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SPEED CONTROL OF PMSM DRIVE USING ANFIS BASED SPEED CONTROLLER

(Comparison with Ziegler Nichols' technique)

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Abstract— *Nowadays, PMSM drive systems are being employed in many industrial applications ranging from low to medium power because of their simple structures, ease of maintenance and efficiency. However the non-linear behavior which arises mainly from motor dynamics and load characteristics and the presence of uncertainties makes control an extremely difficult task. So, the speed control technique should be adaptive and robust for better performance of the drive. The conventional PID controllers are used to control speed of the drive. Various tuning techniques are employed such as Z-N tuning, Cohen- Coon, manual tuning etc. of which Z-N tuning is the most widely used method. Since, PID controllers work well under linear operating conditions and fails when non-linearity arises. Therefore, Artificial Intelligence techniques are being implemented to achieve better performance either in isolation i.e. Fuzzy, ANN, GA, PSO etc. or in hybrid as Artificial Neuro Fuzzy Inference System. This project work presents design and simulation of a modern approach of speed control of PMSM using ANFIS based speed controller. Hence an artificial intelligence control strategy namely ANFIS has been used as it requires only a reduced computation power while maintaining satisfactory static and dynamic performance and a good insensitivity to perturbations and parameter uncertainties. A model of PMSM drive is simulated under various dynamic conditions like starting, load application and removal, speed reversal. The combined capability of Neuro Fuzzy Controller in handling uncertainties and learning process is proven to be advantageous in modeling highly non-linear systems. The designed ANFIS based speed controller is presented to develop a dynamic model of PMSM as it does not require the explicit mathematical model of the plant and automatically takes care of changing conditions as well. Hence ANFIS based speed controller gives better performance of the drive with linear as well as non-linear load as compared to conventionally used Z-N tuned PID speed controller.*

Keywords—*PMSM, ANFIS, PID.*

I. INTRODUCTION

For the speed control of PMSM, many controllers are used. In conventional P, PI and PID controllers, very fine tuning is required which cannot cope up with system's parameter variations. Also the performance of such controllers is affected due to variations in physical parameters like temperature, noise, saturation etc.

Ziegler Nichols' technique that is probably the most known and the most widely used method for tuning of PID controllers is also known as online or continuous cycling or ultimate gain tuning method. The Ziegler-Nichols' tuning creates 'quarter wave decay'. This is an acceptable result for some purposes, but not optimal for all applications. This tuning rule is meant to give PID loops best disturbance rejection. It yields an aggressive gain and overshoots [1] – some applications wish to instead minimize or eliminate overshoot, and for these this method is inappropriate. Many control systems use adaptive controllers for PMSM, which can track only linear systems. Therefore, fuzzy logic based controller may be used to achieve more accurate and faster solutions and to handle complicated non-linear characteristics. A simple structure fuzzy logic controller (FLC) is used in the speed control loop to regulate the motor speed.

The fuzzy logic controller used here to control PMSM takes two inputs i.e. E (error) and CE (change in error) and gives controlled output (DU). A fuzzy logic controller with rule viewer block is used to control the output of PMSM. In this block FIS file is saved which includes input and output membership functions and fuzzy set of rules. Different membership functions can be selected to control the output variable.

The main aim of this paper is to obtain better transient as well as steady state response for proposed PMSM drive by using ANFIS speed controller as this cannot be achieved from the Ziegler Nichols' PID tuning technique. Because, the outcome of the controller is also random and optimal results may not be obtained. Selection of the proper membership functions and in turn selecting the right rule base depending on the situation can be achieved by the use of an ANFIS controller, which becomes an integrated method of approach for control purposes and yields excellent results, which is the highlight of this paper. In the designed ANFIS scheme, neural network techniques are used to select a proper rule base, which is achieved using the back-propagation algorithm. This integrated approach improves the designed controller's performance in many ways in terms of cost-effectiveness and reliability. The aim is to reduce the dynamic parameters like rise time, peak time, settling time, maximum peak overshoot and steady state error during various changing conditions like starting, load application and load removal and speed reversal. A comprehensive comparison is being made between the two techniques in order to draw conclusions about the suitability of the ANFIS logic controller.

II. LITERATURE SURVEY

In the 21st century artificial intelligence has become an important area of research in virtually all fields: engineering, science, education, medicine, business, accounting, finance, marketing, economics, stock market and law, among others. The field of AI has grown enormously to the extent that tracking proliferation of studies becomes a difficult task. Apart from the application of AI to the fields mentioned above, studies have been segregated into many areas with each of these springing up as individual fields of knowledge.

A neuro-fuzzy approach as a combination of neural networks and fuzzy logic has been introduced to overcome the individual weaknesses and to offer more appealing features. Pixel greyness ambiguity, geometrical segmentation of the image and the uncertain interpretation of a scene. This exploits, respectively, the learning capabilities and the descriptive power of systems, thus providing results characterized by a high interpretability and good degree of accuracy [5]. ANFIS is one of the widely used neuro-fuzzy systems.

There are several training algorithms for feed forward networks. The gradient is determined using a technique called back propagation, which involves performing computational backwards through the network. The simplest implementation of back propagation learning adjusts the network weights in the direction in which the performance function decreases more rapidly. The algorithm used in this paper is extracted from [6]. In this paper, the application of ANFIS for speed control of PMSM is explored. Experimental results yield promising results for ANFIS as a speed controller.

III. PERMANENT MAGNET SYNCHRONOUS MOTOR

There are two types of techniques used for PMSM speed control:-

1. Field Oriented Control (FOC)
2. Direct torque control (DTC)

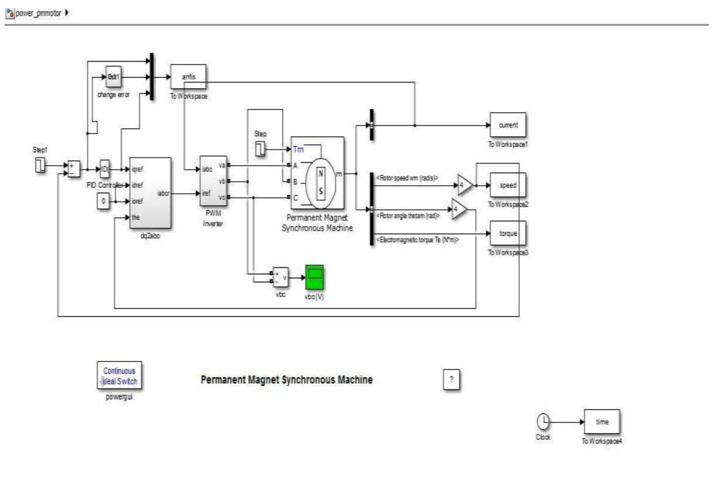

Figure 1 PMSM model

The parameters for the modelling are given as below:

A three phase motor of 3000 rpm is fed by a PWM inverter. The PWM inverter is built entirely with standard blocks. Its output goes through Controlled Voltage Source blocks before being applied to the PMSM block’s stator windings. The load torque applied to the machine's shaft is originally set to its nominal value (3 N.m) and steps down to 1 N.m at t = 0.04 s. Two control loops are used. The inner loop regulates the motor's stator currents. The outer loop controls the motor's speed.

Back emf waveform	Sinusoidal
Mechanical input	Torque
Stator phase resistance (ohm)	2.875
Flux linkage established by magnets(Wb-t)	0.175
Torque Constant(N.m/A)	1.05
Rating of motor(kW)	1.1
Voltage rating(V)	220

Table 1 Parameters of PMSM

IV. PID CONTROLLERS

The PID controller is the most common form of feedback. It was an essential element of early governors and it became the standard tool when process control emerged in the 1940s. In process control today, more than 95% of the control loops are of PID type [1]. PID controllers are today found in all areas where control is used. The controllers come in many different forms. There are standalone systems in boxes for one or a few loops, which are manufactured by the hundred thousand yearly. PID control is an important ingredient of a distributed control system. The controllers are also embedded in many special purpose control systems. PID control is often combined with logic, sequential, selectors, and simple function blocks to build the complicated automation systems used for energy production, transportation, and manufacturing [2]. Many sophisticated control strategies, such as model predictive control, are also organized hierarchically. PID control is used at the lowest level; the multivariable controller gives the set points to the controllers at the lower level. The PID controller can thus be said to be the "bread and butter" of control engineering. It is an important component in every control engineer's tool box.

PID controller consists of Proportional, Integral and Derivative gains. The feedback control system is illustrated where r, e, u, y are respectively the reference, error, controller output and controlled variables. The PID controller in a closed loop control system is shown:

$$u(t)=K_p e(t) + K_i \int_0^t e(t)dt + K_d\, de(t)/dt \qquad (1)$$

The PID controller is described in equation (1)

Where u(t) is the controller output, e(t) is the error, and t is the sampling instance. The factors K_p, K_i and K_d are the proportional, integral and derivatives gains (or parameters) respectively that are to be tuned.

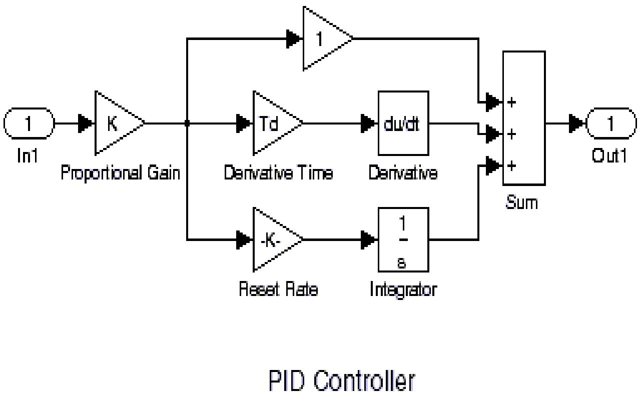

Figure 2 System of PID controller

The Ziegler-Nichols' closed loop method is based on experiments executed on an established control loop. The tuning procedure is as follows:

i. Bring the process to (or as close to as possible) the specified operating point of the control system to ensure that the controller during the tuning is "feeling" representative process dynamic and to minimize the chance that variables during the tuning reach limits. We can bring the process to the operating point by manually adjusting the control variable, with the controller in manual mode, until the process variable is approximately equal to the set point.
ii. Turn the PID controller into a P controller by setting set $T_i = \infty$ and $T_d = 0$. Initially set gain $K_p = 0$. Close the control loop by setting the controller in automatic mode.
iii. Increase K_p until there are sustained oscillations in the signals in the control system, e.g. in the process measurement, after an excitation of the system. (The sustained oscillations correspond to the system being on the stability limit.)
iv. This K_p value is denoted the ultimate (or critical) gain, K_{cu}. The excitation can be a step in the set point. This step must be small, for example 5% of the maximum set point range, so that the process is not driven too far away from the operating point where the dynamic properties of the process may be different. On the other hand, the step must not be too small, or it may be difficult to observe the oscillations due to the inevitable measurement noise. It is important that K_p is found without the control signal being driven to any saturation limit (maximum or minimum value) during the oscillations. If such limits are reached, you will find that there will be sustained oscillations for any (large) value of K_p, e.g. 1000000, and the resulting K_p value is useless (the control system will probably be unstable). One way to say this is that K_{cu} must be the smallest K_p value that drives the control loop into sustained oscillations.
v. Measure the ultimate (or critical) period Pu of the sustained oscillations.

vi. Calculate the controller parameter values according to Table 2, and use these parameter values in the controller. If the stability of the control loop is poor, try to improve the stability by decreasing Kp, for example a 20% decrease.

PID GAINS	VALUES
K_p	0.34584
Ki	3.460165
Kd	0.008641591

Table 2 Optimized Values of PID gains for Z-N tuning Method

Advantages of Ziegler-Nichols' PID Tuning Procedure

a) It does not require the process model.
b) Easy experiment.
c) Only need to change the P controller [1].
d) Includes the dynamics of whole process, which gives a more accurate picture of how the system is behaving [1]

Disadvantages of Ziegler-Nichols' PID Tuning Procedure

a) It is time consuming because a trial and error procedure must be performed.
b) It forces the process into a condition of marginal stability that may lead to unstable operation or a hazardous situation due to set point changes or external disturbances [1].
c) This method is not applicable for processes that are open loop unstable.
d) Some simple processes do not have ultimate gain such as first order and second order processes without dead time [1].

V. DESIGN OF ANFIS BASED SPEED CONTROLLER

ANFIS based speed controllers are one of the most successful applications of fuzzy set theory, introduced by Zadeh in 1965. Its major features are the use of linguistic variables, defined as variable whose values in natural language may be represented by fuzzy set [4]. ANFIS based speed controllers have the following advantages over the conventional controllers, they are cheaper to develop, they cover a wide range of operating conditions, and they are more readily customizable in natural language terms.

Fuzzy logic control is a control algorithm based on a linguistic control strategy, which is derived from expert knowledge into an automatic control strategy. The operation of a ALC is based on qualitative knowledge about the system being controlled. It doesn't need any difficult mathematical calculation like the others control system [5]. While the others control system use difficult mathematical calculation to provide a model of the controlled plant, it only uses simple mathematical calculation to simulate the expert knowledge. ANFIS is a control method based on ANFIS logic. Just as ANFIS logic can be described simply as "computing with words rather than numbers"; ANFIS control can be described simply as "control with sentences rather than equations". A ANFIS controller can include empirical rules, and that is especially useful in operator controlled plants.

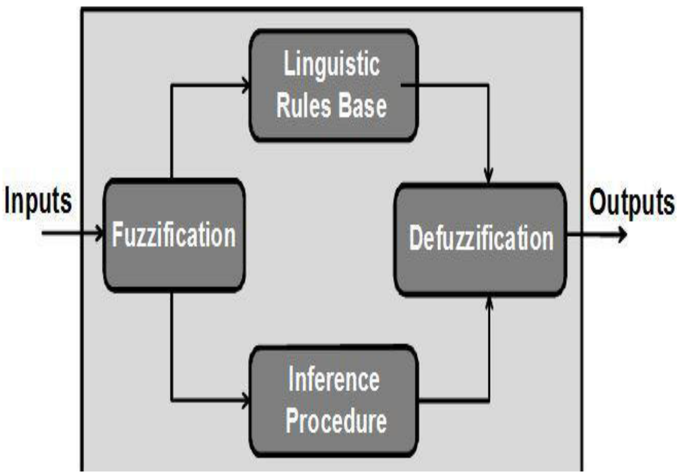

Figure 3 ANFIS logic controller

The ANFIS logic controller consists of four main parts which are

i. Fuzzification
ii. Knowledge base
iii. Inference engine
iv. Defuzzification

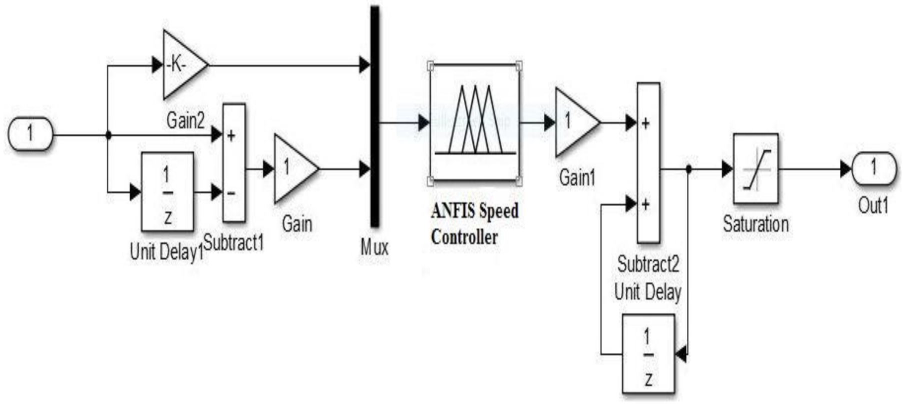

Figure 4 ANFIS based speed controller

Design of Self-Tuning PID Controller consist the following steps [6]
I. Selection of input and output variables.
II. Selection of Membership Function.
III. Making Fuzzy rule base
IV. Defuzzification.

Selection of Input and Output Variables

Define input and control variables, i.e, determine which states of the process should be observed and which control actions are to be considered. ANFIS controller consists of two input variables and one output variables. The input variables are e and ec, the output variable is du. The dynamic performance of the system could be evaluated. The value of du is taken as output from the ANFIS based speed controller [6].
Structure of the Sugeno model is designed in such a way that the input is mapped to input membership function, the input membership function is mapped to rule, then the rule is mapped to output membership function and then the output membership function is mapped to the output.

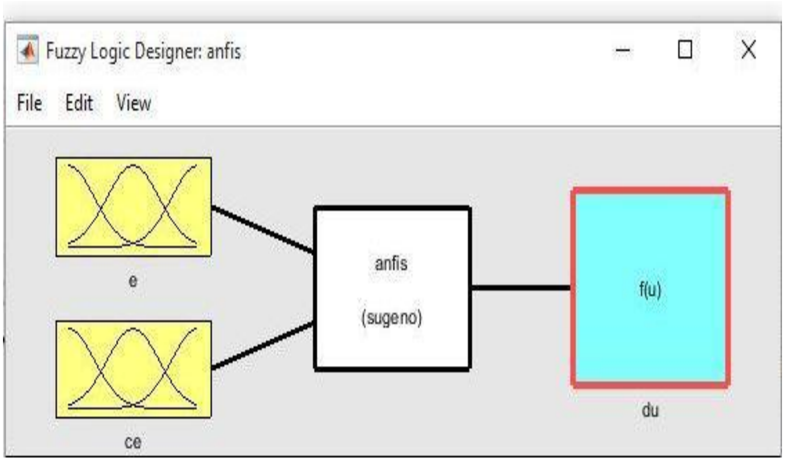

Figure 5 Selection of input variables

Selection of Membership Functions

A major step in defining control variables in fuzzy control applications is the definition of membership functions. Such a task has to be performed in two main underlying steps. The first is the selection of the range of values which the function should cover while the second is the type of membership function to be employed and its relevant parameters. Several membership functions were reported successfully in several fuzzy control applications, such as, triangular, trapezoidal and Gaussian functions etc [7]. For structural control applications it is expected that either triangular and/or Gaussian membership functions would be suitable for modelling control input and output variables. The proper identification of a representative range of values for properly defining such membership functions should be based on actual results of the modelled system. The number of linguistic variables describing the fuzzy subsets of a variable varies according to the application. Usually an odd number is used. A reasonable number is three. However, increasing the number of fuzzy subsets result in a corresponding increase in the number of rules. Each linguistic variable has its fuzzy membership function, the membership function.

N Negative
Z Zero
P Positive

The membership function maps the crisp values in to fuzzy variables. The triangular membership functions are used to define the degree of membership. It is important to note that the degree of membership plays an important role in designing a fuzzy controller [7].

Each of the input and output fuzzy variables is assigned three linguistic fuzzy subsets varying from negative (N) to positive (P). Each subset is associated with a triangular membership functions to form a set of three membership functions for each fuzzy variable. The membership function has inputs and three output controller, and their values divided in

to seven levels {N,Z,P} [3]. The element in the subset represent the negative big, negative medium, negative small, zero, positive small, positive medium and positive big. In the membership function the range of the variables "e", "ec", du are {-1, 1}. In the fuzzy logic toolbox of the membership function editor, trimf and gaussmf is selected by membership functions of input as "e", "ec" and output as "du" shown in Figure. 6, Figure 7 respectively.

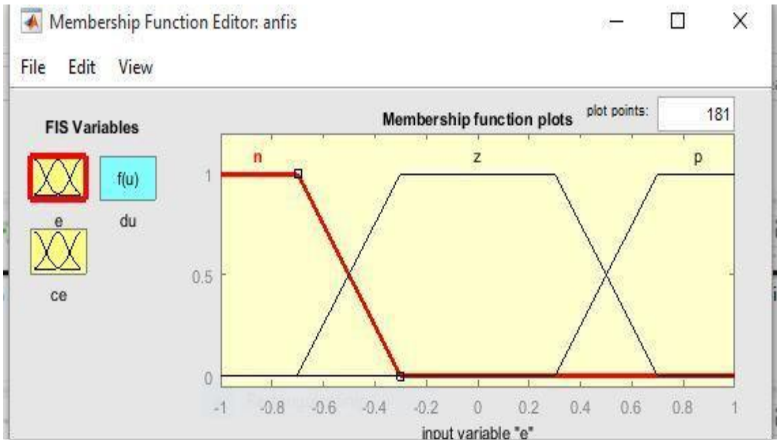

Figure 6 Membership functions of input 'e'

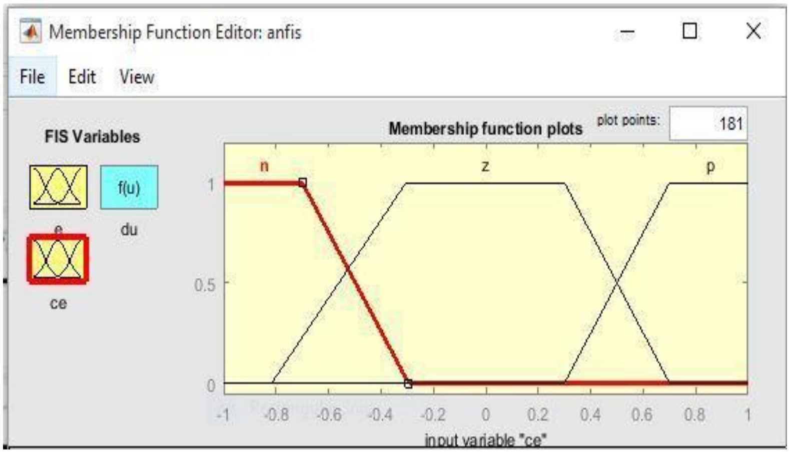

Figure 7 Membership functions of 'ec'

Making Fuzzy Rule Base

A set of rules which define the relation between the input and output of fuzzy controller can be found using the available knowledge in the area of designing the system .The self tuning rule is deferent e, ec, du. These rules are defined using the linguistic variables . The two inputs, error and rate of change in error, results in 9 rules we can get 9 fuzzy rules following [6],

1. If (E is N) and (EC is N) then (DU is N) (1)
2. If (E is N) and (EC is Z) then (DU is N) (1)
3. If (E is N) and (EC is P) then (DU is Z) (1)
4. If (E is Z) and (EC is N) then (DU is N) (1)
5. If (E is Z) and (EC is Z) then (DU is Z) (1)
6. If (E is Z) and (EC is P) then (DU is P) (1)
7. If (E is P) and (EC is N) then (DU is Z) (1)
8. If (E is P) and (EC is Z then (DU is P) (1)
9. If (E is P) and (EC is P) then (DU is P) (1)

Defuzzification

The input for the defuzzification process is a fuzzy set and the output is a single crisp number. As much as fuzziness helps the rule evaluation during the intermediate steps, the final desired output for each variable is generally a single number. However, the aggregate of a fuzzy set encompasses a range of output values, and so must be defuzzified in order to resolve a single output value from the set. The most popular defuzzification method is the centroid calculation, which returns the center of area under the curve and therefore is consider for defuzzification [6].

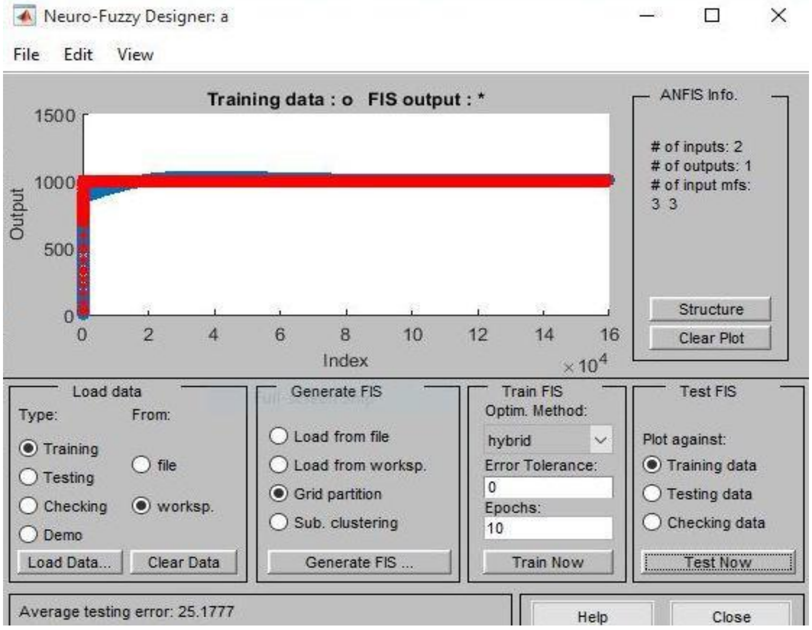

Figure 8 Training data for starting characteristics

For the proposed ANFIS architecture, a gradient descent technique is used to reduce the error (usually a cost function given by the squared error), where the weights are iterated by propagating the error from output layer to input layer. This backward trip of such a calculation is termed as "back propagation". The training algorithm is completed in two stages, known as precondition parameter tuning and consequent parameter tuning, where the objective function to be minimized is defined as:

$$(\xi_{\alpha\beta})^2=(i_{\alpha\beta}-\hat{i}_{\alpha\beta})^2 \qquad (2)$$

The training data, trnData, is a required argument to ANFIS, as well as to the ANFIS Editor GUI. Each row of trnData is a desired input/output pair of the target system to be modeled. Each row starts with an input vector and is followed by an output value. Therefore, the number of rows of trnData is equal to the number of training data pairs, and, since there is only one output, the number of columns of trnData is equal to the number of inputs plus one. A plot is obtained as shown in Figure 9 for load application and load removal and in Figure 10 for speed reversal.

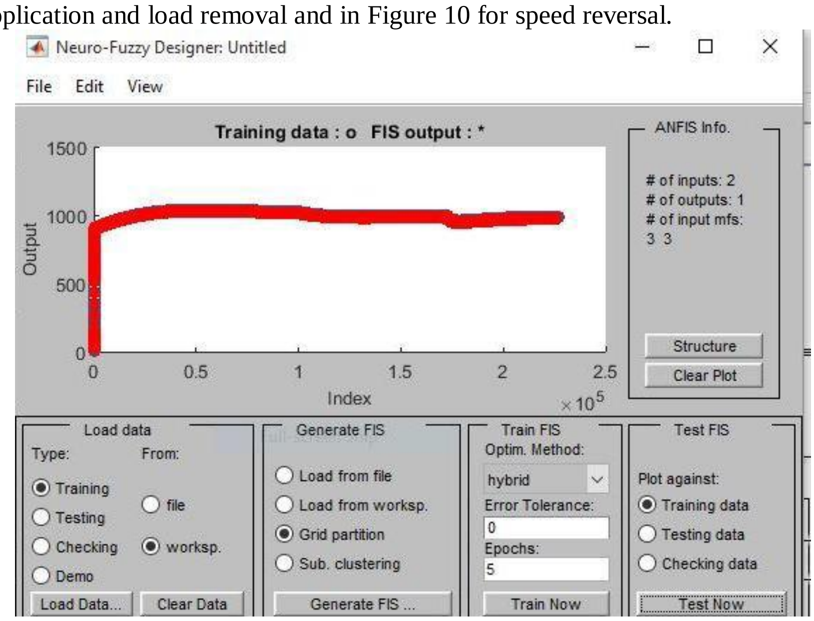

Figure 9 Training data for load application and load removal

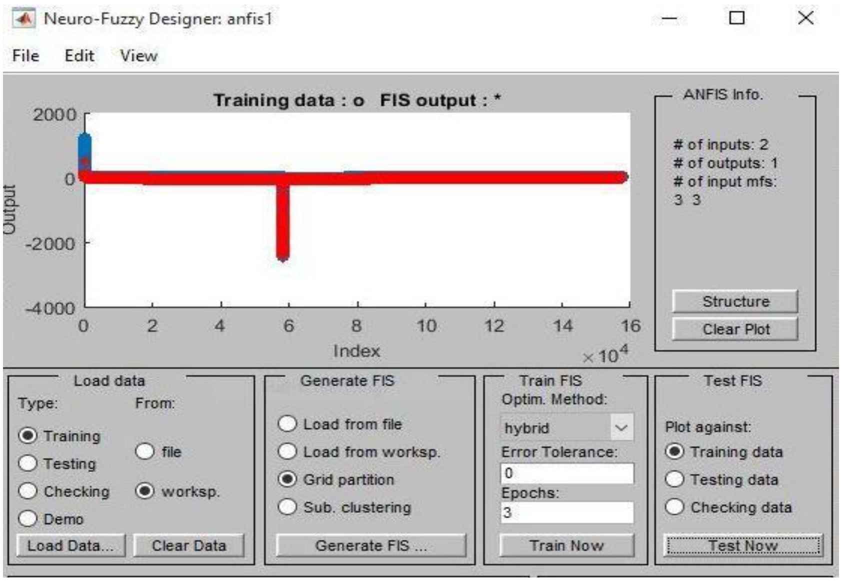

Figure 10 Training data for speed reversal

VI. RESULTS

COMPARISON BETWEEN PERFORMANCE OF Z-N TUNED PID CONTROLLER AND ANFIS BASED SPEED CONTROLLER

Starting

At t = 0 sec motor is started at reference speed of 1000 rpm. Figure (11) and Figure (12) shows the starting characteristics of proposed PMSM model using Z-N tuned PID speed controller and ANFIS controller respectively. From the graph we can clearly see that the speed vs. time characteristics is smoother with ANFIS controller. The initial irregularity in the plot for conventional Z-N PID is removed by using ANFIS controller. The torque and current characteristics are also better at starting with ANFIS than conventional Z-N PID controller.

From the graph we can see that with the ANFIS technique the motor attains its reference speed in lesser time as compared to Z-N method.

In the torque-time graph we can see that at the starting of the motor torque is very high and as the motor reaches its reference speed, torque gets settled with less transients in ANFIS method as compared to Z-N method.

In the current-time graph we can see that at the starting of the motor the current is very high (nearly 15 times of the rated value) and as the motor reaches its reference speed the current gets settled in less time with the ANFIS method than Z-N method.

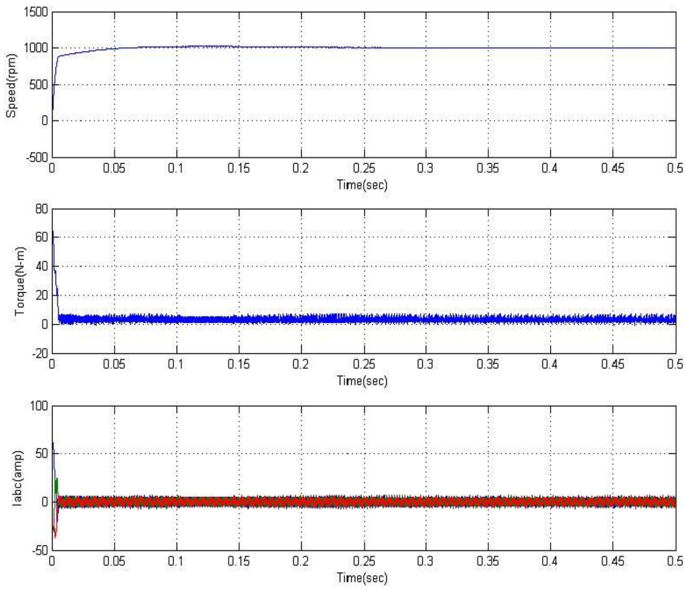

Figure 11 Starting characteristics of Z-N tuned PID controller

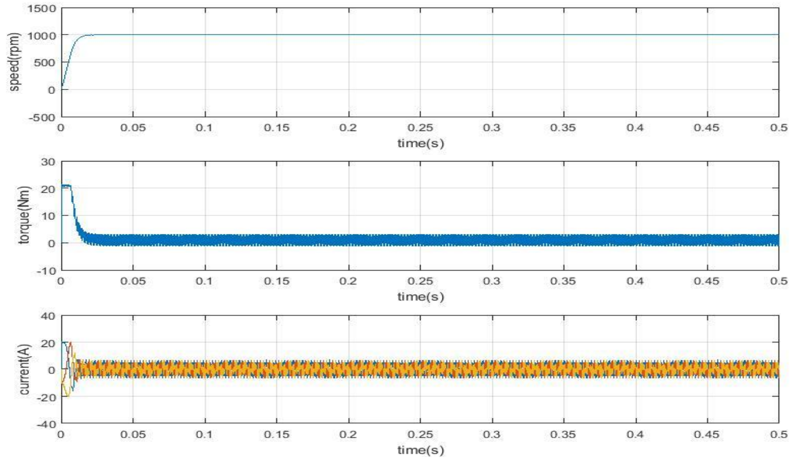

Figure 12 Starting characteristics of ANFIS based speed controller

Load application and load removal

At t = 0.15sec load is applied and at t = 0.35sec load is removed. Figure (13) and Figure (14) shows the loading characteristics of proposed PMSM model using Z-N tuned PID speed controller and ANFIS speed controller respectively.

From the graph we can see that during the period of application load, the speed of motor decreases and after its removal the motor regains its reference speed more quickly in ANFIS speed control method than Z-N method.

In the torque-time graph during the period of application of load the torque increases and at after its removal torque decreases to its original value with less transient in ANFIS method than Z-N method. In the current-time graph during the period of application of load the magnitude of current increases due to load and after removal of load the current decreases to its original value.

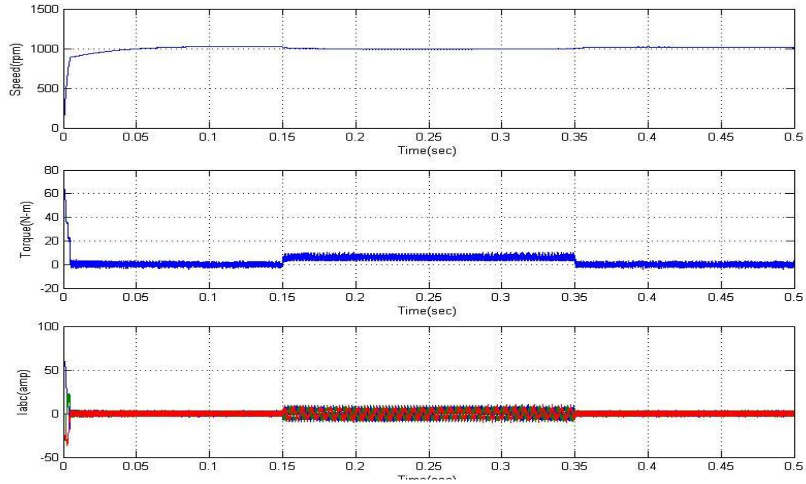

Figure 13: Load application and removal characteristics of Z-N tuned PID controller

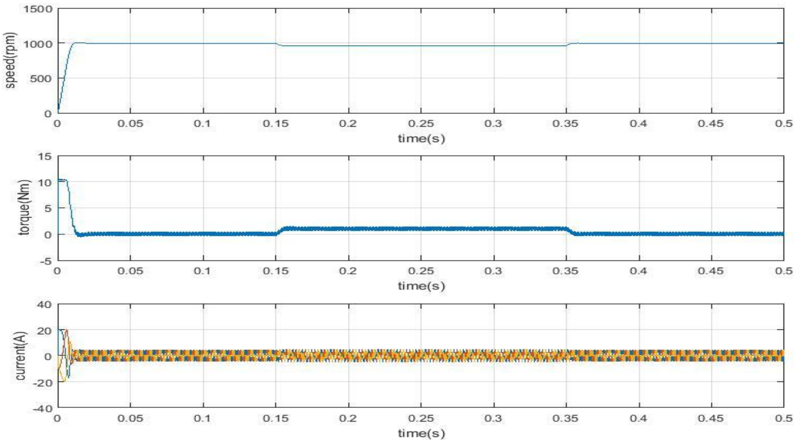

Figure 14: Load application and removal characteristics of ANFIS based speed controller

Speed Reversal

From the Figure (15) and Figure (16) we can observe the characteristics of PMSM due to speed reversal with Z-N tuned PID controller and ANFIS controller respectively.

From the graph we can see that at time t = 0.08 speed reversal is applied and hence the motor starts rotating in the opposite direction and attains reference speed in negative direction.

From the torque-time graph we can see that at the time of speed reversal there is sudden increase in torque in negative direction and then it gets settled with much improved transients with ANFIS than Z-N tuned PID controller.

From the current-time graph we can see that at the time of speed reversal the current gets disturbed and reaches to a very high value for some time. When the motor attains its reference speed the three phase currents settled to its rated value much faster in ANFIS than PID controller. The following table consists of rise time (T_r), settling time (T_s), peak overshoot percentage (M_p) and error data.

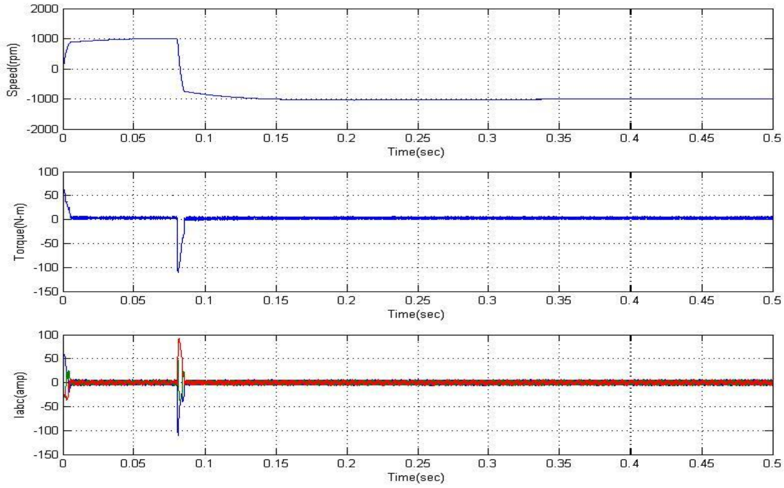

Figure 15: Speed reversal characteristics of Z-N tuned PID controller

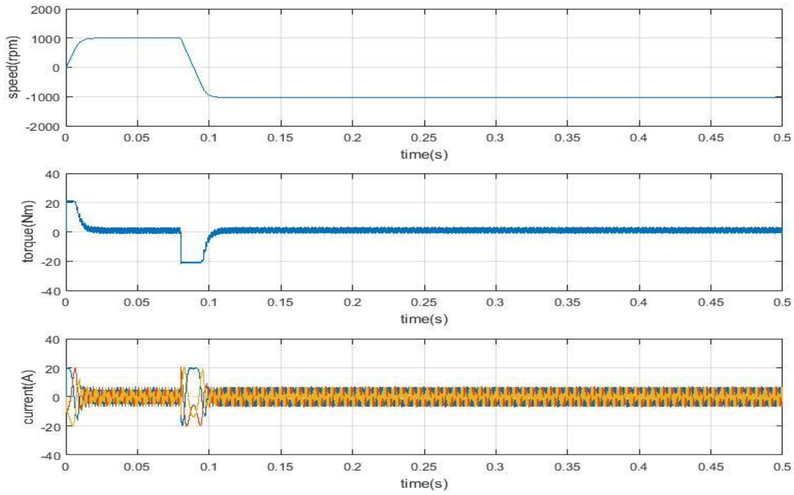

Figure 16: Speed reversal characteristics of ANFIS based speed controller

Controller	Operation	t_r(sec)	M_p(%)	t_s(sec)	E_{ss}
Z-N TUNED PID CONTROLLER	Starting	0.01	2.6	0.118	0.44
	Loading	0.03	3.85	0.13	0.40
	Load Removal		1.2	0.09	0.18
	Speed Reversal		2.1	0.06	0.38
ANFIS CONTROLLER	Starting	0.008	2	0.04	0.41
	Loading	0.008	1.2	0.05	0.39
	Load Removal		0.5	0.05	0.15
	Speed Reversal		2	0.055	0.35

Table 3 Comparison between Z-N tuned PID controller and ANFIS based speed controller

VII. CONCLUSION

This paper has analyzed PMSM drive using one of the Artificial Intelligence techniques viz. ANFIS based speed controller. The rigorous and comprehensive performance analysis has been carried out under various dynamic conditions in the light of improving transient response specifications i.e. rise time, peak time, maximum peak overshoot and steady state error.

From the results, it is found that the ANFIS based speed controller produces better speed response than conventional Z-N tuned PID speed controller, in terms of rise time, overshoot, settling time and steady state. ANFIS based speed controller has significantly reduced the overshoot as well as the settling time in comparison to rest of controllers. It has also mitigated the disturbance effects such as speed and torque change and maintained steady-state accuracy. The ANFIS Controller has significantly reduced the time for designing an optimal Neuro-Fuzzy Controller.

It is also worth noticing that the ANFIS controller has improved the transient response as well as the steady state response to a great extent, better than conventional Z-N tuned PID controller. A systematic ANFIS structure is presented to develop a dynamic model of PMSM as it does not require the explicit mathematical model of the plant and automatically takes care of changing conditions as well. Hence it is a useful technique to study the dynamic characteristics of the motor with much ease and better controllability options.

The paper in future may be carried out in achieving better results with certain modifications in the rule base design with improvements in the limits decided for several ANFIS parameters. The simulated results may be validated through hardware implementation of the simulation model which will help to realize the proposed model and hence will prove the results in a more authentic fashion.

VIII. ACKNOWLEDGMENT

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