by continuous membership functions. After defining the fuzzy sets and assigning their membership functions, rules must be written to describe the action to be taken for each combination of control variables. These rules will relate the input variables to the output variable using If-Then statements which allow decisions to be made. Each rule is represented as follows:

IF (antecedent) Then (consequence)

For instance:

If the tank is full, then stop the pump.

If the speed of the car is less, then apply more acceleration.

4.3.6 Inference Engine

Inference engine is a software code that processes the rules based on the facts of a given situation. It is an information processing system, which employs inference steps similar to that of a human brain.
4.3.7 Defuzzification

The output membership functions obtained from the inference engine are converted into the crisp values in the defuzzifier. This process is termed as defuzzification. There are different methods of defuzzification and the common methods are:

1. Centre of Gravity (COG)
2. Bisector of Area (BOA)
3. Mean of Maximum (MOM)

4.3.7.1 Centre of Gravity (COG)

COG is called centre of gravity for singletons (COGS), where the crisp control value is the abscissa of the centre of gravity of the fuzzy set is calculated using Equation 4.1.

\[ U_{CGS} = \sum \mu_A(x_i) x_i / \sum \mu_A(x_i) \tag{4.1} \]

Where, \( x_i \) is a point in the universe of the conclusion (\( i=1, 2, 3, \ldots \)) and \( \mu_A(x_i) \) is the membership value of the resulting conclusion set.

4.3.7.2 Bisector of Area (BOA)

The Bisector of Area (BOA) defuzzification method is a computationally complex method, in which the abscissa of the vertical line is calculated that divides the area of the resulting membership function into two equal areas. For discrete sets, uBOA is the abscissa \( x_f \) that minimizes

\[ \min \left| \sum_{i=1}^{j} \mu_A(x_i) - \sum_{i=j+1}^{i_{\text{max}}} \mu_A(x_i) \right|, i < j < i_{\text{max}} \tag{4.2} \]

Here \( i_{\text{max}} \) is the index of the largest abscissa \( x_i \).
4.3.7.3 Mean of Maximum (MOM)

In Mean of Maximum (MOM) method the crisp value is to choose the point with the highest membership. When there are several points which have maximum membership value, then, the mean of all the maximum membership values is calculated using Equation 4.3.

\[
U_{\text{MOM}} = \frac{\sum_{i=1}^{\mu_{\text{max}}(x_i)} x_i}{|I|}, \quad I = \{ i | \mu_{\text{A}}(x_i) = \mu_{\text{max}} \} \tag{4.3}
\]

Here \( I \) is the (crisp) set of indices \( i \) where \( \mu_{\text{A}}(x_i) \) reaches its maximum \( \mu_{\text{max}} \), and \( |I| \) is its cardinality (the number of members).

Based on the defuzzification process the fuzzy logic controllers are classified into two types namely, Mamdani Fuzzy controller and Takagi – Sugeno Fuzzy Controller.

4.3.8 Mamdani Fuzzy Controller

The Mamdani Fuzzy Controller is a crisp based controller which produces crisp outputs from crisp inputs. The inference engine utilizes Mamdani fuzzy inference method proposed by Ebrahim Mamdani (1975). In this model the output membership functions are of fuzzy sets. These fuzzy sets are defuzzified to crisp values. In Mamdani method, commonly the COG method of defuzzification is used to obtain the crisp outputs. The structure of Mamdani fuzzy controller consists of four main parts: Fuzzification of the inputs, Rule Evaluation, Aggregation of the rules and Defuzzification.
Fuzzification converts the input data to degree of membership functions. The data is matched with the rule condition and for any particular instance it’s determined how well the data is matched with the rule. In this way, the degree of membership is determined. Based on the system requirement, the If – Then rules are written. Generally the fuzzy controller works on both multiple input and multiple output and single input and single output logics. The inference engine aggregates the degree of fulfillment of the fuzzy sets according to the conditions specified in the rule base. In activation minimum of two aggregated value is selected and only thickened part of singleton are activated. Its multiplication result in slighter smooth control. Then all activated conclusions are accumulated using max operations. The resulting fuzzy set is converted into its crisp value by using centre of gravity method of defuzzification.

4.3.9 Takagi–Sugeno Fuzzy Controller

The Takagi-Sugeno fuzzy controller is another type of fuzzy controller, in which, the membership functions are not used by the defuzzification process to obtain the crisp outputs. This model was proposed
by Takagi, Sugeno and Kang (1985). They made an effort to develop a systematic approach to generate fuzzy rules from a given input-output dataset. The typical fuzzy rule of Takagi-Sugeno model is as follows:

If $x$ is $A$ and $y$ is $B$, then $z = f(x, y)$

where, $A$ and $B$ are fuzzy sets in the antecedent, while $z=f(x, y)$ is a crisp function in the consequent. The block diagram of Takagi-Sugeno fuzzy controller is shown in Figure 4.4. The block diagram shows that the crisp outputs are obtained directly from the inference engine without using defuzzification block.

![Figure 4.4 Takagi – Sugeno Fuzzy Controller](image)

### 4.4 DEVELOPMENT OF FUZZY TUNED AWPI CONTROLLER SCHEME

The fuzzy controller proposed in this Thesis is a Mamdani Fuzzy controller which works on Multiple Input and Single Output (MISO) logic. The structure of fuzzy tuned AWPI controller scheme proposed is shown in Figure 4.5.
Figure 4.5 Structure of Fuzzy Tuned AWPI Controller Scheme

The error between the set speed and the current speed and the rate of change of speed error are fed as input to the fuzzy logic controller. These values are fed as crisp inputs to the fuzzy logic controller and are converted into fuzzy sets by using min-max method. The input functions are framed from the following expressions.

\[
\text{Error, } e(t) = \omega_r(t) - \omega_a(t) \tag{4.4}
\]

\[
\text{Change in error, } de(t) = e(t) - e(t-1) \tag{4.5}
\]

Where,

\( \omega_r = \) reference speed in rad/s

\( \omega_a = \) actual speed in rad/s

\( e(t) = \) instantaneous error

\( e(t-1) = \) error of the previous instant

These inputs are fuzzified as Negative Big (NB), Zero Error (ZO) and Positive Big (PB). To have efficient and smooth control, the output membership functions are framed as Zero (Z), Small (S), Medium (M) and Big (B). The input functions are matched with output functions through the
fuzzy If-Then rule and the corresponding output functions to tune the values of gain functions $K_p$ and $K_i$ are determined. The chosen output function is then defuzzified by using centre of gravity method. The crisp values are given to the AWPI controller module. The AWPI module generates the necessary signal to control the modulation index of the PWM generator and the corresponding PWM signal needed for the chopper is generated.

4.4.1 Design of Membership Functions

The membership functions of the input and output variables are framed from the numerical range of their crisp values and the shape of the membership functions. In this fuzzy logic controller, triangular and trapezoidal membership functions have been used. The tables 4.1, 4.2 and 4.3 shows the range of numerical values, their description and function used for framing the membership function of input variable speed error $e(t)$, change in speed error $de(t)$ and the output functions of $K_p$ and $K_i$. In the traditional PI and AWI controllers the gain values are fixed as $K_p = 7$ and $K_i = 3$ by Ziegler Nicholas Method. As fuzzy logic system is a knowledge based approach, the gain functions $K_p$ and $K_i$ are fixed in the range of 7 and 3 respectively. The table 4.2 and 4.3 shows the numerical range of the crisp values fixed for the $K_p$ and $K_i$ gain functions respectively.

**Table 4.1 Input Membership Functions**

<table>
<thead>
<tr>
<th>Fuzzy set</th>
<th>Description</th>
<th>Shape of the Membership Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative Big (NB)</td>
<td>Large error difference in negative direction</td>
<td>Triangular Membership Functions</td>
</tr>
<tr>
<td>Zero (ZO)</td>
<td>Zero error difference</td>
<td></td>
</tr>
<tr>
<td>Positive Big (PB)</td>
<td>Large error difference in positive direction</td>
<td></td>
</tr>
</tbody>
</table>
### Table 4.2 Output Membership Functions for $K_P$

<table>
<thead>
<tr>
<th>Fuzzy set</th>
<th>Numerical Range</th>
<th>Params</th>
<th>Shape of the Membership Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero (Z)</td>
<td>5.5 to 7</td>
<td>[5.001 5.5 6.001]</td>
<td>Triangular Membership Function</td>
</tr>
<tr>
<td>Small (S)</td>
<td></td>
<td>[5.5 6.001 6.499]</td>
<td></td>
</tr>
<tr>
<td>Medium (M)</td>
<td></td>
<td>[6.001 6.499 7]</td>
<td></td>
</tr>
<tr>
<td>Big (B)</td>
<td></td>
<td>[6.499 6.8 7.5]</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4.3 Output Membership Functions for $K_i$

<table>
<thead>
<tr>
<th>Fuzzy set</th>
<th>Numerical Range</th>
<th>Params</th>
<th>Shape of the Membership Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero (Z)</td>
<td>2.5 to 3</td>
<td>[2.333 2.5 2.667]</td>
<td>Triangular Membership Function</td>
</tr>
<tr>
<td>Small (S)</td>
<td></td>
<td>[2.5 2.667 2.833]</td>
<td></td>
</tr>
<tr>
<td>Medium (M)</td>
<td></td>
<td>[2.667 2.833 3]</td>
<td></td>
</tr>
<tr>
<td>Big (B)</td>
<td></td>
<td>[2.833 3 3.167]</td>
<td></td>
</tr>
</tbody>
</table>

### 4.4.2 Rule Base

The If-Then rules of the fuzzy logic controller are framed from the membership functions. The rules are evaluated according to the compositional rule of inference. These rules decide the working of the fuzzy logic controller. From the input membership functions nine fuzzy If-Then rules are framed. The fuzzy rules framed are as follows:
IF E is NB and EC is NB KP is B and KI is Z
IF E is NB and EC is ZO KP is B and KI is Z
IF E is NB and EC is PB KP is M and KI is Z
IF E is ZO and EC is NB KP is M and KI is B
IF E is ZO and EC is ZO KP is Z and KI is Z
IF E is ZO and EC is PB KP is B and KI is B
IF E is PB and EC is NB KP is M and KI is Z
IF E is PB and EC is ZO KP is B and KI is B
IF E is PB and EC is PB KP is B and KI is B

The fuzzy rules are framed based on the error and change in error values. For instance, at starting the error between set speed and actual speed of the motor will be very high. This needs more the proportional gain values to be chosen. The speed increases and the error decreases, when the motor starts to rotate. During the steady state condition, the error will be minimum and so the change in speed error. In order to reduce the steady state error large value of integral gain is selected with moderate proportional function. Employing this combination, the fuzzy rules are framed.

4.5 SIMULATION MODEL

The MATLAB simulation model of the fuzzy tuned AWPI controller based chopper controlled drive is shown in Figure 4.6 (a). The fuzzy subsystem and its components are shown in Figure 4.6 (b). The fuzzy editor is used to create the fuzzy membership functions. The FIS editor shows the methods used for fuzzification, defuzzification and also the numerical range of the linguistic variables used. The FIS Editor used for the simulation is shown in Figure 4.7 (a). The input membership function editor generates
the error fuzzy sets from the linguistic variables and the corresponding membership function plots are shown in Figure 4.7 (b) and Figure 4.7 (c) respectively. The sets NB, ZO and PB are framed using triangular membership function. The Figure 4.7 (d), 4.7 (e) and 4.7 (f) and 4.7 (g) shows the output membership functions of $K_p$ and $K_i$ respectively. Figures 4.7 (h), 4.7 (i) and 4.7 (j) portrays the rule editor, rule viewer and surface viewer of the MATLAB fuzzy logic tool box. Using these dialog boxes, the fuzzified and crisp values can be obtained.
Figure 4.6 (Continued)

(a) Simulation Model
(b) Fuzzy Controller Subsystem

Figure 4.6 MATLAB/Simulink Model of Fuzzy Tuned AWPI Controller

(a) FIS Editor

Figure 4.7 (Continued)
(b) Input Membership Function Plots

Figure 4.7 (Continued)

The output membership function for the proportional gain $K_p$ is framed in the range of 5.5 to 7. The fuzzy sets Z, S, M and B are generated as trapezoidal membership functions. The FIS editor to generate the output $K_p$ function and its corresponding membership functions are shown in Figures 4.7 (d) and 4.7 (e) respectively. Similarly, the output membership function for the proportional gain $K_i$ is framed in the range of 2.5 to 3 using triangular membership function. The FIS editor to generate the output $K_i$ function and its corresponding membership functions are shown in Figures 4.7 (f) and Figure 4.7 (g) respectively.

(c) Output Membership Functions Plot for $K_p$

Figure 4.7 (Continued)
(d) Output Membership Functions Plot for $K_i$

(e) Rule Viewer

Figure 4.7 (Continued)
(f) Surface Viewer

Figure 4.7 FIS Editor for PMDC Motor

4.6 SIMULATION RESULTS AND DISCUSSIONS

(a) Drilling Mode

Figure 4.8 (Continued)
(b) Screwing Mode

Figure 4.8 Response of Fuzzy Tuned AWPI Controller

The proposed fuzzy tuned AWPI controller is simulated for a set speed of 1000 rpm. The response of the system for the drilling and screwing modes are shown in Figures 4.8 (a) and 4.8 (b) respectively. In the drilling mode the response depict that the speed gives rise to peak overshoot and it settles down nearer to the set speed within a short duration of time. From the response of the screwing mode it is found that, when the torque is increased, the motor tends to stop. However, there is a delay in the motor idling period i.e. the motor takes some time to achieve zero speed when the torque is increased beyond the set torque value.
### Table 4.4 Simulated Parameters for Fuzzy Tuned AWPI Controller

<table>
<thead>
<tr>
<th>Set Speed (rpm)</th>
<th>Peak Overshoot (%)</th>
<th>Steady State Error (%)</th>
<th>Motor Idling Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>27.3</td>
<td>0.52</td>
<td>0.58</td>
</tr>
<tr>
<td>600</td>
<td>14.5</td>
<td>0.42</td>
<td>0.62</td>
</tr>
<tr>
<td>900</td>
<td>8</td>
<td>0.28</td>
<td>0.65</td>
</tr>
<tr>
<td>1000</td>
<td>7.6</td>
<td>0.22</td>
<td>0.76</td>
</tr>
<tr>
<td>1200</td>
<td>4.5</td>
<td>0.16</td>
<td>1.1</td>
</tr>
<tr>
<td>1500</td>
<td>3.5</td>
<td>0.12</td>
<td>1.4</td>
</tr>
<tr>
<td>2000</td>
<td>2.1</td>
<td>0.08</td>
<td>1.8</td>
</tr>
</tbody>
</table>

(a)

Figure 4.9 (Continued)
Figure 4.9 Performance Characteristics of Fuzzy Tuned AWPI Controller
4.6.1 Inferences

The table 4.4 elucidates the performance characteristics of the chopper drive for various set speed values. From the simulated results the performance characteristic curves are plotted as shown in Figure 4.9. The peak overshoot and the steady state error values decreases with increase in set speed values. The peak overshoot and steady state error are very high at low set speed values. For instance, the overshoot and the steady state error are 21.1% and 0.52% respectively for set speed of 300 rpm. At higher set speeds, the fuzzy tuned AWPI controller provides superior performance by offering reduced peak overshoot and steady state error. When the set speed is 1000 rpm, the peak overshoot is 7.6% and the steady state error is 0.22%. 2.1% of peak overshoots and 0.08% of steady state error have been observed for high set speed of 2000 rpm. These values corroborates that the proposed fuzzy tuned back calculation AWPI controller offers good steady state and transient state response.

The motor idling time is observed to be increased for the increase in set speed values. For low speed of 300 rpm, the motor takes a very small duration of 0.58 seconds. Upto 1000 rpm, the idling time is less than 1 second, whereas for the set speed greater than 1000 rpm, the idling time is more than one second. For the speed of 1200 rpm it is 1.1 seconds and at 1500 rpm it is 1.4 seconds. At a speed of 2000 rpm the motor runs idle for 1.8 seconds.

4.7 CONCLUSION

A novel fuzzy tuned AWPI controller has been proposed for the chopper drive of PMDC motor. The basics of a fuzzy system, fuzzification, defuzzification, rule base and fuzzy inference systems have been studied for the applications of to verify the compatibility of fuzzy systems with chopper
controlled drive. The fuzzy logic approach has been employed to tune the proportional and integral gains of the AWPI controller of the closed loop chopper control drive. The design of the proposed system, its working principle and performance characteristics of the scheme for various speed values have been presented. The proposed system has been simulated using MATLAB/Simulink. Its performance during drilling and screwing mode of operations has been studied. The simulation results reveals that the proposed fuzzy tuned AWPI scheme results in reduced peak overshoot, steady state error and motor idling time. At the outset, it is construed that the proposed fuzzy tuned AWPI controller scheme offers better steady state and transient state performance.