VOL. 16, NO. 11, JUNE 2021 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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DEVELOPMENT OF A HYBRID CONTROLLER FOR THE SPEED CONTROL OF SINGLE-PHASE INDUCTION MOTOR

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ABSTRACT

For complex nonlinear control systems, using an individual fuzzy logic controller or a conventional PID controller cannot satisfy the requirements of these systems. A PID controller had been previously designed, and has been redesigned in the current research using the Ant Lion Optimization (ALO) algorithm to determine the gains of the PID controller necessary to achieve the desired speed for a single-phase induction motor (SPIM). A Fuzzy logic controller was subsequently designed, and the fuzzy rules and membership functions were used to find the controller gains built on the input variable error and the derivative error signals. However, the simulation results of both the PID and Fuzzy logic controllers could not give satisfactory results for the SPIM. To overcome these problems, a novel hybrid controller was developed that is a combination of fuzzy logic and the proportional (P), integral (I) and differential (D) controllers. This is also called as Fuzzy rule based PID controller. The experimental results from this development demonstrated the technical and operational feasibility of this controller which produces fast rise time, fast setting time, and minimum steady state errors as well as improvements in other parameters. When the simulation results of the three controllers were compared, the Fuzzy rule based PID controller demonstrated the best performance parameters of the three.

Keywords: PID controller, fuzzy logic controller, fuzzy rule based PID controller, optimization algorithm, speed control of single-phase induction motor, controller comparison.

INTRODUCTION

Single phase induction motors (SPIMs) are widely used in many industrial and home applications such as pumps, fans, compressors, and drilling machines. Given that the automation industry has growing rapidly, there is significant scope for development and upgrading of any systems. The main advantages of using SPIM's in any system are low cost, less maintenance, ease of handling, good starting torque and variable speed control [1]. Methods such as stator voltage control, variable frequency control, V/F control, and Rotor resistance control are mainly used for precise speed control of these motors.

Many researchers and engineers are working on the new methods and techniques for the speed control of induction motors, but there is always room for new researchers to work on control mechanisms and algorithms for induction motors and to develop new techniques for speed control of these motors.

It is difficult to constantly control these motors, for example in unstable, non-linear power conditions. Having a simple voltage control, which is limited to controlling in a narrow range, cannot solve these instability problems that occur due to sudden change in the load. A solution to this problem, is the SPIM which can be varied by either supplying constant voltage or frequency (V/F control) or by varying supply voltage making frequency constant [2]. To effectively monitor the motor speed and performance in unstable conditions, it is necessary to know the current speed of the motor in real-time and in the current conditions and to use effective feedback control to minimize the generated errors with constant comparison of the reference values. To achieve the desired speed at motor terminals, the stator voltage of SPIM is controlled by varying the firing angle of the triac [3]. In terms of the efficient speed control of SPIM, the controller must be able to generate the desired gate pulses to the triac thereby achieving smooth speed control with less power loss.

Conventionally, different types of motor controllers have been used by researchers to trigger the gate of the triac. These have not always produced satisfactory results in the closed loop systems. The concepts of artificial intelligence, fuzzy logic, technical optimization, genetic algorithm have been adopted by some researchers to solve various complex problems especially nonlinear systems or challenging mathematical models [4].

This paper describes how the three controllers PID, Fuzzy logic and Fuzzy rule based PID controllers were each independently used to control the speed of SPIM. Each controller performance was examined, compared, and explained. The simulation results showed that the proposed Fuzzy rule based PID controller obtained the best performance characteristics of the three controllers.

LITERATURE SURVEY

This section explains about the related research work done by various researchers in the same area of motor speed control.

Abdel, H. M. A. *et al.* developed a new method for the speed control of SPIM with two symmetrical stator windings by placing two triacs, one in series with the main winding and the other with the auxiliary winding. Also, the authors developed a state space mathematical model to calculate the transient and steady state performance characteristics. Further, a computer program was

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developed to govern the performance of the SPIM using the fourth order Runge-Kutta method [3] to solve the state space equations by numerical integration. The experimental results showed that this method was successful in starting, speed control and reversing the direction of rotation of the SPIM [3].

Dirman, H. *et al.* designed a fuzzy logic controller (FLC) to improve the speed of SPIM. The phase angle control method was used to apply the controlled time-based firing pulses to the triac. The type of fuzzy logic control used was a Mamdani type fuzzy inference system. The FLC was designed and simulated in MATLAB/SIMULINK software. The simulation results showed that FLC has better performance characteristics than the PID controller [5].

Smriti, K. R. *et al.* presented a comparative analysis of Proportional (P), Proportional Integral (PI) and Proportional Integral Derivative (PID) controllers for the speed control of VSI-fed induction motors. They discussed each controller and calculated the rise time, overshoot, settling time, steady state error and stability of each. Their results showed that, for the PID controller, the rise time, overshoot and settling time were decreased, but there was no change in the steady state error. Thus, the authors concluded that the PID controller was better than both the P and PI controllers [6].

Zeyad, O. *et al.* developed a PIDFLC to control the rotor position in the AC motor by adopting the VHDL language to merge FLC in the field programmable gate array (FPGA). Then, the new version of this controller was emerged. The first version consisted of 6-bits per input and output variable. The second version had 8 bits for each input and output variable. Meanwhile, all triangular fuzzy sets and all singleton fuzzy sets were used for input and output variables in MATLAB/SIMULINK software for simulation purposes. As a result, the second order mathematical model signifies the rotor position control in an AC motor which was used in a unity feedback control system with this proposed controller [7].

Ahmad, A. H. *et al*. proposed a technique called the Frog jumping technique for designing a controller for SPIM. This technique determines the best possible values of voltage and frequency and applies these values to the single-phase inverter to control the speed of the motor. The input values of this controller are the difference between the reference value and the actual speed value, and the output is designated as voltage and frequency. This algorithm was developed in MATLAB/SIMULINK software and the simulation results showed that the Frog technique gave the best combination of voltage and frequency values with minimum errors and with the desired speed approximately equal to any reference speeds [8].

Khan, A. A. *et al*. proposed the Fuzzy PID controller where the PID controller is tuned by the Zeigler Nichols Method [9] and by bringing these PID tuning rules to the fuzzy region. The proposed controller was simulated using MATLAB/SIMULINK, and the simulation results showed that the performance parameters of Fuzzy PID were better than for the conventional PID controller [9].

These cited researchers worked on designing a new controller for the speed control of SPIM and achieved satisfactory results, yet the work of each had certain limitations. However, few researchers have worked on a combination of Fuzzy and PID controllers, and limited researchers have designed and implemented such a controller for SPIM. This paper describes the three main contributions of our research. First, we modelled a PID controller in MATLAB/SIMULINK and used the Ant Lion algorithm (ALO) for tuning purposes. Also, we defined a fitness function using Integral Square Error (ISE) to reduce the error and to find the best possible combination of PID parameters. This ALO algorithm can provide the best tuning results compared with other tuning process. Next, for the same system model, we used a fuzzy logic controller with three membership functions and noted its performance characteristics. In this paper, the novel Fuzzy rule based PID controller was finally discussed and designed the same control system by delivering faster speed response and performance characteristics for the SPIM when comparing to the two conventional controllers: PID and Fuzzy.

METHODOLOGY

The speed control of the motor is an important application for rotating machines. There are many controllers available that have been developed using the best combination of conventional and intelligent controllers based on the concept of motor speed control. This section explains the design and implementation of a simple PID controller with the Ant Lion algorithm, a Fuzzy logic controller with fuzzy rules and membership functions, and Fuzzy rule-based tuning of the PID controller for the speed control of a single-phase induction motor. The parameters of the experimental motor used for this work are given in Table-1.

Table-1. SPIM parameters.

No.	Motor Parameter	Value	
1.	Reference Speed	1345	RPM
2.	Voltage applied	230	V
3.	Power of motor used	0.054	HP
4.	Frequency	50	Hz
5.	Stator resistance, Rs	2	ohms
6.	Stator Inductance, Ls	0.0074	H
7.	Rotor resistance, Rr	4	ohms
8.	Rotor inductance, Lr	0.0056	H
9.	Mutual inductance of main winding	0.1772	H
10.	Auxiliary winding Resistance	4.12	ohms
11.	Auxiliary winding Inductance	0.0085	H
12.	Number of poles	4	

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ARPN Journal of Engineering and Applied Sciences

PID CONTROLLER

The PID controller is extensively used in many industrial and domestic applications because of its arrangement, robustness and to ability to provide optimized control. This conventional PID controller has been upgraded and expanded by integrating with different tuning methods, thus making this controller more efficient [10]. For any controller, tuning is the main factor for obtaining the best performance. The main task in designing a PID controller is to choose the controller parameters to achieve the best results. There are many ways of tuning PID controllers including trial and error, the Ziegler-Nichols method, Runge-Kutta method, Cohen Coons method and others [10]. However, the time delay constraint in indefinite nonlinear systems and uneven changes in the system parameters of the PID controller are limited to meet the desired performance. The objective of basic principle of the PID controller is to minimize the error generated from the processed value and the desired value. The basic block diagram of the PID controller is shown in Figure-1. The basic mathematical equation of PID controller is:

$$u(t) = K_p\, e(t) + K_i \int e(t)d(t) + K_d\, de(t)/d(t), \quad (1)$$

where K_p is the proportional gain coefficient,
K_i is the integral gain coefficient,
K_d is the derivative gain coefficient

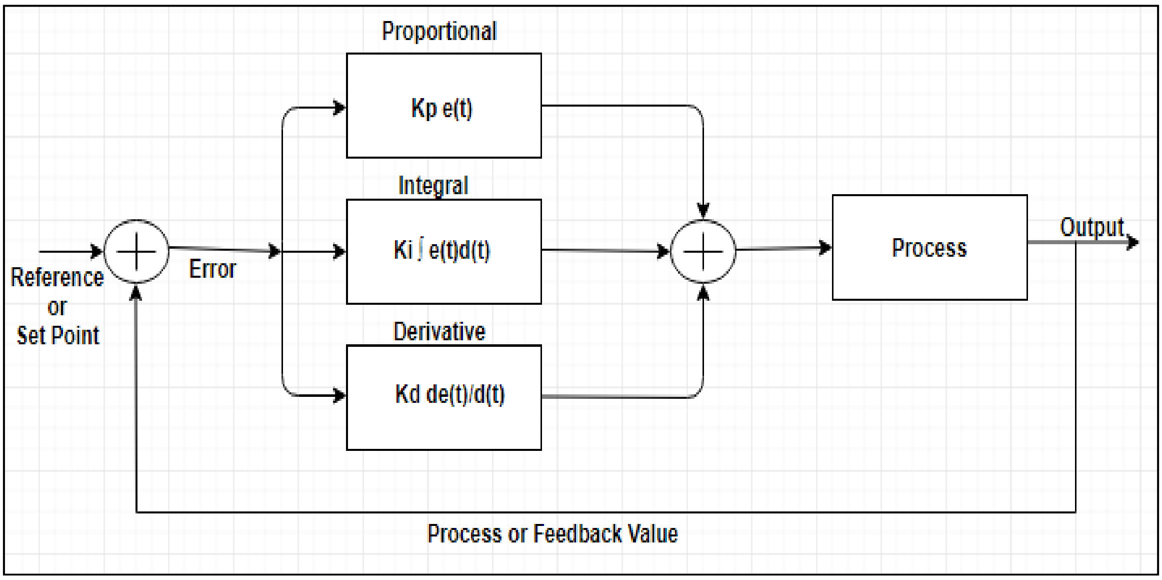

Figure-1. PID Controller.

The Simulink model of the SPIM with PID controller is shown in Figure-2. The values of the three gain coefficients (K_p, K_i and K_d,) are obtained by using the Ant Lion Optimization (ALO) technique. In our work, an Objective function was defined to calculate the Integral Square Error (ISE) to minimize the error and to find the best possible combination of these three PID constraints. The main objective of the ISE calculation is to monitor the error between the desired reference step input and the measured process value. To define the ISE, the integral time limits 0.001 were chosen as the lower limit and 10 as the upper limit. The step response was sampled every 0.1 second. The maximum number of iterations was 100. The MATLAB code of the ISE calculation is:

```
error = 1-y.
deltat = 0.1.
ISE = trapz(deltat, error.^2);                (2)
```

Where y is output, t is time from the clock “to workspace” as shown in Figure-2.

The Ant Lion Optimization Algorithm

The Ant Lion Optimizer (ALO) is a unique algorithm presented by S. Mirjalili [11] that adopts the hunting method of ant lions in Mother Nature. Ant lions build a trap that captures passing prey and falls into the trap. The Ant Lion Opimizer algorithm captures the best values for K_p, K_i, and K_d that give the best possible combination of K_p, K_i, and K_d to achieve the desired output.

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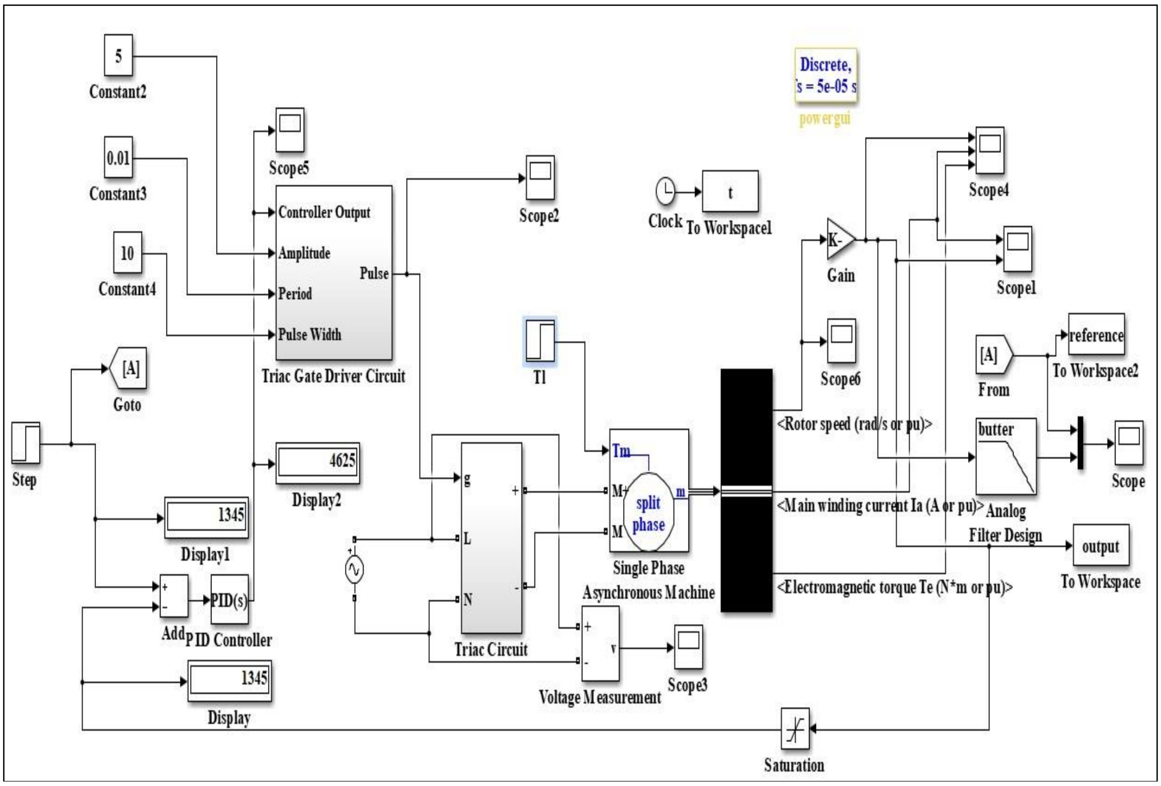

Figure-2. Simulink model of the SPIM with PID controller.

FUZZY LOGIC CONTROLLER

Fuzzy Logic controller (FLC) is the most competent controller in use as it handles nonlinearities effectively and it is autonomous of the control system.

Any fuzzy based controller consists of Four Parts: namely a Rule base, an Inference system, the Fuzzification process and the Defuzzification process, as shown in Figure-3. The fuzzy logic studies are helpful to design and develop the fuzzy controller, which is highly effective to compare the real time problems. This type of control system helps to solve any type of problem accurately and effectively [12]. FLC works with a rule-based system and its algorithm is built on the linguistic variables that try to imitate a human's knowledge and apply it to govern a system without the necessity of a mathematical model. Fuzzy membership functions are used to characterize the fuzziness in a fuzzy set and take the values between 0 and 1. To define the membership function, the researcher has more choices of shapes such as a triangular, trapezoid and bell-shaped function.

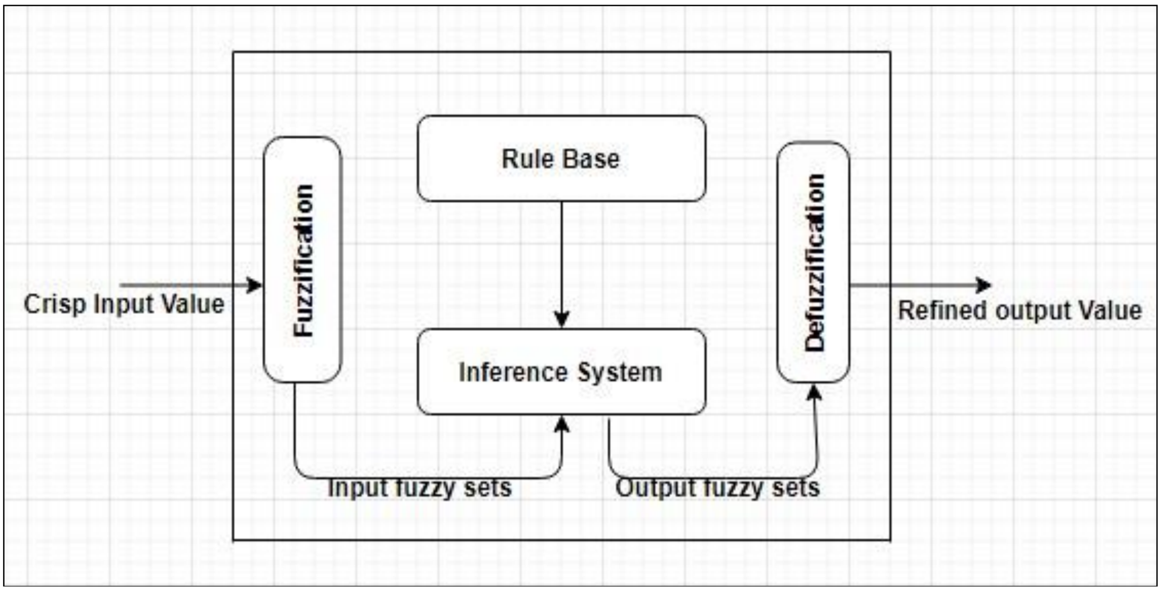

Figure-3. Block diagram of Fuzzy logic control.

ISSN 1819-6608
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The selection of membership functions for the input and output variables are highly significant as it affects the accessibility of rules and the control system consecutively. FLC was designed and developed to process the error which is generated from the difference between the set point or reference value and the processed value. The inputs to the fuzzy controller are represented as the error e(t), and the change of error Δe(t). The output from the fuzzy controller is the time-based firing angle delay (α). The inference mechanism provides the information about the change in the rotation speed of the single-phase induction motor which is contributed by the change of error Δe(t). The difference between the previous error and the present error is used to measure the value of change of error Δe(t). The error and the change of error is written as:

$$e(t) = N_{ref}(t) - N_{act}(t) \quad (3)$$

$$\Delta e(t) = e(t) - e(t-1) \quad (4)$$

The next step in this fuzzy logic control is the fuzzification process which is defined as the process of converting a crisp numerical input value to a fuzzy linguistic variable by using the data from the knowledge base. Next is the rule base and the Inference System. The Rule base is a simple set of rules framed in the form of IF-THEN statements [13]. The rules are represented in the form given below:

IF error is A and change of error is B, THEN output is C

The rule editor of the FLC is shown in Fig. 5. The Inference system is used to evaluate the rules created from the rule base [14, 15]. The Fuzzy Inference System (FIS) was developed in MATLAB for the speed control of the SPIM using this Fuzzy controller, and has two input errors; e(t) (ERROR) and change of errors Δe(t) (DERROR) and one output α or SALIDA as the membership functions which are generated using the Mamdani type fuzzy logic control system, as shown in Figure-4.

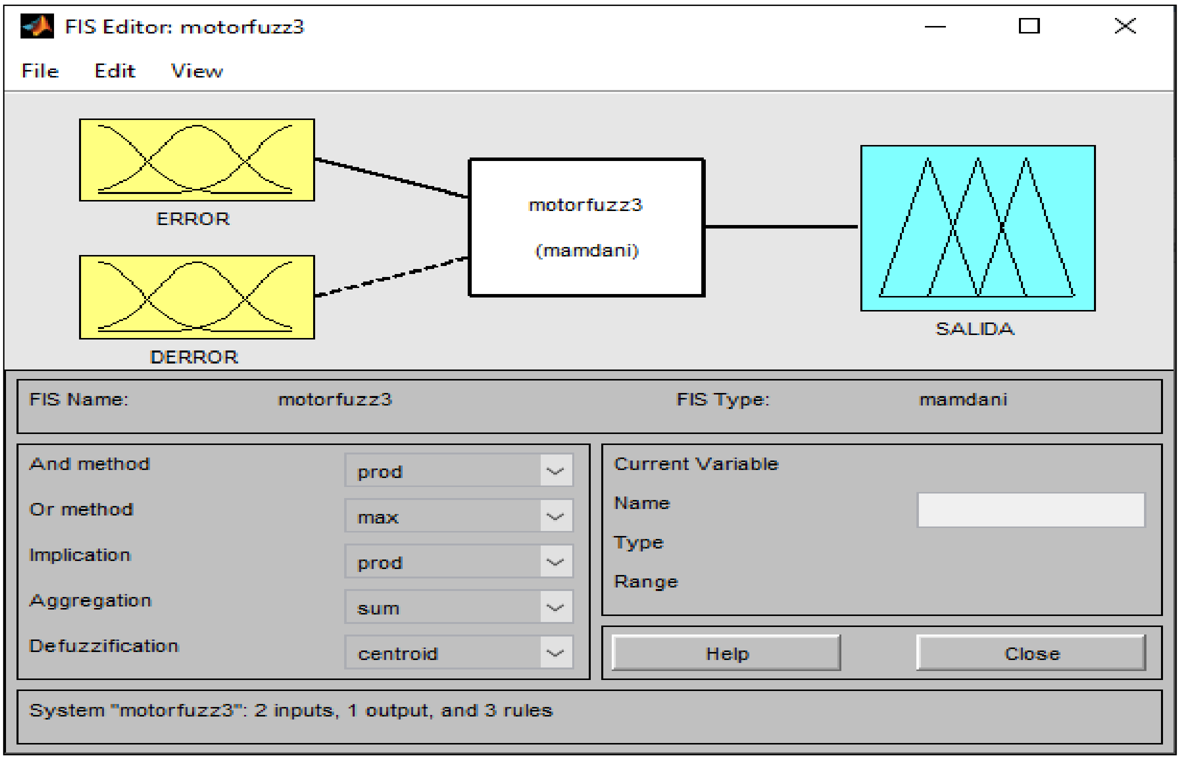

Figure-4. Fuzzy Inference System Editor in MATLAB.

The final process in this system is the defuzzification, where the output of the inference mechanism is converted to the crisp value again. The Centre of Area (CoA) method is used for this purpose. Figure-6 represents the Simulink model of the designed fuzzy logic controller for the speed control of SPIM [16].

For the speed application of SPIM, the input error (ERROR) is the difference between the reference speed and the feedback speed and the derivative error (DERROR) is the difference between the present speed value and the previous speed value. All the rules are initiated according to the demand of the control system to generate the output signal. This signal is again sent back to the fuzzy controller. The speed of the single-phase induction motor is controlled by controlling the firing pulses of the triac [17].

Depending on the current speed, the controller generates a sequence of PWM signals to increase or decrease the speed. Whenever the pulses are given to the triac, the current will flow in both the triac and the motor.

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Therefore, the stator voltage is reduced by increasing the triac firing pulse [18]. Thus, the FLC has been validated for the critical, nonlinear, and roughly characterized forms for which prototypical based control systems are unreasonable.

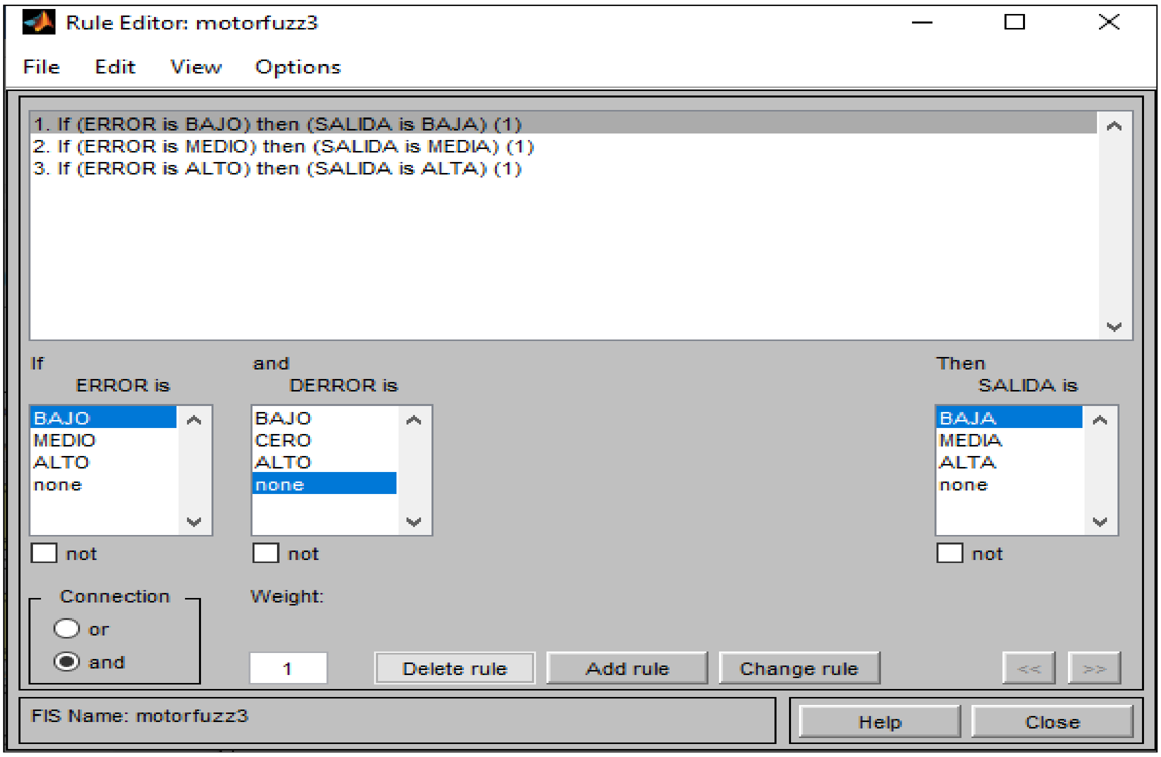

Figure-5. Rule editor of FLC in MATLAB.

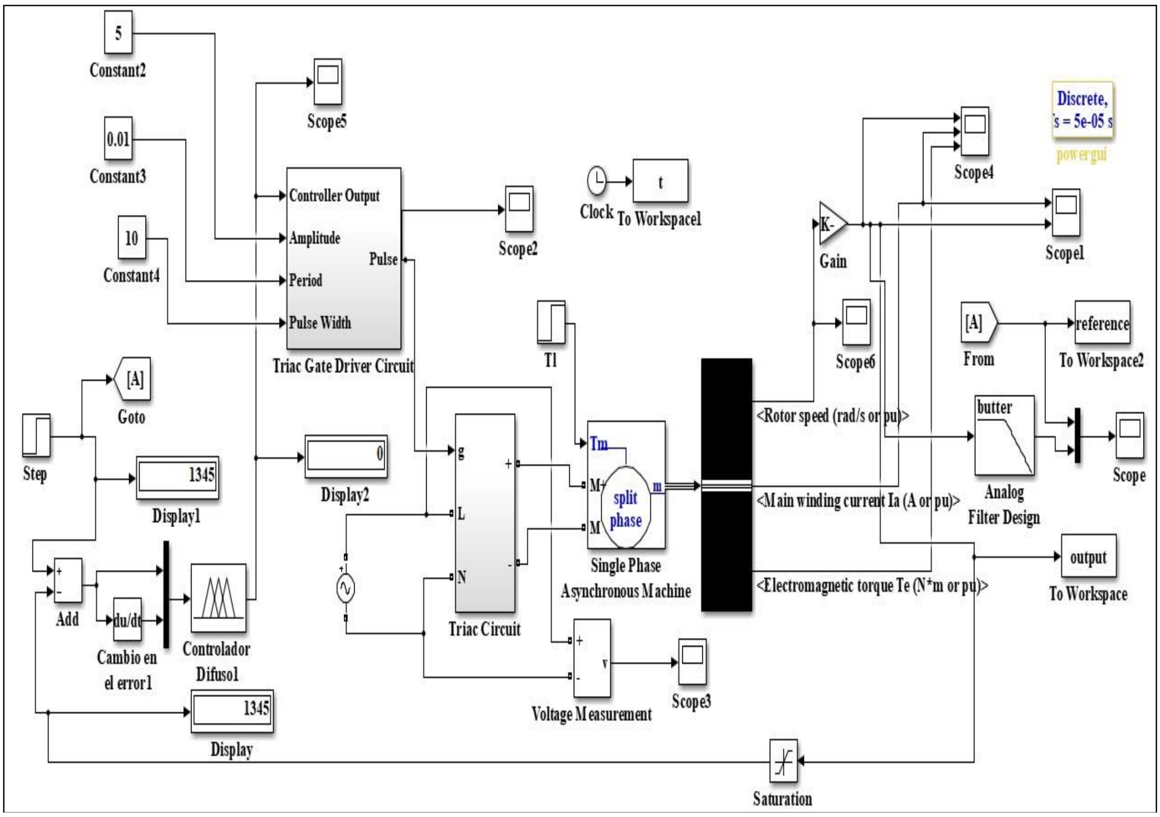

Figure-6. Simulation circuit of the SPIM with Fuzzy controller.

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HYBRID CONTROLLER

This section discusses the hybrid controller that we developed by integrating the fuzzy controller with a simple PID controller. The resultant controller is then termed a hybrid or Fuzzy rule based PID controller. The different types of Direct Action Fuzzy rule based PID controllers are categorized based on the input variables [19]: they are (a) Single Input Fuzzy PID controller, (b) Two Input Fuzzy PID controller and (c) Three Input Fuzzy PID controllers. This paper discusses a fuzzy controller that uses the Two Input Fuzzy PID controller, represented as error (e) and derivative error (de), which also has three outputs represented as K_p, K_i and K_d. This is a rule-based controller which is designed based on human knowledge with intellectual mechanism rather than depending on a mathematical model of the control system [20]. The tuning of the PID controller constraints have become a very tedious task. Though Ziegler and Nichols have recommended tuning methods for PID that work efficiently in case of linear control system only and cannot be trusted for nonlinear control systems [21]. Since our real time motor is a single-phase induction motor with low power ratings and it is very difficult to derive the mathematical model, the PID and Fuzzy controllers failed to achieve the satisfactory results.

Hence, we integrated the fuzzy logic controller with the PID controller and the PID parameters were tuned based on the rule base and fuzzy gain scheduling. This controller was constructed by combining a fuzzy controller and Proportional (P) and Derivative (D) controller connected in series with an Integrator (I) to generate the output signal. The other way of modelling a second type of Fuzzy rule based PID controller is by combining the fuzzy PI and PD controllers [22], which requires more rules rather than the first type. That means it is more complicated and more complex. The Simulink model for the speed control of SPIM using Fuzzy rule based PID controller is shown in Figures 7 and 8. To modify the PID controller constraints on-line the system needs to access the fuzzy rules which are emerged from human intelligence and knowledge about the control system. Therefore, all in input and output data were applied based on these rules [23]. In fact, any number of rules can be defined to initiate the actions of the fuzzy logic controller.

In this proposed method, the PID parameters were calculated based on the error (e) and derivative error (edot) using fuzzy inference system as shown in Figure-9. The parameters K_{pp}, K_{dp} and alpha are determined by the fuzzy set of rules framed like (Figure-10)

If e is NB and edot is NB, then K_{pp} is Big, K_{dp} is Small and alpha is 2 (5)

where NB, K_{pp}, K_{dp} are the fuzzy set of rules and alpha is constant. Figure-11 shows the membership functions of the above input and output parameters. From Figures 10 and 11, NB stands for negative big, NM for negative medium, NS for negative small, Zo for zero, PS for positive small, PM for positive medium and PB for Positive Big [24]. The output variables K_{pp} and K_{dp} could be small or big were characterized by Gaussian membership functions as shown in Figure-12.

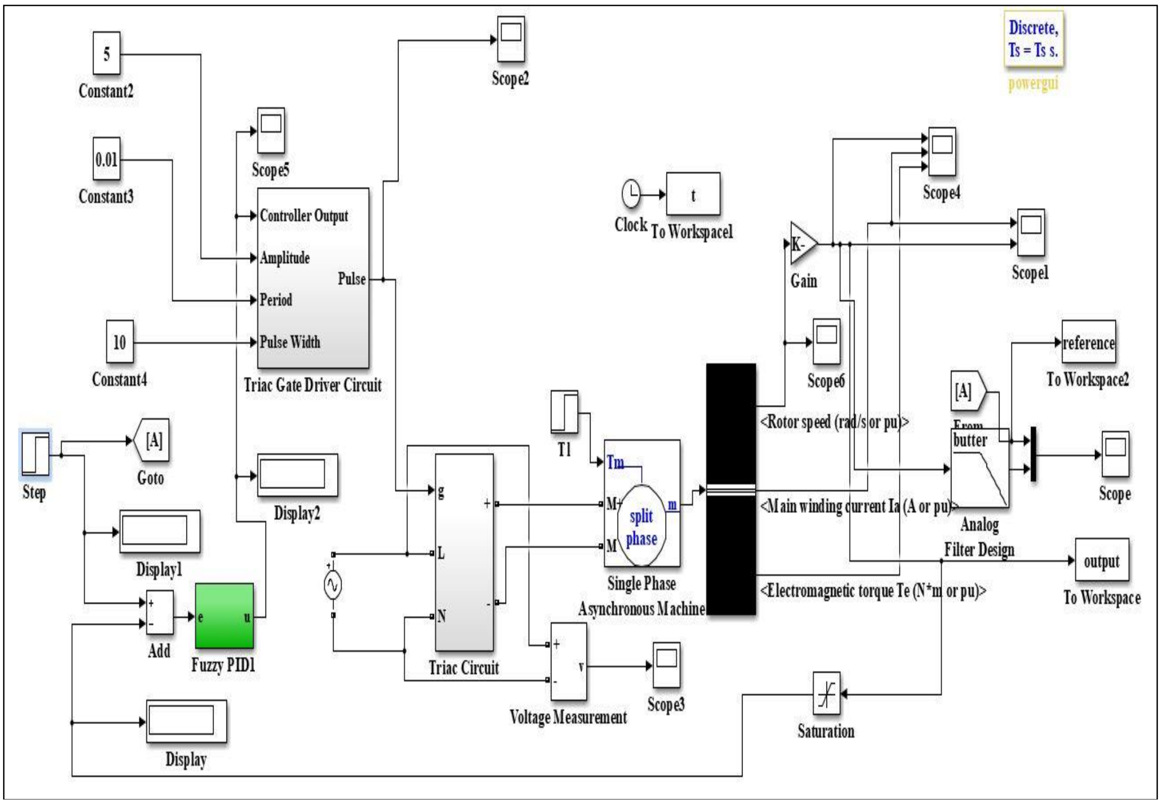

Figure-7. Simulation circuit of the SPIM with Fuzzy rule based PID controller.

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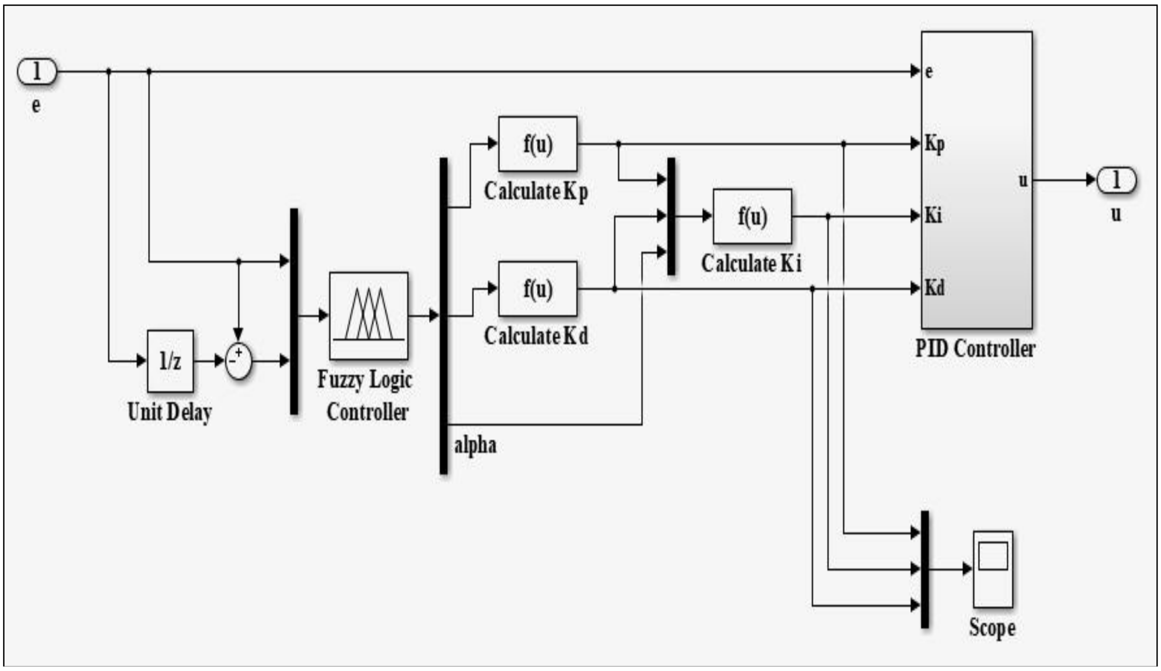

Figure-8. Construction of Fuzzy rule based PID controller.

From the designer's experience, the rules in equation (5) can be derived and these rules can be initialized depending on the step response of the system. For instance, if the motor needs high power at starting for a faster rise time it requires a high-power signal. To get this high-power signal, the controller parameters should maintain large K_p, large K_i and low K_d. Therefore, the output variable K_{pp} and K_{dp} should have big and small values, as shown in Figure-12. The third output variable alpha is a constant used for maintaining the integral control action within the limits. It is also treated as a singleton membership function which has fuzzy number. In this case, alpha is equal to 2 when alpha is small as shown in Figure-13. In the same way, all the 49 rules are fired as shown in the Table-2 for tuning the PID parameters and to generate the corresponding output signal [22].

Table-2. Rule table of fuzzy inference system.

e / edot	**NB**	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	NB	NB	NM	NM	NS	NS	ZO
NM	NB	NM	NM	NS	NS	ZO	PS
NS	NM	NM	NS	NS	ZO	PS	PS
Zo	NM	NS	NS	ZO	PS	PS	PM
PS	NS	NS	ZO	PS	PS	PM	PM
PM	NS	ZO	PS	PS	PM	PM	PB
PB	ZO	PS	PS	PM	PM	PB	PB

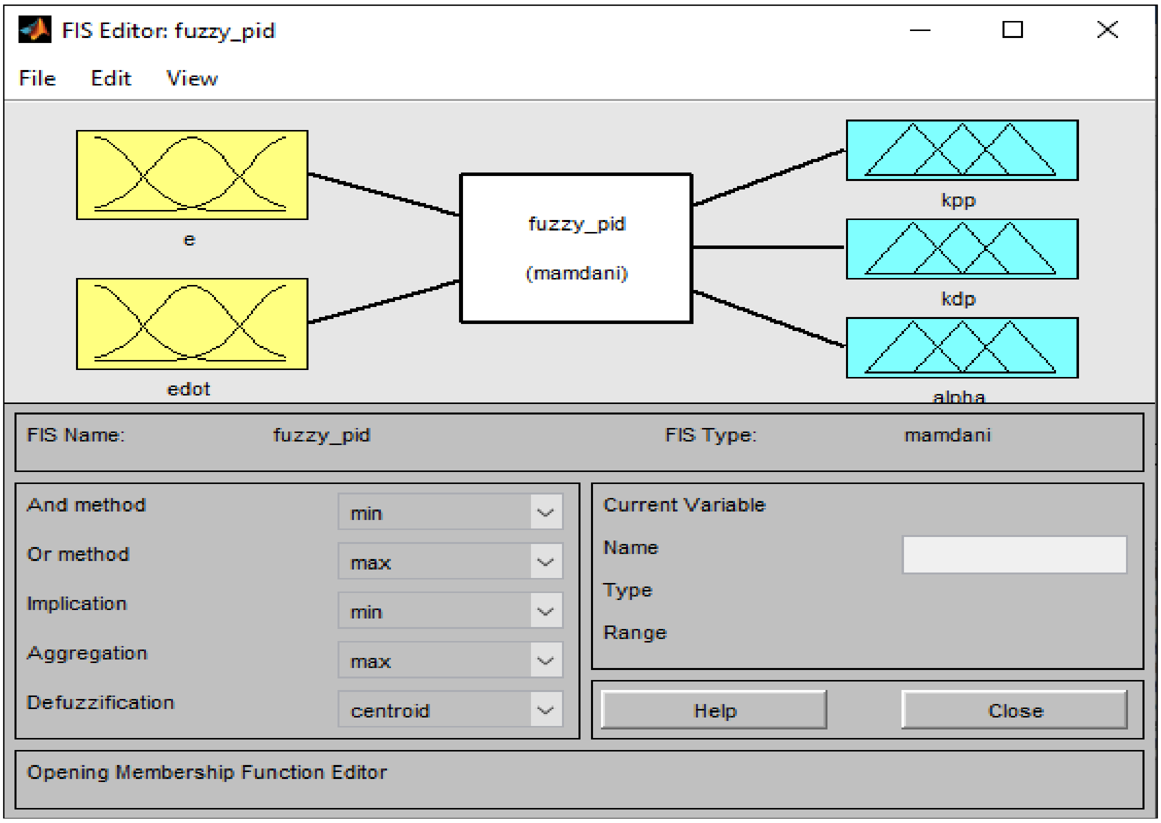

Figure-9. Fuzzy Inference System Editor of Fuzzy rule based PID in MATLAB.

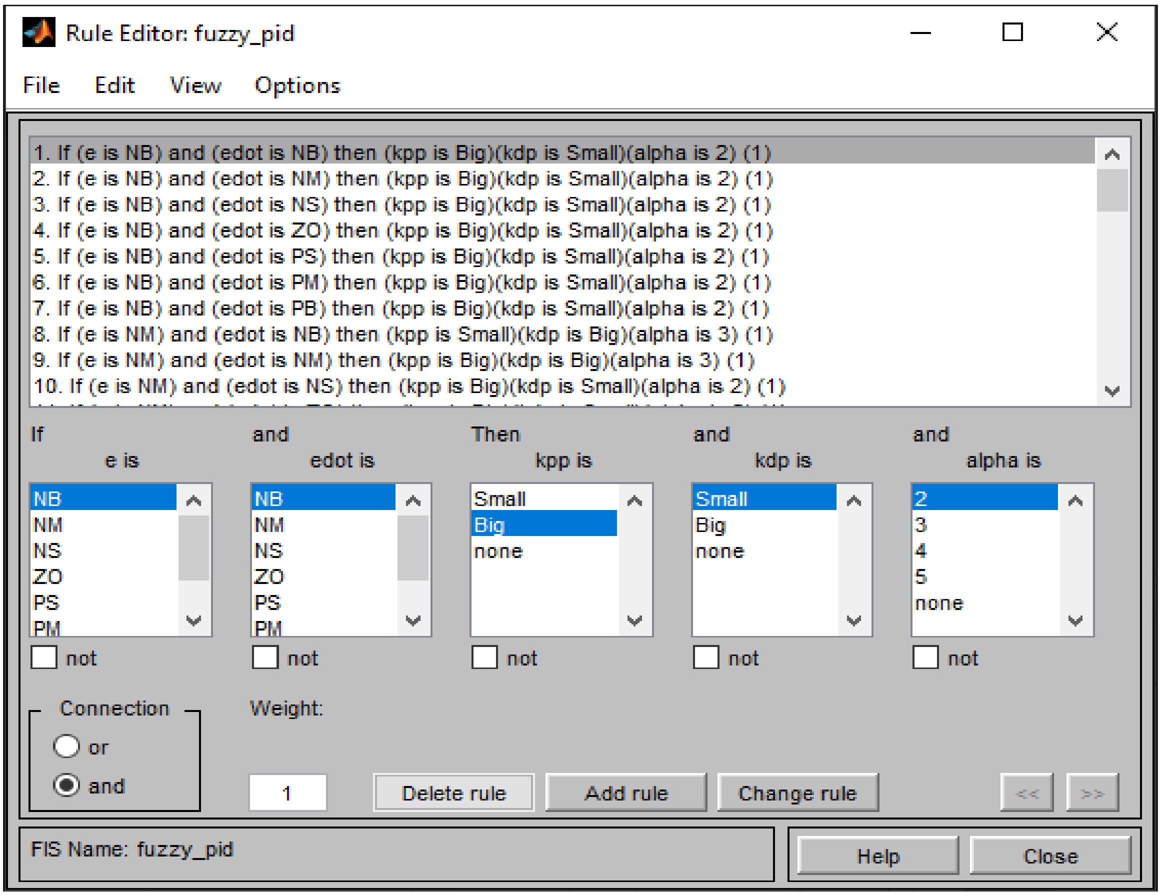

Figure-10. Fuzzy rule based PID rule editor in MATLAB.

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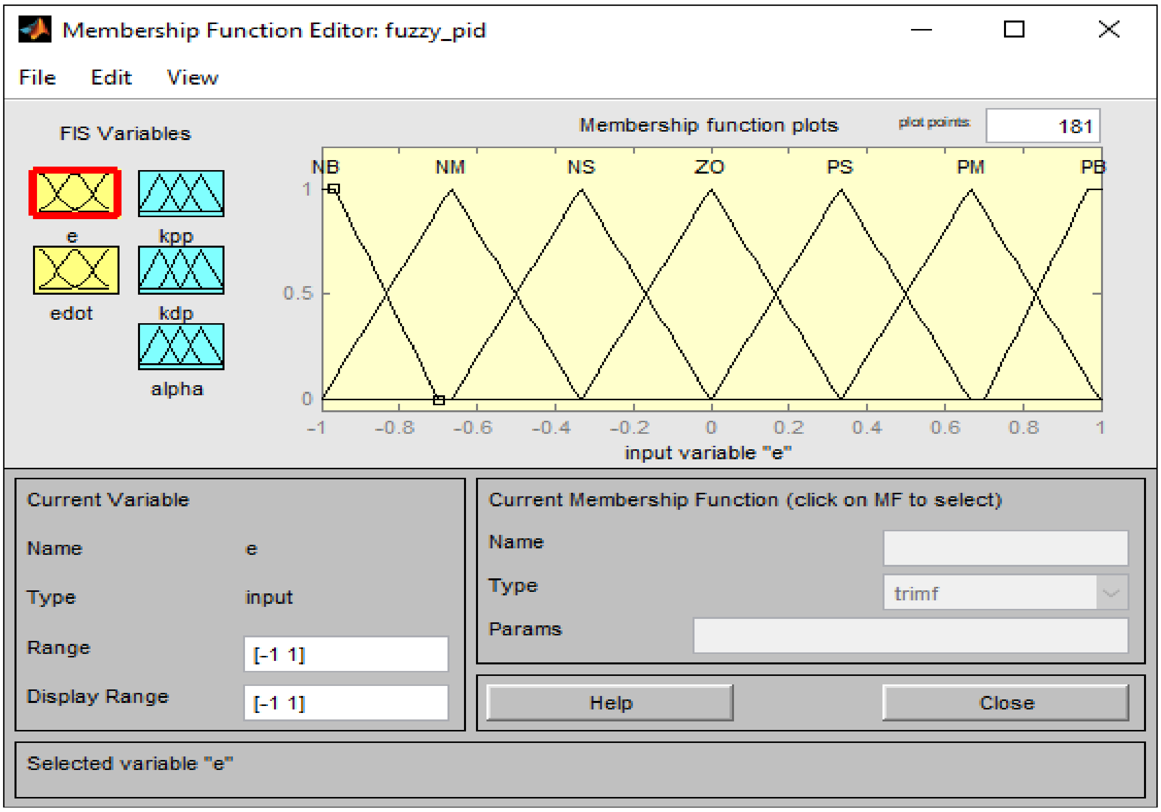

Figure-11. Membership Function for Fuzzy rule based PID in MATLAB.

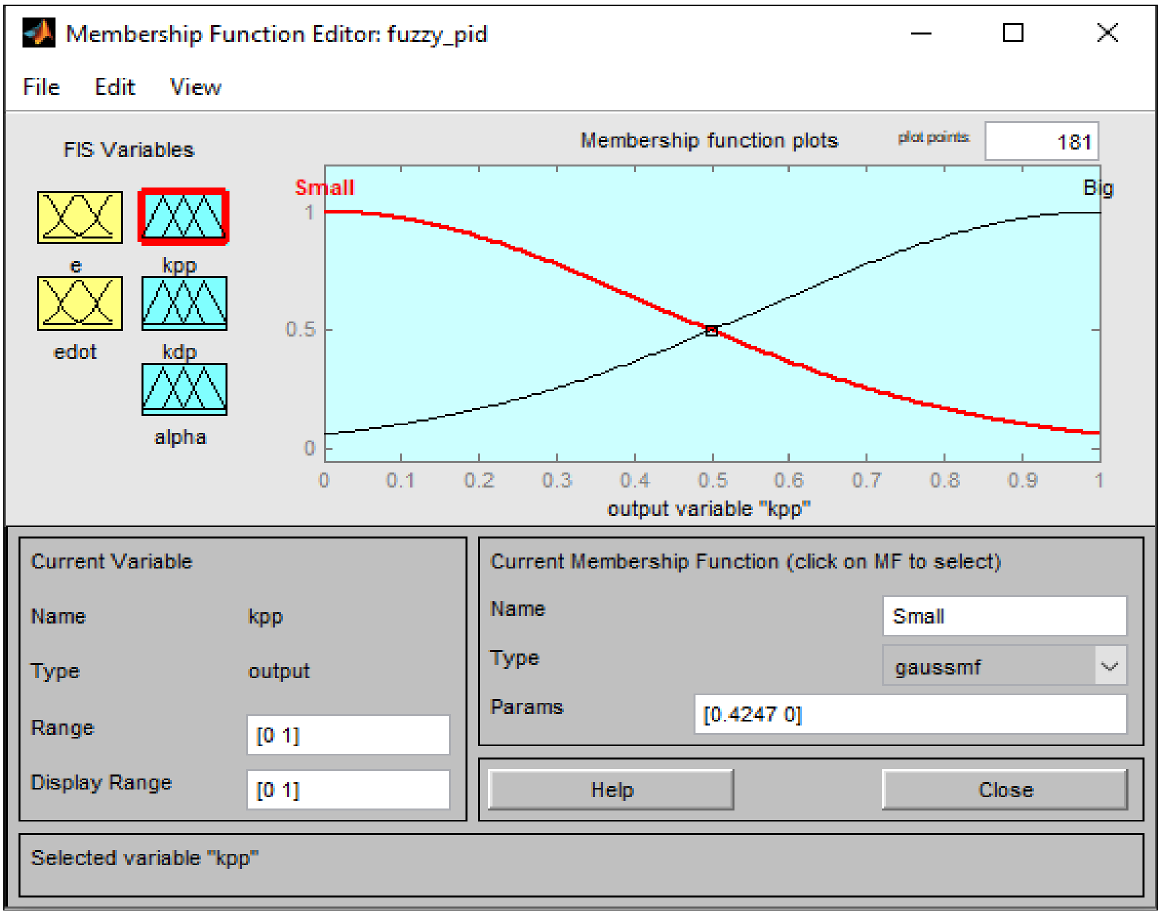

Figure-12. K_{pp} and K_{dp} membership functions.

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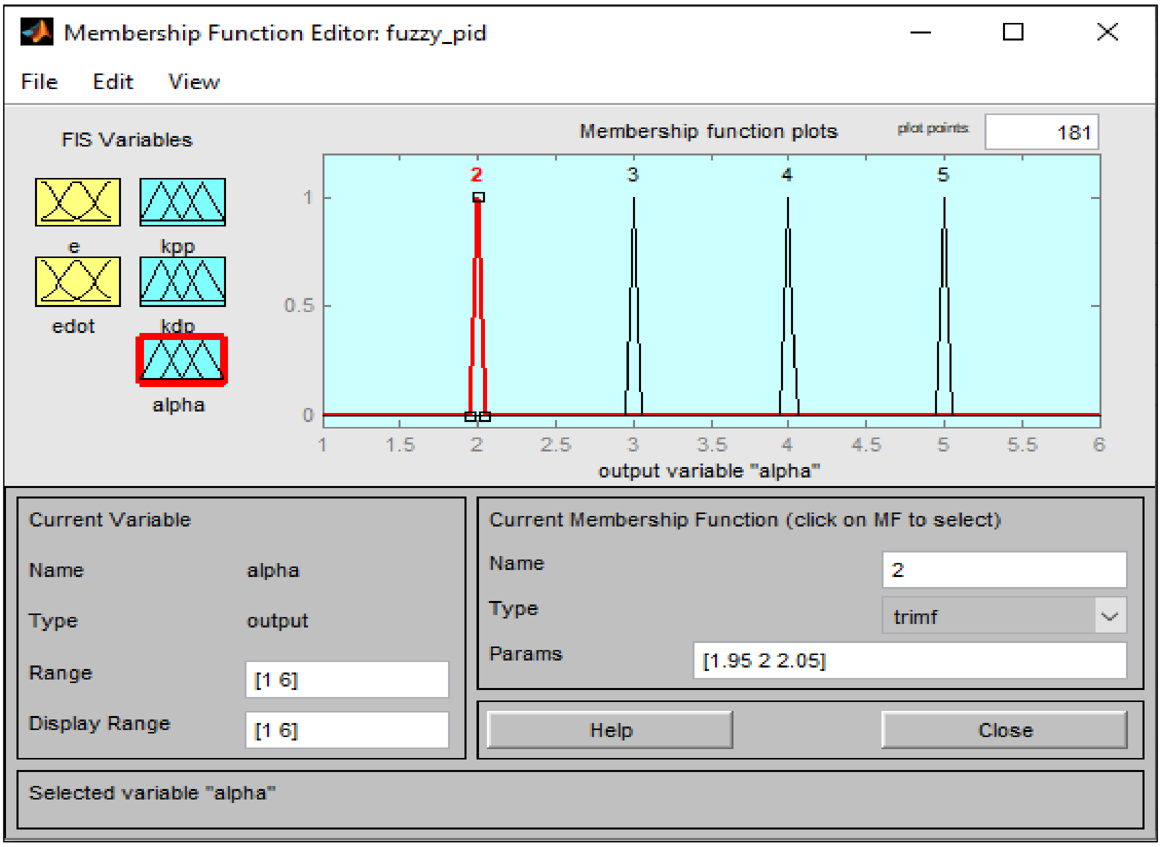

Figure-13. "alpha" membership functions.

RESULTS AND DISCUSSIONS

The design of the controller to achieve better performance of SPIM, is a challenging task. Even though many control algorithms are available to use in many applications, there is always room to develop new control algorithms based on the latest technologies. The three controllers PID, Fuzzy and Fuzzy rule based PID were designed, developed, and implemented effectively for the speed control of SPIM using MATLAB/SIMULINK 2014. The reference speed or step input for the SPIM is 1345 rpm. The simulation results describe most processes can be adequately controlled by hybrid controller, and produced better performance results, which is better than the PID and Fuzzy logic controllers. This can be seen by comparing the performance parameters of rise time, peak time, settling time, overshoot, and steady state error, as shown in Table-3. The speed response of the PID controller is good, but it takes longer settling time, rise time, peak time, and overshoot, as illustrated in Figure-14. In the same way, the performance characteristics of the Fuzzy logic controller is shown in Figure-15, which shows that it took less time to achieve all the performance parameters than the PID controller. The speed response of the Fuzzy rule based PID controller is shown in Figure-16. For ease of understanding, the comparative analysis of the three controller's speed response has been represented in Figure-17. Table-3 and Figures 14-17 reveal that the speed control of the single-phase induction motor with this hybrid or fuzzy rule based PID controller has offered effective results for rise time, settling time, peak time, overshoot and steady state error, all better than for the other two controllers: PID and Fuzzy.

In Figure-17, the blue waveform represents the values from the PID Controller, which took longer settling time with more oscillations. The red waveform represents the Fuzzy logic controller, and its parameters such as rise time, settling time, peak time, overshoot, and steady state error are better than the PID controller. Finally, the green waveform represents the Fuzzy rule based PID controller where all the parameters are better than both the PID and Fuzzy controllers, as shown in Table-3.

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Table-3. Comparison between PID, Fuzzy and Fuzzy rule based PID Controllers.

No.	Parameter	PID	Fuzzy	Fuzzy rule based PID
1.	Rise Time (s)	0.143	0.137	0.135
2.	Peak Time (s)	0.501	0.490	0.480
3.	Settling Time (s)	0.790	0.772	0.762
4.	Overshoot (-)	11.65	11.46	10.72
5.	Steady State Error	1.03%	0.59%	0.29%

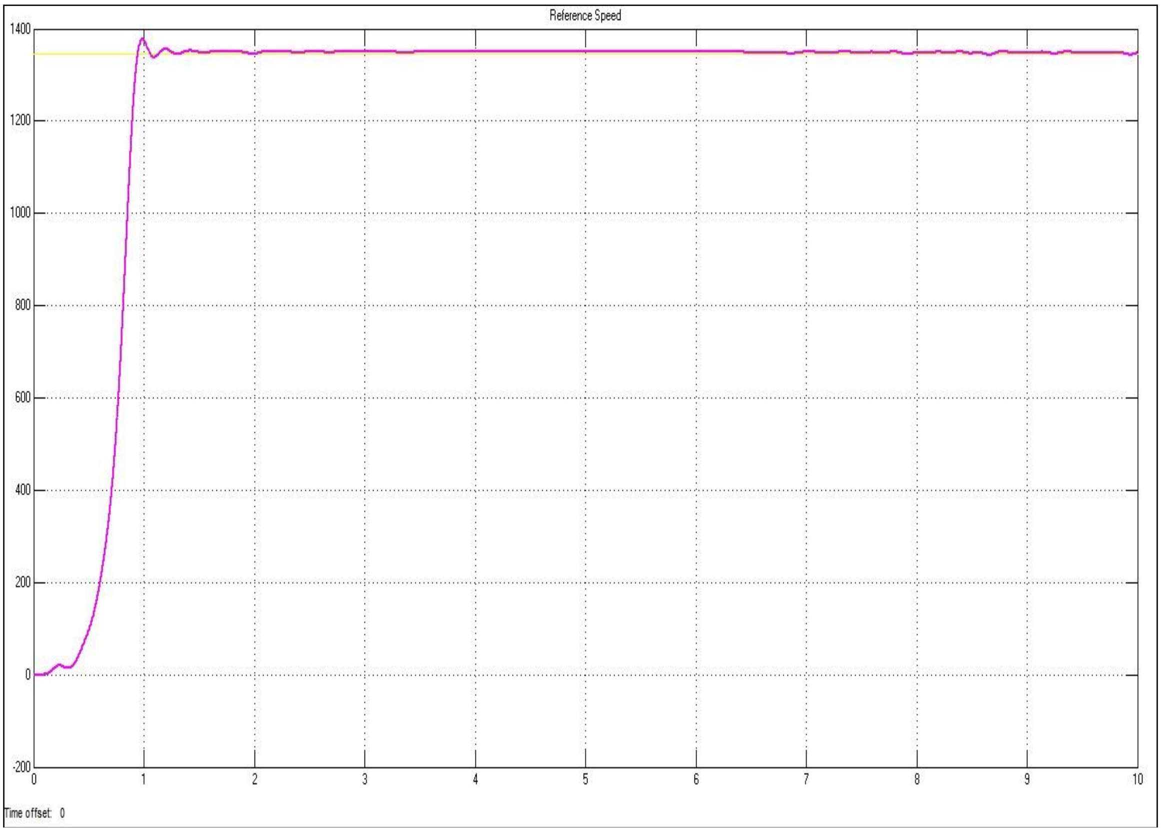

Figure-14. Speed response of SPIM with PID controller.

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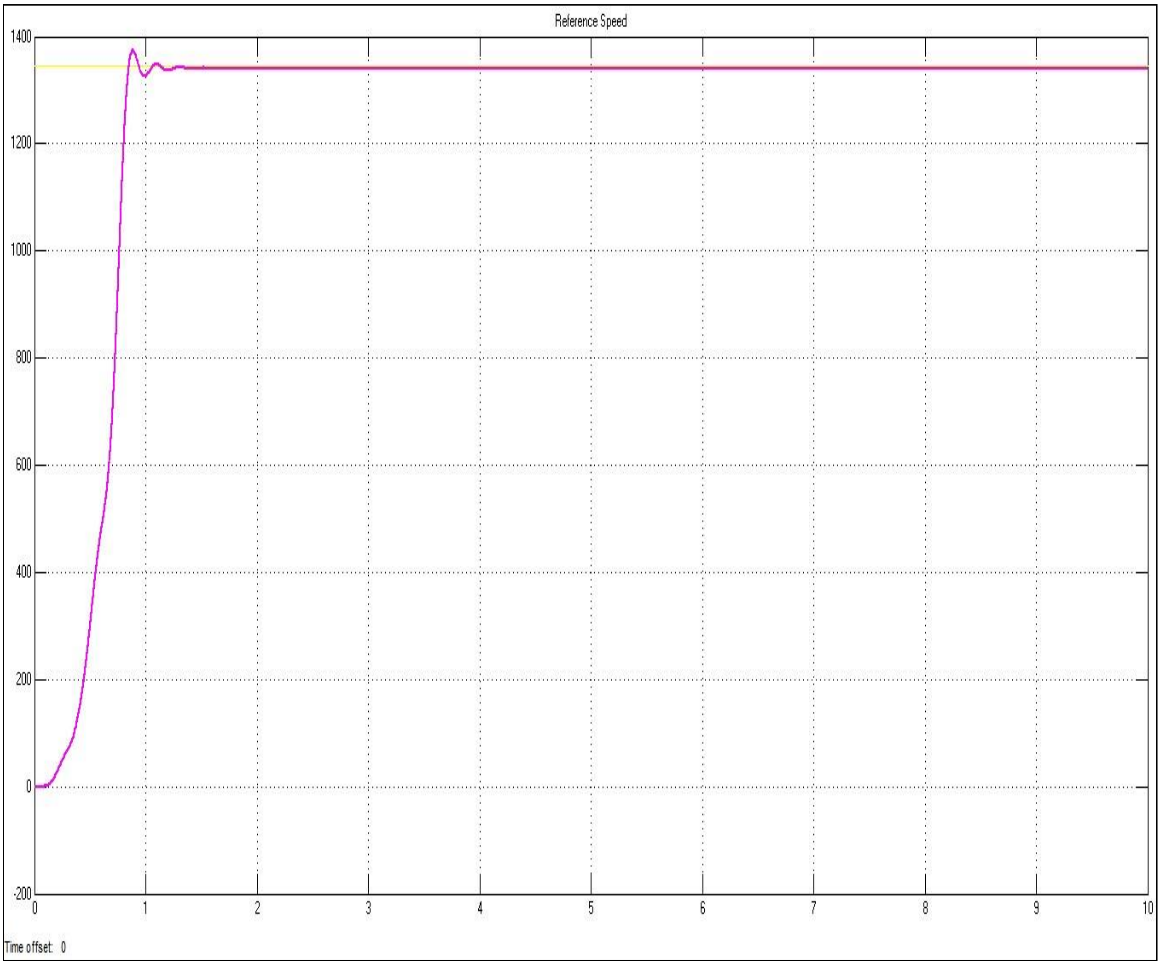

Figure-15. Speed response of SPIM with Fuzzy controller.

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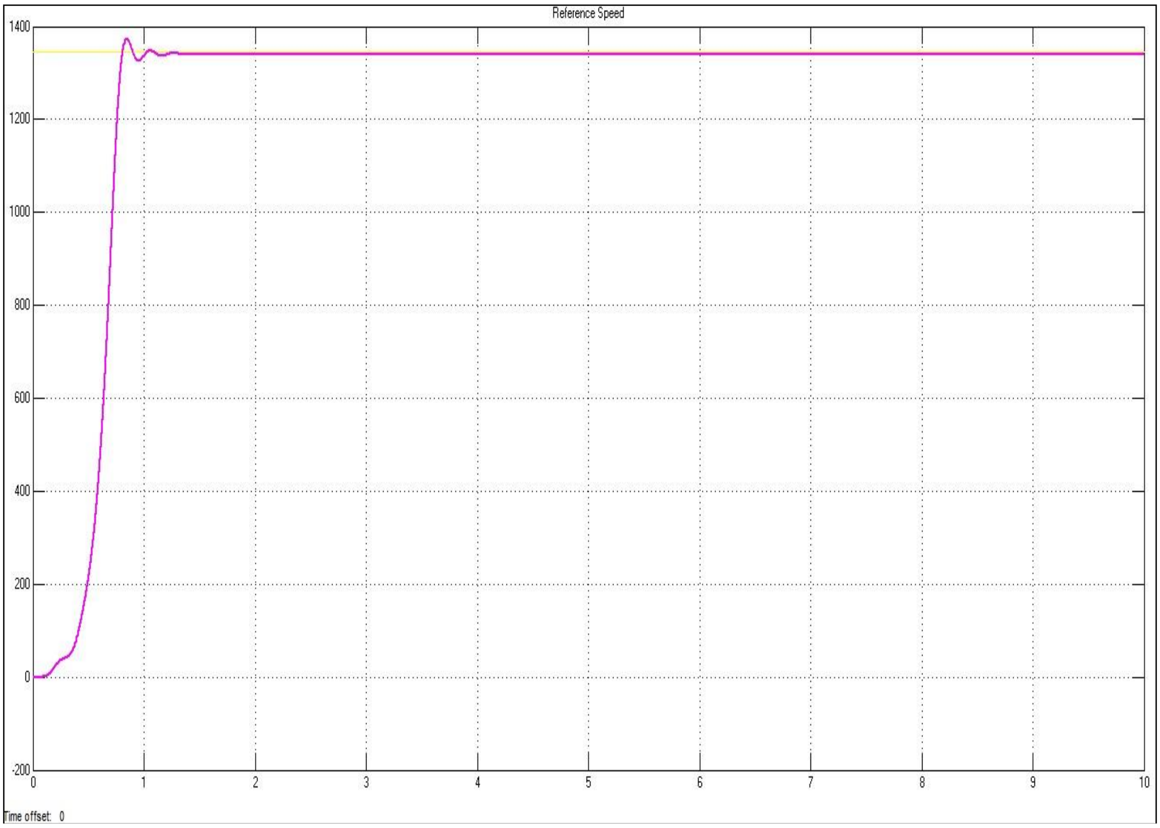

Figure-16. Speed response of SPIM with Fuzzy rule based PID controller.

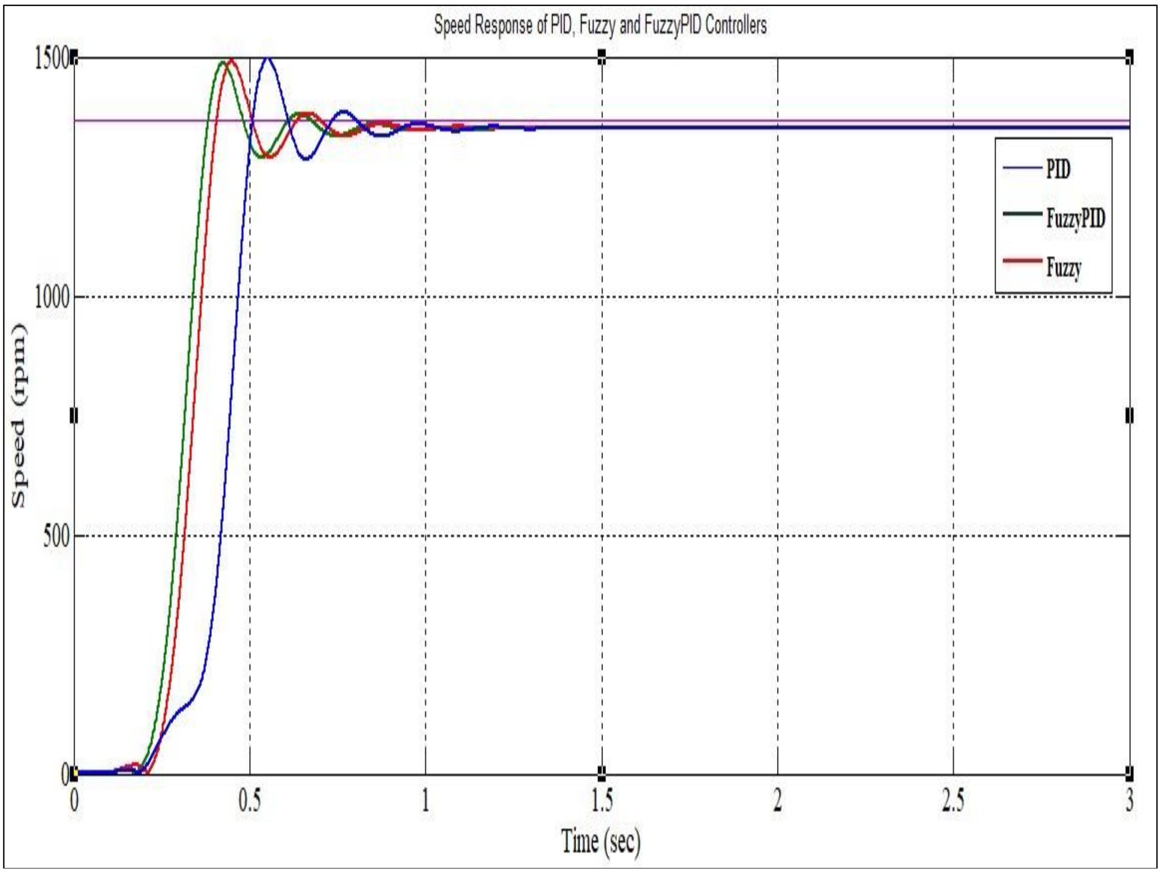

Figure-17. Comparative Speed response of SPIM with PID, Fuzzy and FuzzyPID controllers.

CONCLUSIONS

This paper validates the speed control of SPIM, which uses a non-fuzzy controller i.e. PID controller, Fuzzy logic controller and a hybrid or Fuzzy rule based PID controller. The two inputs and three outputs fuzzy rule based PID controller is designed to apply the speed control of SPIM. The fuzzy rules and membership functions determine the three parameters of the PID controller with respect to the error and derivative of error. All these controllers were designed and modelled using the MATLAB/SIMULINK, and the simulation results of all the three controllers were addressed in the form of graphs and table. From the results as shown in Table 3, it is clearly seen that the Fuzzy rule based PID controller has better performance characteristics for rise time (0.135s), settling time (0.762s), peak time (0.48s), and steady state error (0.29%) which are superior to the parameter values of PID and Fuzzy logic controllers. Hence, this Fuzzy rule based PID controller could be successfully implemented in real-time applications for the effective speed control of single-phase induction motor.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. Karchung, Lecturer, Jigme Namgyel Engineering College, Royal University of Bhutan, and Mr. A. K. Vamsi Krishna Reddy, Teaching and research Assistant, VIT, Vellore, India who gave any help related to this work. Also, the authors would like to express their sincere gratitude to Mr. Roy I. Morien of the Naresuan University Graduate School for his assistance in editing the grammar and English expression in this paper.

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