Speed Control of Separately Excited DC Motor using Fuzzy Logic Controller

A thesis submitted in fulfilment of prerequisites of

Bachelor's Degree

in

Electrical Engineering

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I am privileged by this opportunity to present my thesis to the Department of Electrical Engineering, National Institute of Technology, Rourkela.

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This thesis on '**Speed control of Separately Excited DC motor using Fuzzy Control Logic**' is presented in completion of partial requirement of Bachelor's degree in Electrical Engineering is written by us, **T. Yuva Radha Krishna** and **Kishore Biswal** under the guidance of **Dr. Kanungo Barada Mohanty**.

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Abstract:

DC Motors are widely used in industries for various purposes. It is a doubly fed system. Many situations demand change in the speed of the DC Motor. This makes it a necessity to employ a method to effectively control the speed of a separately excited DC motor. Many methods are available to regulate the speed of a separately excited DC motor such as PID control, Fuzzy Logic Control, Neural Network Method. The Fuzzy method gives a human like intuition to the control strategy and is self-tolerant to inputs which are no so precise. The Fuzzy Logic Controller contains different components like Fuzzification, Defuzzification and Fuzzy Rule inference. The Objective is to understand the Fuzzy Rule base and inference methods and employ them in controlling the speed of the motor. It is very efficient where the precision required is not too high. It is a robust, easily controllable strategy. It is capable of realizing multiple inputs and producing different numerous outputs. Here, we discuss the Fuzzy Logic Control of the speed of DC Motor. We make use of this this strategy to achieve a flexible control of the speed of the Separately Excited DC Motor. Error in speed and the derivative of Error are taken as the inputs to the Fuzzy controller and by selecting suitable membership functions we control the output of the Fuzzy controller which is subtracted from the armature supply and then supplied to the armature. In this way the speed of the DC motor is controlled by regulating the armature supply voltage.

1. Introduction:

1.1 Importance of DC Motors in practice:

A DC motor is an electrical machine which coverts direct current electrical power into mechanical power. We use DC motors in almost every aspect of our daily life like in Toys, Fans, Automobile drives. Small DC motors are used in toys, tools and appliances. Larger DC motors are used in electrical automobiles, propulsion systems and elevators. Industrially a good performing DC motor is required of high speed controllability, steady and transient state stability and good Torque-Speed characteristics. The speed of a DC motor is very easily controlled compared to AC motors. The making of highly controlled motors is critical for Industrial purposes. For a satisfactory operation, a DC motor must have an excellent speed tracing and regulation of load. DC motors are easily constructed when compared to the AC motors which are bulky. DC motors are very economical when the requirement of horse power is high. An estimation states that more than 95% of controllers used for controlling speed of a DC motor are PID controllers. But they performance degrades in case of the non-linearity [1] [2] in characteristics.

1.2 Approaches to Speed control

Speed control of the DC motor is realised by following methods:

- In constant torque region, we can vary the armature voltage to achieve speeds below the rated speed.

- In constant power region, we can increase the field flux to obtain speeds beyond the rated speed.

Here field control is not generally used because the machine core will be rendered under-utilized. In armature control, the range of speed control is more but the ohmic losses will increase considerably.

Methods of control:

Following methods are the most generally used methods for controlling speed of a separately excited DC motor. They are:

- In low power DC motors, we can use the Armature rheostat control method.
- P or PI or PID control depending upon the requirement of the application.
- Neural Network Controllers are used where continuous control of speed is required.
- Adaptive method in Field weakening to achieve speeds above rated speed.
- PWM inverter method for variable armature voltage control.
- Fuzzy Logic Control method.
- Neuro - Fuzzy Logic controller inherits advantages of both Neural Network Controller and Fuzzy Logic Controller.

Aforementioned control methods have certain dis-advantages. Here we discuss mainly the Fuzzy Logic Control. There has been very productive research in this region of. Fuzzy Logic Controller [3].We face some difficulties in speed these methods like:

- Different indefinite inputs,
- Unpredictable Load dynamics,
- Unidentified parameters,
- Undesired Noise,
- Non-linearity in motor characteristics.

Literature Review:

In contrast to the classical concepts of control a novel methodology is introduced, an approach proposed by Hanss and Kistner. The authors proposed a design based on combination of classical controller and fuzzy arithmetic where uncertainties are assigned in the form of fuzzy values. Then again P. Albertos, M. Olivares and Antonio Sala in *Fuzzy Logic Controllers.* Methodology have argued that depending on the level of interactivity with the end user and ease to modify controller parameters either in on-line or off-line operation (simulation) several solutions may be possible. The main argument is the cooperative use of fuzzy logic techniques together with other well-established control techniques.

In 1973, Lakoff argued that the membership function is perceived more like a continuum than a discrete set of membership values, although it may be sampled for practical purposes. The author stresses that the choice of continuous set-theoretic operators is consistent with knowledge of membership functions; a slight modification of the membership values does not radically affect the rough shape of the result of a set operation. In 1978, Kickert and Mamdani said that, under certain limiting assumptions, the fuzzy controller can be seen as a multidimensional multilevel relay.

2. Separately Excited DC Motor:

2.1 Construction:

- Separately Excited DC Motor has separate supplies for each Armature and Field.
- Field Winding supply the excitation to provide field flux.
- Field winding is generally provided on the stator.
- The Current in armature circuit is supplied to the rotor via brush and commutator setup to reduce friction.
- The Armature is generally provided on the rotor.

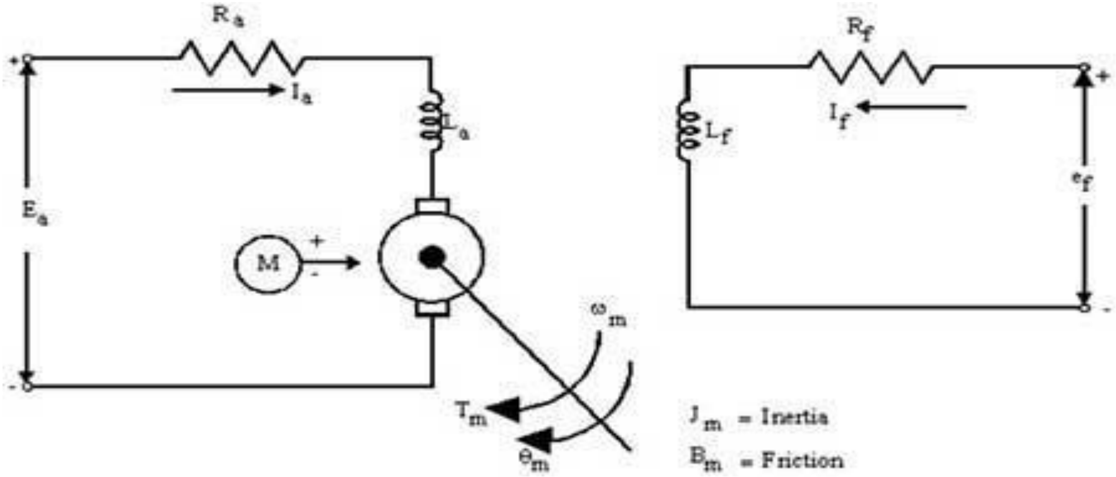

Figure 1 Construction of a Separately Excited DC Motor

2.2 Operation:

First the motor is excited by a separate supply to the field which creates a flux in the field. The supply for armature sets up a current 'Ia' in the armature and also a flux in the rotor. The interaction between these two fluxes creates a torque which starts to rotate the rotor. The field current is independent of the armature current. Thus, this motor can be controlled without disturbing the filed flux using the armature control.

2.3 Torque and Speed Equations:

Torque Equation: T= KFI_a

Speed Equation: $\omega = \frac{V_f - I_a R_a}{KF}$

Back EMF Equation: $E_b = KF\omega$

Armature Voltage:

$$V = E_b + I_a R_a + L_a \frac{dI_a}{dt}$$

The Torque equation is written as: [9]

$$T_m = J_m \frac{d\omega}{dt} + B_m \omega + T_L$$

Where,

F - Field Flux Webers,

T – Torque in N-m,

ω – Speed in rad/sec,

V_f - Terminal Field Supply Voltage in volts,

I_a- Armature Current in amperes,

R_a - Armature Resistance in Ohms,

L_a – Armature Inductance in milli Henry,

K – Constant,

J – Rotational Moment of Inertia in Kg/m^2,

B_m – Viscous friction coefficient,

T_L – Load Torque.

Viscous friction is very small for small power rating and small motors. We can assume

‘$B_m = 0$’.

$$T_m = J_m \frac{d\omega}{dt} + T_L$$

Taking Laplace Transform for the Armature voltage equation we get,

$$I_a(S) = \frac{V - E_b}{R_a + L_a s}$$

Substituting $E_b = KF\omega$ in the above equation we get,

$$I_a(S) = \frac{V - KF\omega}{R_a + L_a s}$$

Armature time constant, $T_a = \frac{L_a}{R_a}$

Taking Laplace transform for Torque equation we get,

$$\omega(S) = \frac{(T_m - T_L)}{J_m s} = \frac{(KFI_a - T_L)}{J_m s}$$

Solving, we get the transfer function as

$$\frac{\omega(s)}{V(s)} = \frac{(1 / K_m)}{[(1 + sT_m)(1 + sT_a)]}$$

Where,

$$T_m = \frac{JR_a}{(kF)^2}$$

2.4 <u>Steady State Operation:</u>

From the equation:

$$\omega = \frac{(V_f - I_a R_a)}{KF}$$

We can say that the speed depends on field flux, armature current and supply voltage. But normally the armature resistance in the circuit is negligible. So, the voltage drop across the armature resistance will be very small and can neglected. Since in steady state the field supply and Load torque are constant the speed finally depends on the Supply voltage for the armature. As shown the speed can be varied using Armature Voltage and Rheostat control. Here, we use the armature voltage control.

As the change in speed during steady state is zero.

$$T_m = B_m \omega + T_L$$

2.5 <u>Variation of Speed:</u>

Using Fuzzy Logic Controller, the armature voltage is varied which gives rise to a change in speed. The range of speed variation can be very small as the range of armature voltage control is generally very limited and also the armature resistance is assumed to be very small.

$$\omega = \frac{(V_f - I_a R_a)}{KF}$$

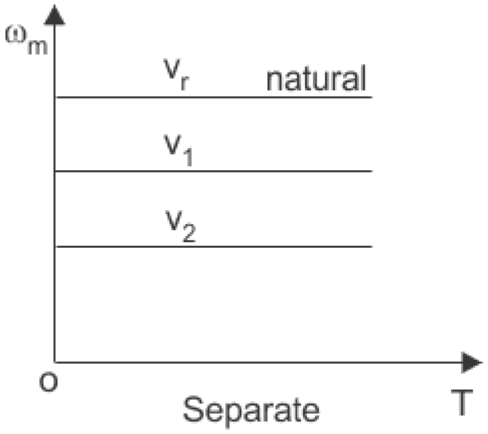

Figure 1 Speed vs. Torque Characteristic for Armature voltage control

Here $V_r > V_1 > V_2$.

2.6 <u>Ranges of Speed variation:</u>

Base Speed:

Base Speed is the speed of the motor at the rated armature voltage, rated armature current and rated field current.

Constant Torque Region:

This is the region where speed of the motor is below the rated speed and armature voltage is controlled to change the speed with I_a and I_f is fixed to generate constant torque.

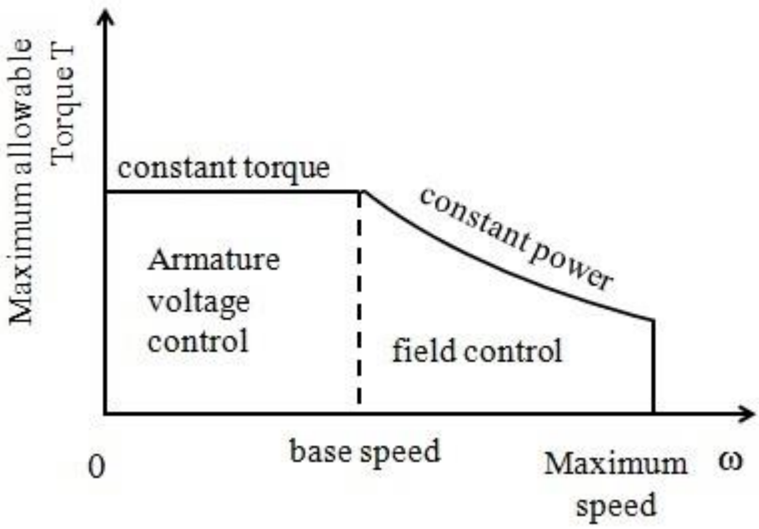

Figure 3 Torque vs. Speed Characteristics

Constant Power Region:

Here the speed is increased beyond the rated speed but armature voltage is kept constant. The field current is varied to increase the speed by weakening the field.

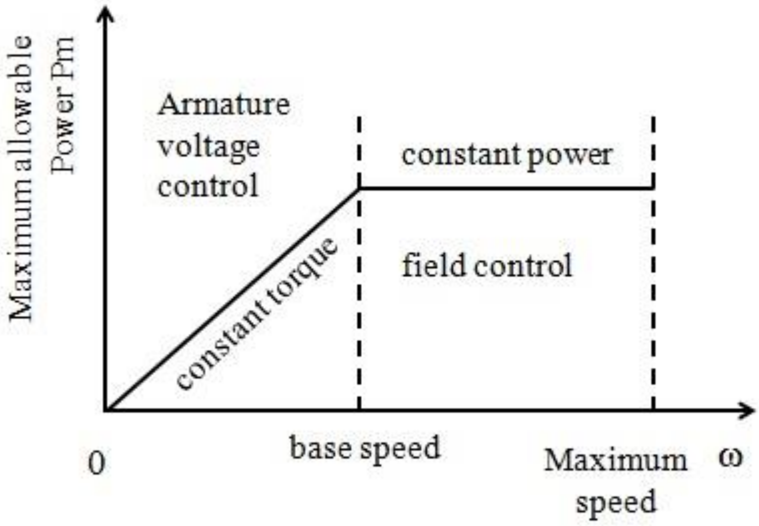

Figure 4 Power vs. Speed Characteristics

3. Fuzzy Theory:

3.1 Definitions and Basics:

The Fuzzy theory was first put forward by L.A. Zadeh in 1965. He felt that the classical theory concentrates much on precision rather than easy and efficient controlling mechanism. Unlike classical sets, the Fuzzy sets have a certain degree of membership for each element.

If-Then Rules:

Fuzzy sets depend on certain rules. The rule base is the most important requirement for the fuzzy logic. The rule base generally consists of various cases of If-Then rules. First the fuzzy sets and the membership functions are declared. Then the If-Then rules for the membership functions are decided for the particular control. The output is controlled by these rules on input.

A typical If-Then rule consists of two parts. They are 1) Antecedent and 2) Consequence or Conclusion. The ‘If’ statement is the Antecedent and the Then statement is the Consequence.

If - (Antecedent) & Then - (Consequence).

Examples:

If the fan is slow, then increase the speed.

If the temperature is high, then decrease the setting on an air conditioner.

3.2 Sets and Operations:

Classical Set: In a classical set for a universe of discourse the elements belonging to the set must satisfy the rules specified by the set. It is represented by

A={x ϵ U| x meets some conditions}

It can also be denoted by

μA(x) = {1 if x ϵ A

0 if x not ϵ A}

Fuzzy set: In a fuzzy set each element has a certain degree of membership unlike the classical set, with which it belongs to the particular fuzzy set.

$$A = \{(x, \mu_A(x)) | x \epsilon U\}$$

Operations:

Consider two Fuzzy A and B sets such that A, B ∈ U. Where, U is the Universe of Discourse.

Main set operations are: [4]

1. Complement,
2. Intersection,
3. Union.

Complement:

The Complement of a fuzzy set can defined as a fuzzy set with the membership function shown below:

$$\mu_{\bar{A}}(x) = 1 - \mu_A(x)$$

Intersection:

It can be defined as the biggest fuzzy set in both A and B which contains both the elements in A and B. It can also written as 'A ∩ B'. The membership function for Intersection is defined as:

$$\mu_{A \cap B}(x) = \mu_A(x) \cap \mu_B(x)$$

Union:

It can be defined as the smallest set which contains all the elements in 'A' or 'B'. It can be written as 'A + B' or 'A U B'. The membership function for Union is defined as:

$$\mu_{A \cup B}(x) = \mu_A(x \mu_B) \cup (x)$$

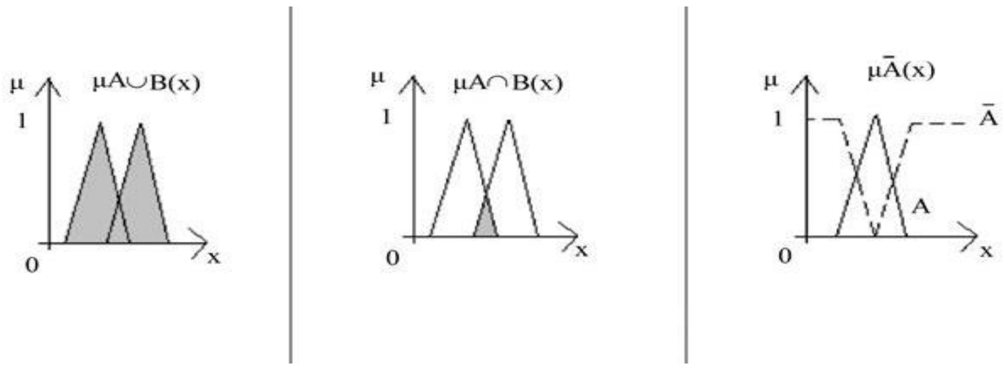

Figure 5 Membership functions of a) Union b) Intersection c) Complement

4 Importance of Fuzzy Logic:

4.1 <u>Advantages of Fuzzy Control:</u>

It has certain advantages which make it preferable to the other controllers. They are: [5]

- Very easy to comprehend because the concept behind the control is very simple.
- It possesses the intuition like a human which gives it the strength to adapt to the difficulties in the control.
- It can work well even with noisy inputs.
- It can be worked with multiple inputs and can provide multiple outputs as it solely works on rule basis. Creating the rule base for fuzzy control is easier than optimising the parameters for PID control.
- When any sensor stops working it can be programmed to turn off safely, instead of keep on working which could be dangerous to the plant.
- It does not consist of complex mathematical analysis, hence very easily designed.
- It does not require high precision sensors but compensates for the precision making use of the intuitive control which makes this method very economical.
- It operates very well even in highly non-linear systems adapting to the situation. But designing other conventional controllers to adjust in case of non-linearity in characteristics is very difficult.
- Very simple user interface. Easier end-user interpretation when the final user is not an expert.
- Easy calculation. Extensively existing toolboxes and dedicated integrated circuits.

- Ambiguousness. Fuzzy logic is a “natural” way of expressing unknown information. Tools available to the fuzzy logic helps in concluding different actions depending on the *possibility* or *necessity* of certain plant situations.

4.2 Implementation of Fuzzy Logic:

It maps the input to an output in a very efficient and the mapping can be very easily controlled without much complex knowledge about the process. Steps to be performed in Fuzzy control:

- First, study how the rule base system and the operator can be applied to this control.
- Understand the concept of membership functions and linguistic variables.
- Analyse the power system to be controlled and decide the state variables to be considered as inputs to the system.
- Form an understanding as how to control the state variables to get the required control in the plant.
- Now form the Rule base for the linguistic variables of inputs and outputs.
- Try to optimize the membership functions to make the control more efficient.
- Integrate the fuzzy controller into the plant and check the result.

5 Fuzzy Control Method:

5.1 Basic Components in Fuzzy control:

Fuzzy logic control mainly depends upon the rules formed by the Linguistic variables. Fuzzy logic control is free of complex numerical calculations, unlike other methods. It only uses simple mathematical calculations to control the model. Despite relying on basic mathematical analysis it provides good performance in a control system. Hence, this method is one of the best methods available and also easier one to control a plant.

Fuzzy logic control is based on the Fuzzy set theory. In fuzzy set theory, each element has a degree of membership with which it belongs to any particular set. We can say that fuzzy sets are like classical sets without much sharper boundaries. Fuzzy Logic Controller (FLC) is more used when the precision required is moderate and the plant is to be devoid of complex mathematical analysis. Other advantages are:

- It does not require highly precise Inputs.
- It does not require fast microprocessors to bring about an efficient response.
- It needs very fewer data comparatively which is mainly rules and membership functions.
- It is more efficient and can perform better even in non-linear models.

The three main components of a Fuzzy Logic controller are

1. Fuzzification,

2. Fuzzy Rule base and Interfacing engine,

3. Defuzzification.

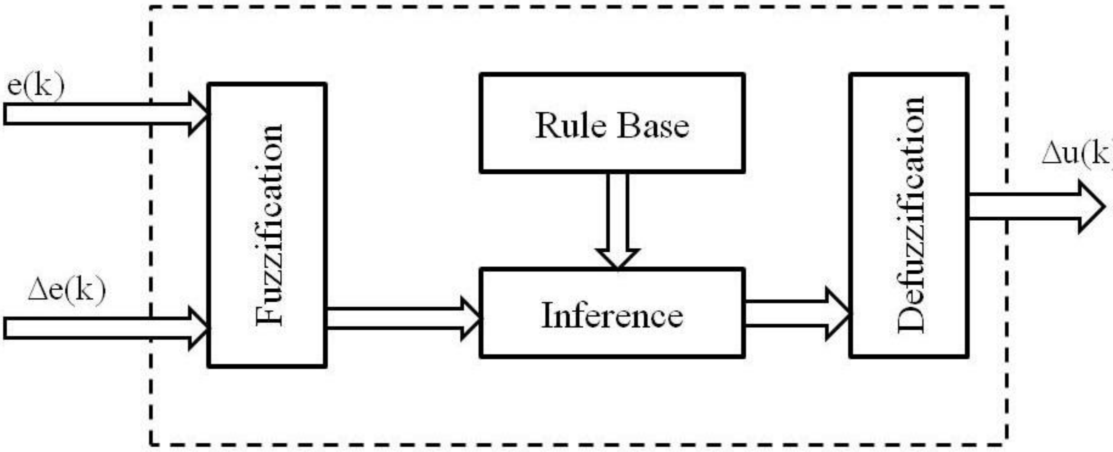

Figure 6 Fuzzy Control Internal Block diagram

5.2 <u>Fuzzification module:</u>

The most important step in formulating a design for the fuzzy controller is to identify the state variables which efficiently control the plant. After figuring out the state variables, they are to be passed through the fuzzification block to fuzzzify the inputs as the FLC works with only the Fuzzy inputs. As the Fuzzy Rule base employs rules on only linguistic variables, the numerical inputs have to be converted to fuzzy linguistic variables first. This process of converting a numerical state variable into a fuzzy input linguistic variable is called Fuzzification process. The variables generally used comprise of state error, the rate of change of state error (derivative of state error), or the area of a state error (integral of state error). The membership function is the graphical representation of the degree of belonging of an element to the fuzzy set. We can use different membership functions for an input and output depending upon the requirement of the precision to be provided. Generally used membership functions are triangular and trapezoidal membership functions. Gaussian and Bell shaped are some other available membership functions. For number of membership functions, the accuracy of control increases and the control works effectively. Complexity and time delay due to calculations increase with the number of membership functions taken for a linguistic variable. Hence, the number of membership functions to be used is a judgement that has to be made considering the quickness and efficiency of control to be delivered. In this model five membership functions for the Error and 2 membership functions for the Rate of change of error have been considered and the output has been given five membership functions.

5.3 <u>Fuzzy Rule Inference:</u>

Fuzzy inference is of two methods. They are Mamdani and Sugeno [6]. They are explained as below:

Mamdani Method:

Mamdani's methods of the Fuzzy interface is the most commonly used method. It was among the first control systems built using fuzzy set theory. It was first put forward by Ebrahim Mamdani as an attempt to control a steam engine and boiler combination by synthesizing a set of linguistic control rules obtained from experienced human operators. This inference method expects the output variable to be fuzzy sets. It is possible and also efficient to use a single spike in the output as membership function rather than a distributed fuzzy set. This is known as singleton output membership function. It enhances the Defuzzification process because it greatly simplifies the computation required by the more general Mamdani method which finds the centroid of the two dimensional function. But in the Sugeno type of inference can be used to model any inference system in which the output membership function is either linear or constant.

5.4 <u>Defuzzification</u>:

General methods adopted for Defuzzifying are:

1. Centre of Gravity Method,
2. Bisector of Area Method,
3. Mean of minimum Method.

The converse of Fuzzification is called Defuzzification. The Fuzzy Logic Controller (FLC) produces output in a linguistic variable (fuzzy number). As indicated by true prerequisites, the linguistic variables must be changed to crisp output. Centre of gravity strategy is the best understood Defuzzification system and utilized as a part of this exploration work. It acquires the centre of gravity of a region involved in the fuzzy set.

Defuzzification is the methodology of delivering a quantifiable result in the fuzzy form. A fuzzy control system has certain rules that change various variables into a "fuzzy" form, that is, the outcome is shown as membership functions and their degree of membership in fuzzy sets. The easiest but not much useful technique is to select the fuzzy set with the highest membership belonging, for this situation. The disadvantage of this methodology is that some data gets lost in this process. The rules that performed "Reduce Pressure" might as well have been absent with this process.

A helpful Defuzzification procedure should first include the outcomes of the results together somehow. The most average fuzzy set enrolment capacity has the shape of a triangle. Suppose, if this triangle were to be cut in a straight level line some place between the top and the base, and the top segment were to be removed, the remaining figure is in the shape of a trapezoid. This procedure removes parts of the figures to give trapezoids if the membership function used earlier was triangular (or different shapes if the initial shapes were not triangles). Generally these trapezoids are superimposed one upon another, giving a single shape. Finally, the centroid of this is computed. The abscissa of the centroid gives the defuzzified output.

6 Different Fuzzy Control Methods:

6.1 Types of Fuzzy Control Methods:

Fuzzy interface systems can be designed using two different methodologies. They are:

- Mamdani,
- Sugeno.

The outputs of these two methods vary somewhat in these two methods.

6.2 Mamdani Method:

Mamdani's methods of the Fuzzy interface is the most commonly used method. It was among the first control systems built using fuzzy set theory. This inference method expects the output variable to be fuzzy sets. It is more advantageous to use a single membership function of a linguistic variable instead of number of fuzzy sets which can be tedious in some cases. This method of using a single linguistic variable in output is called as Singleton output mechanism. It enhances the Defuzzification process because it greatly simplifies the computation required by the more general Mamdani method which finds the centroid of the two dimensional function. But in the Sugeno type of inference can be used to model any inference system in which the output membership function is either linear or constant.

6.3 Sugeno Method:

The first two parts namely, fuzzifying the inputs and applying the fuzzy operator, of the Sugeno method are similar to the Mamdani method. [8]

If the first input is x and the second input is y, then the Output is of the linear form

$$O = Kx + Ly + M$$

For a zero-order Sugeno model, the output O will be a constant (K = L = M).

The output level Oi of each rule is only weighted by the weightage W_i of the rule.

Comparison: When the performances of Mamdani and Sugeno models are compared with each other, the superlative outcome is obtained from the Sugeno mode. [7]

Mamdani Advantages:

- It is instinctual. Can be trained in human intuition.
- More generally acknowledged.
- It is more effective to human input.

Sugeno Advantages:

- It is very effective in calculations and controlling.
- It is generally used to enhance the linear techniques.
- It is used to optimize the parameters and works adaptively.

7 Simulation Work:

7.1 Variables Used:

The Linguistic variables considered in the control are

- ZE - Zero
- PS - Positive Small
- NS - Negative Small
- PL - Positive Large
- NL – Negative Large

We have considered 5 Linguistic variables (NL, NS, ZE, PS, PL) for the Input 'Error' and only 2 Linguistic variables (NL, PL) for the Input 'Rate of Change in Error'. In case of Output 'Control', we have considered 5 Linguistic variables (NL, NS, ZE, PS, and PL).

7.2 Membership Functions used:

Error:

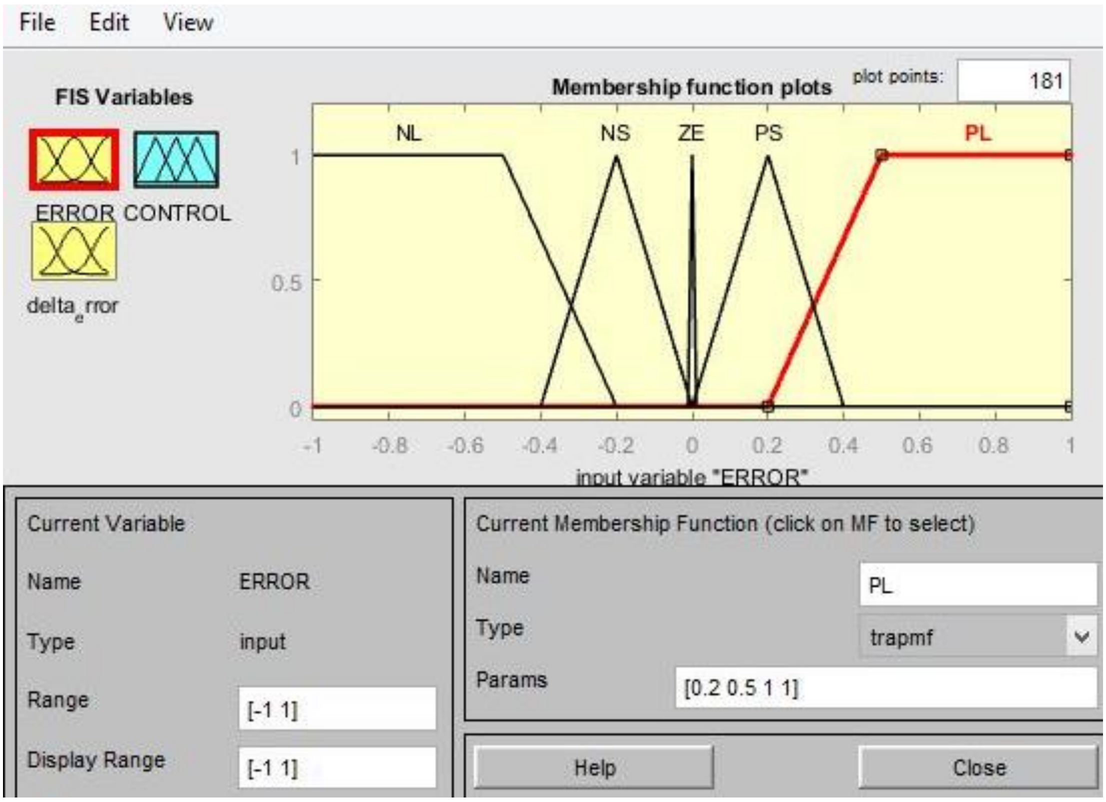

Figure 7 Error Signal Membership Functions

Change in Error:

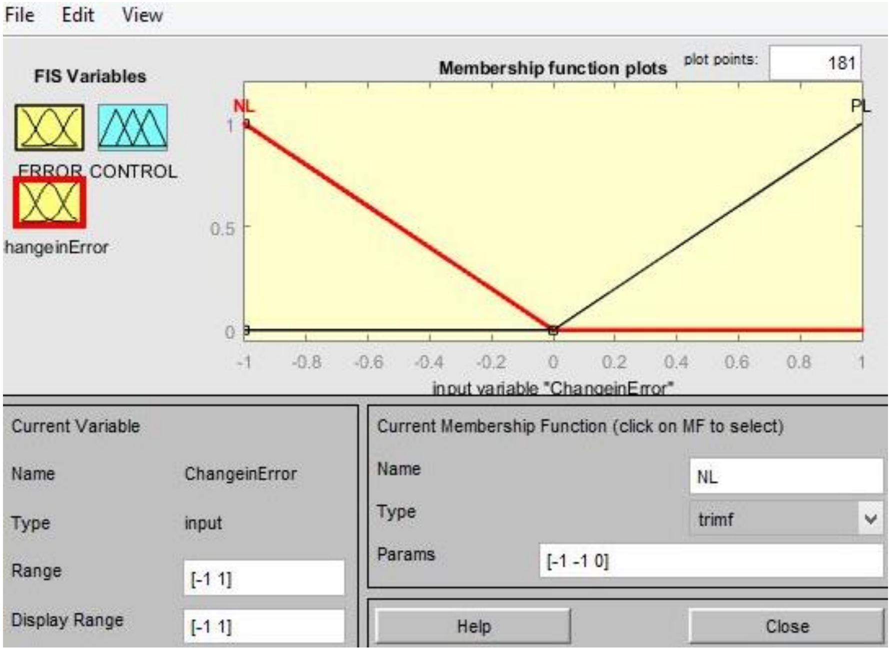

Figure 8 Change in Error Signal Membership Functions

Control Signal:

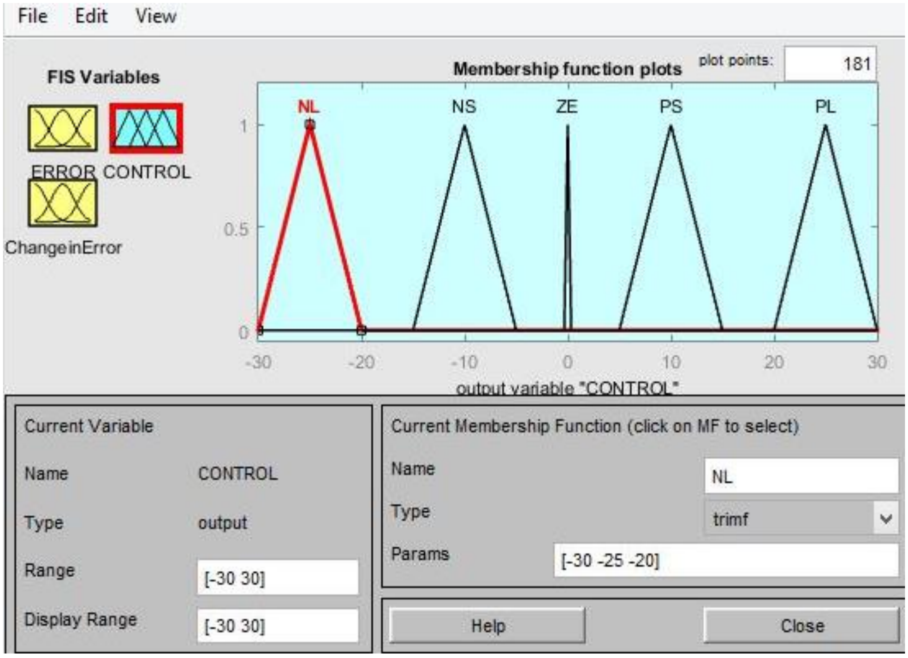

Figure 9 Control Signal Membership Functions

7.4 <u>Fuzzy Rule Base:</u>

General Interpretation of the control rules to be set to the Fuzzy control:

- If Error = 0 and Change in error = 0, then do not change the present setting.

- If Error is non-zero but Error is tending to zero at an acceptable rate, then do not change the present setting.

- If Error is increasing or decreasing, then make the control signal according to the magnitude and sign of the Error and Change in Error to make the Error = zero.

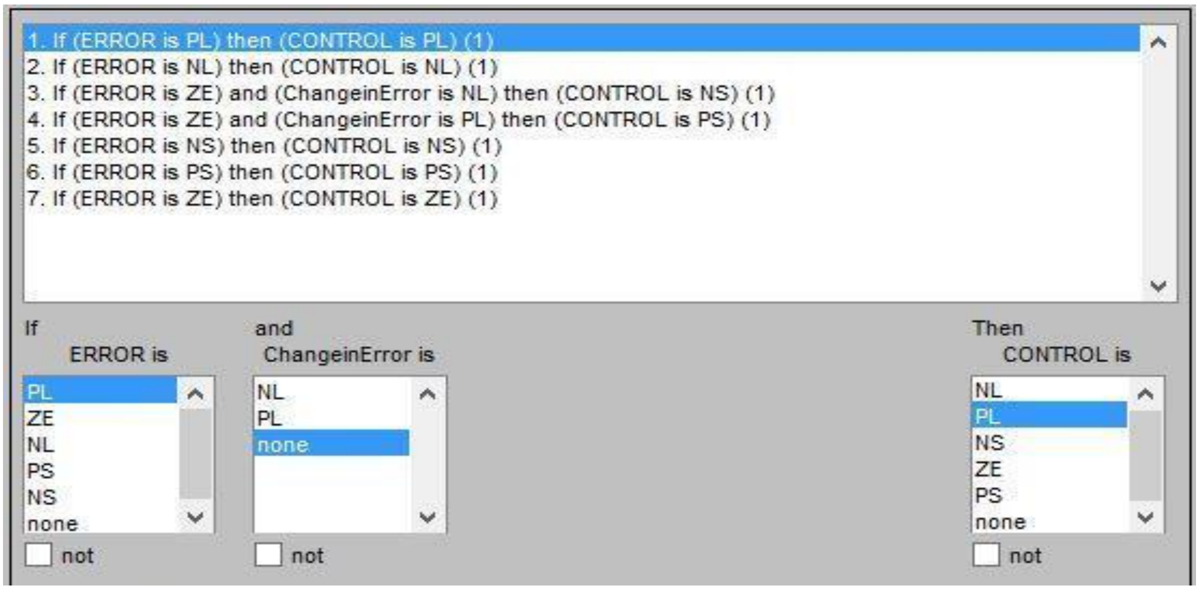

Figure 10 Fuzzy Rule Viewer

1) If Error (Reference speed – Observed speed) is PL and the de is neither NL nor PL, then the motor speed is very less than the reference speed. Then the armature voltage needs to be increased which can be done by setting the Control signal at PL. Similarly when Error is NL, the control signal is NL.
2) If Error is ZE, then the motor is at reference speed at that instant. But the de is NL. This shows that the speed of the motor is increasing. So, the control signal is NS. Similarly when de is PL, the control signal is PS.
3) If Error is NS, then the motor speed is close to the reference speed but greater than the reference speed. This requires a decrease in the armature voltage. So, the control signal is NS for any value of de. Similarly when the Error is PS, the control signal is PS.

4) If the Error is ZE, then the motor speed is at the reference speed. Unless de is either NL or PL, the control setting has to be ZE so as to keep the motor close to the reference speed.

Table 1: Rule base for Fuzzy control:

de/e	NL	NS	ZE	PS	PL
NL	NL	NS	NS	PS	PL
PL	NL	NS	PS	PS	PL

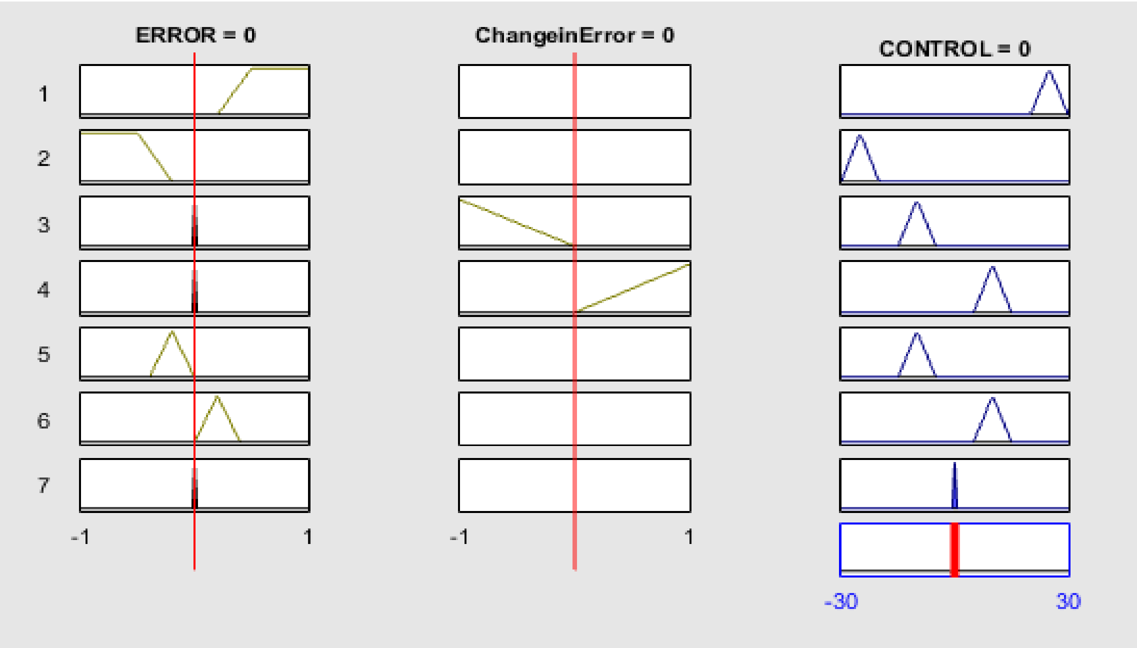

Figure 11 Rule Viewer

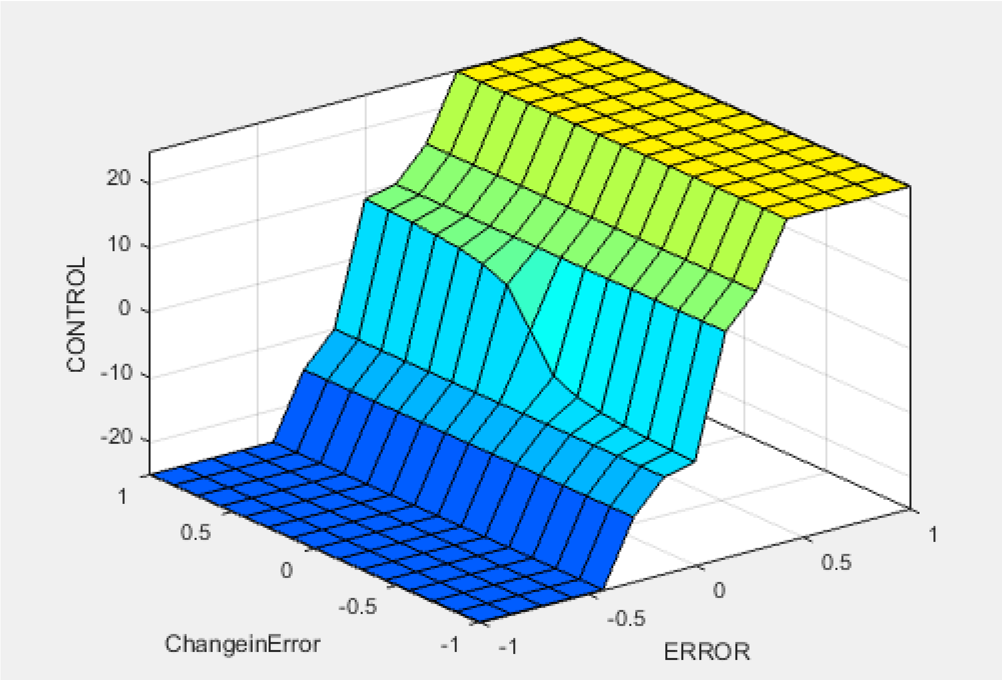

Figure 12 Fuzzy Rule Surface Viewer

7.4 <u>Parameter specifications for Motor:</u>

Armature Resistance = 1 Ohm.

Armature Inductance = 2 mH.

Moment of Inertia = 100 Kg-m^2.

Viscous Friction Coefficient = 0.1 N-m/rad/sec.

Back EMF constant = 0.01 V/rad/sec

Rated Speed = 1500 rad/sec.

Reference Speed = 1450 rad/sec.

Load Torque = 10 N-m.

7.5 **Modelling in SIMULINK:**

Model:

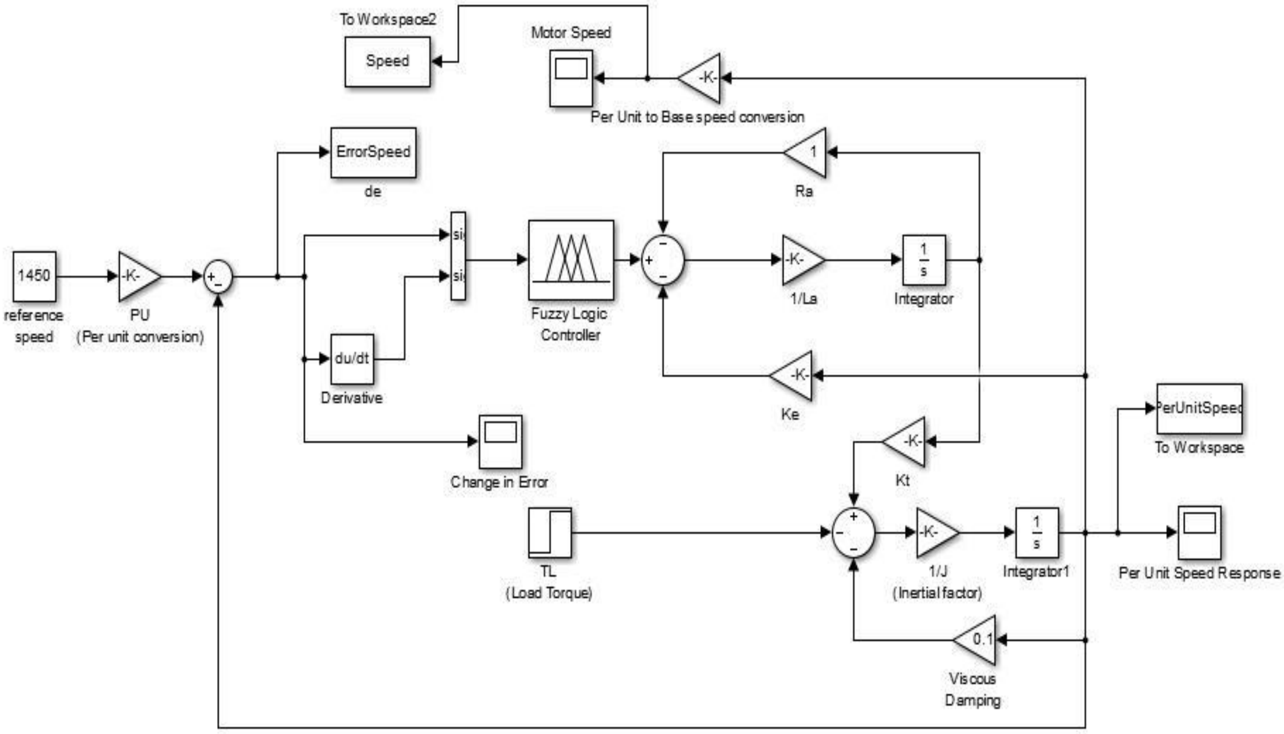

Figure 13 Simulink Model for Fuzzy Logic Control

The simulation was carried out for 2.5 sec.

The reference speed was converted into Per Unit speed for ease of designing the range of the linguistic variables in the Fuzzy tool box. Then the motor output speed at that instant is taken and subtracted from the reference speed to calculate the error signal. This Error signal is important as this is one of the inputs to the Fuzzy controller block. Now the other input is taken to fuzzy through the derivative block which gives the rate of change in Error. Now the Fuzzy controller acts according to the Rule base formed before and tries to bring the motor to the reference speed by supplying the output to the Armature. The difference of output of the Fuzzy controller and the armature supply is taken as Armature voltage and this controls the speed of the motor. The load torque is taken as a step for 10 sec with an initial value of 0.001 and Final value of 10 N-m. Now the Per Unit motor speed is obtained. To get the Speed, the per-unit speed is passed through a gain block with gain magnitude equal to the base speed taken in the per unit conversion. This gives the Speed of the motor.

7.6 Simulation Results:

Per-Unit Speed response:

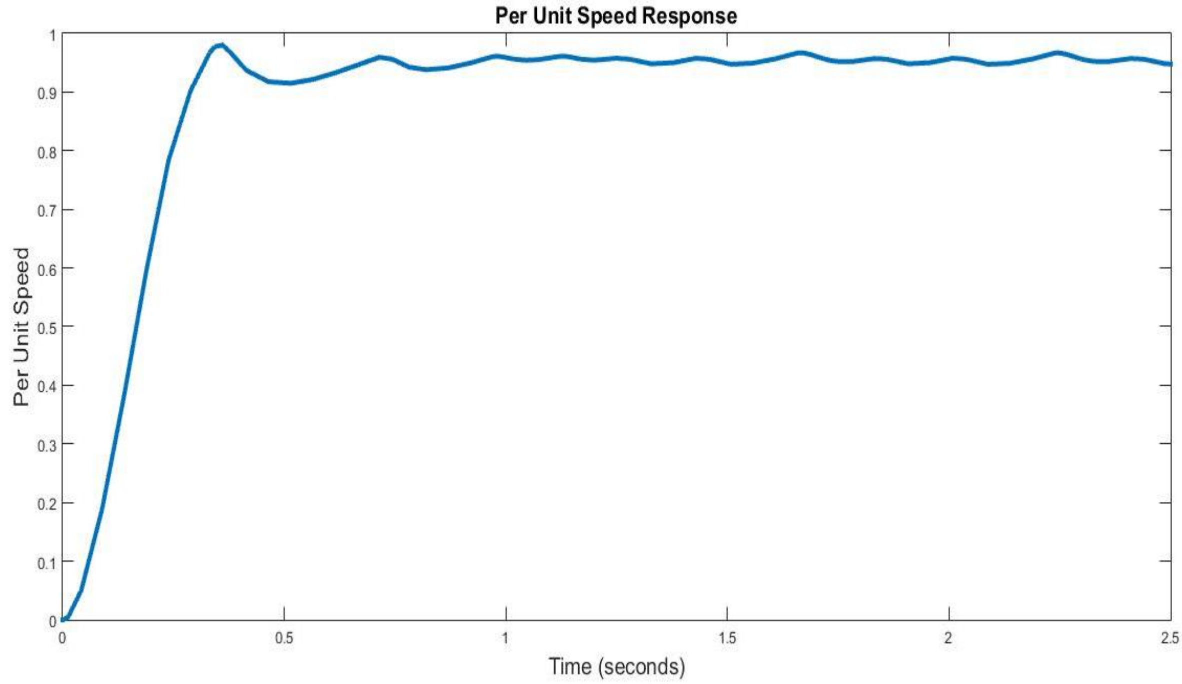

Figure 14 Per-Unit Speed Response

Speed response:

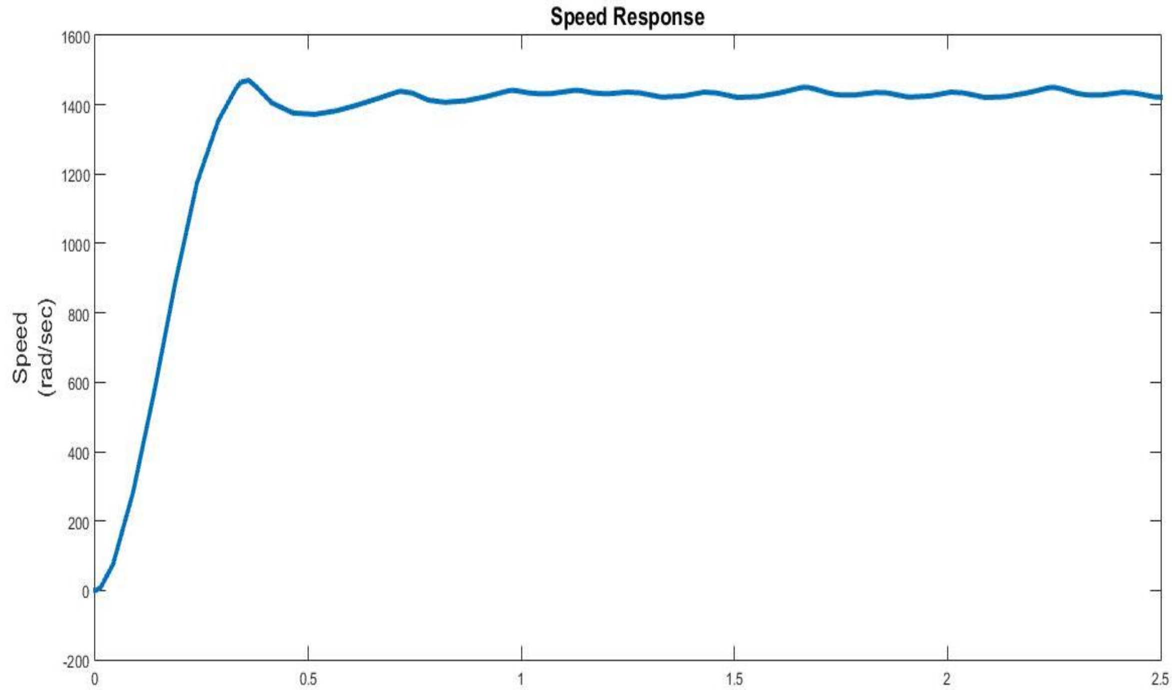

Figure 15 Speed Response

Error in Speed response:

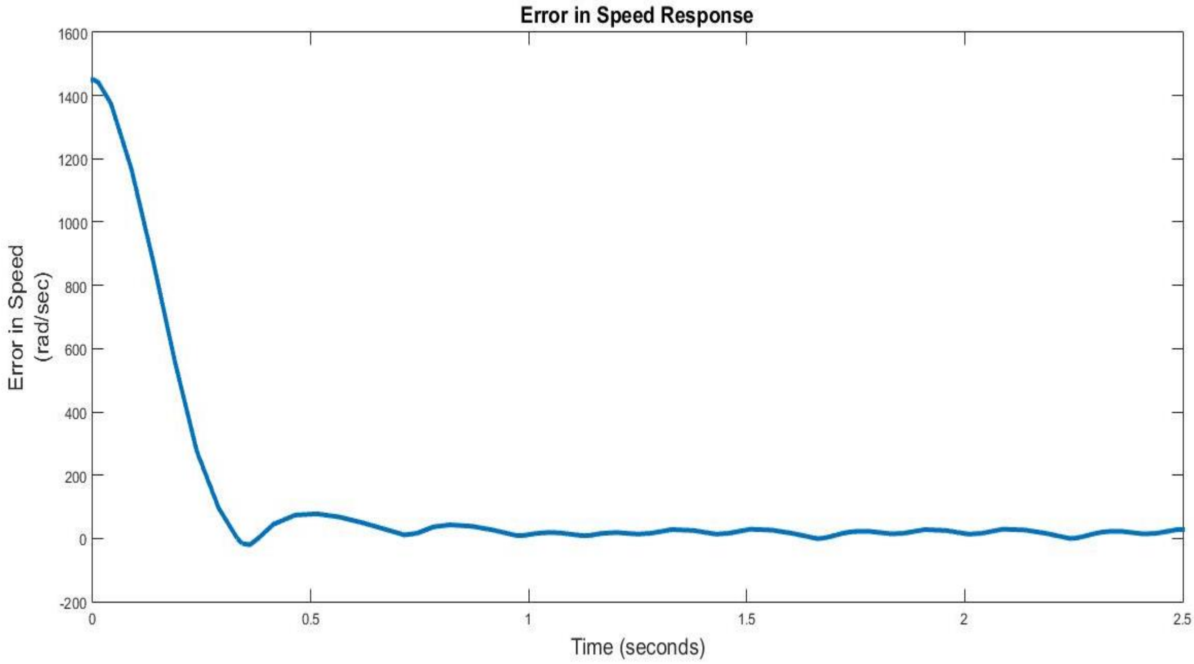

Figure 16 Error in Speed response

From the waveform of the Speed response (Fig. 14),

Table 2 Speed Response parameters

Rise time	Peak time	Peak overshoot
0.3318 sec	0.36 sec	20 rad/sec

8 Conclusion:

Here we have considered different types of speed control for a separately excited DC motor and understood the importance of Fuzzy logic in particular areas. We have also studied and understood various concepts of Fuzzy logic and Fuzzy set theory. We have also studied the Speed-Torque characteristics for the separately excited DC motor.

The inputs are Error is speed and Change in Error. We have studied above the Fuzzy rule base and formed the rules for 5, 2 linguistic variables of the inputs and 5 linguistic variables of the output using Fuzzy tool box. The membership functions used are

Error Signal – 2 trapezoidal and 3 triangular.

Change in Error signal – 2 triangular.

Control signal – 5 triangular.

We have modelled the Fuzzy control scheme using SIMULINK and plotted various waveforms. From the Speed response waveform we can see that the rise time is 0.3318 sec, the peak time is 0.36 sec and the peak overshoot is 20 rad/sec (1.3% of the reference speed). Thus, we have controlled the speed of the DC motor using the Fuzzy control logic.

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