Performance and Comparative Analysis of Speed Control of IM using Improved Hybrid Fuzzy Gain Scheduling of Proportional Integral Derivative Controller

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ABSTRACT

In this paper, an improved Hybrid FGS-PID (Fuzzy Gain Scheduling of Proportional Integral Derivative) controller is presented for governing the speed of IM (Induction Motor). It is compared with the existing conventional controller (PD&PID) which are extensively used in the industries, an indirect vector control technique using "Synchronously Rotating Reference" as an IM's frame model. This model has been used to governor the speed of three phase squirrel cage IM by using various controller techniques. The proposed Hybrid FGS-PID controller method has been designed, which further selects the three different gains of the PID controller by using a fuzzy inference engine while considering the inputs and outputs Fuzzy rules have been designed to calculate the optimum range of gain values. The designed controller has the flexibility of suitably fine-tuning of conventional PID controller's gains to get the desired results under various operating conditions and to fuzzify the gain parameters Gaussian membership functions were used, rules are mapped in Mamdani inference engine corresponding to their inputs and their output. The comparative results show that fresh gain parameters of designed FGS-PID controller have resolved that the limitations regarding parameters changed and load variations quite satisfactorily.

Key Words: Induction Motor, Proportional Integral Derivative, Proportional Derivative, Fuzzy Logic Controller, Proportional Integral, Indirect Field Oriented Control and Fuzzy Gain Scheduling of PID.

1. INTRODUCTION

IM are used in a wide range of industrial and domestic applications. According to the recent research, it is noted that mostly generated electrical energy is used up via electric motors in technologically advanced countries. Among all these motors, more than 90% of them are IMs [1]. The control of IM is challenging due to its intrinsic nonlinear nature and by means of study with a large number of papers and patents. A squirrel cage IMs is extensively used because of its reliability, low cost, simple maintenance and robustness, so it is important to design a controller [2]. To increase efficiency and enhancing its performance, several different techniques have been proposed. Scalar control technique is mostly used because of its easy implementation. The SC drives do not give satisfactory results for extraordinary performance applications. In this manner of control, torque and flux are decoupled and therefore the analysis of IM is greatly simplified and becomes quite similar to DC excited motor.

With the passage of time, in vector control technique, different conventional controllers have been used together for IM to improve its performance. But it is necessary to highlight that, PID controllers have a main drawback i.e. performance degradation because of the variations in its parameter. These issues rises mostly because of the fixed gains, which effect the performance. To control the speed of such motors, FLC (Fuzzy Logic Controller) delivers a positive solution [3].

FLC has the main attribute over classical PID controller is that FLC does not require any mathematical model. By using fuzzy logic, all those complex systems which are difficult to model precisely, can also be controlled effectively [4]. The IM and their robustness with respect to change in parameters can be enhanced the nonlinear techniques which fuzzy control provides [5-6]. Lately, in order to enhance the controller's performance, hybrid control techniques that consist of two or added control approaches are offered.

TS (Takagi-Sugeno) based fuzzy controller presented in [7] to achieve robust speed control of an IM. An applied conventional PI (Proportional Integral) controller as well as a Fuzzy controller has been presented in [5]. They reported that the performance of IM has been upgraded by means of starting current and rise time. The demonstrated performance of SPWM (Sinusoidal Pulse Width Modulation) presented in using different simulation technique combined with PI or FLC, the results shows a better performance of FLC. An adaptive FLC design technique using backtracking search algorithm has been presented in [8]. The results show it was better. FPI control strategy designed for IM is presented in [9] to control the speed in an improved manner. PI controller and FLC have been designed for IM drive in [7]. Fuzzy controller has been designed using TS fuzzy model. The results exposed that TSF controller showed improved performance by means of control delay to load variants. Adaptive FLC based on Levenberg–Marquardt algorithm presented in [10]. In this paper the results show that the controller is robust and is useful for load disturbance rejection. PI controller and FLC four based rules controller presented in [11] for a double star IM driven for its INFOC (Indirect Field Oriented Control). In this case, FLC shows better result than PI controller. The secondary vector model control method for a 3-phase Induction machine using soft calculating technique. ISM (Intellectual Speed Model) is being considered with fuzzy reasoning based controllers presented in [12] and simulated experimentations were done using MATLAB or SIMULINK to attain best results.

It is definitely a challenging task to design the speed controller for induction machines [13]. Some controllers show good performance in some attributes, as from the previous study firstly scalar methods are being looked for speed regulation of the IM. Scalar control drives are easily implemented but does not provide satisfactory results for high performance applications. Vector control technique was invented by Blaschke. Vector control technique provides a decoupling mechanism for IMs such as in DC machines by controlling the torque (Γ) and flux(Θ) independently. PI regulator is most extensively adopted in engineering uses because of its modest assembly, easy structure and a very little cost. Integral control can possess the effect of least error. It has an undesirable consequence on speed of reaction as well as whole firmness of the model. PD controller has the capability to forecast the upcoming fault in system thus increasing the stability of system. PID regulator is extensively used in business and electronic systems. It mainly possesses dynamic firm responses on variation in controller parameters (D controller). FLC is the approach of "if and then" declaration for the regulator and calculated the model of network is not an obligatory in fuzzy controller therefore it can be functional on nonlinear systems. Intellectual Speed Governor is also being planned using fuzzy reasoning controllers. Diverse simulation tests were approved for achieving the finest controller. The guidelines for the mentioned controller were aimed to deal with dynamic conduct. The acts of the presented fuzzy reasoning control relying on induction machine are related with traditional machine having PI controller at various operation circumstances. Results of fuzzy control model prove the progress in stability and dynamic response.

The literature survey concludes that to improve performance parameters of an IM either fuzzy logic or neural networks have been used. By employing these techniques there has been sufficient improvement in the performance parameters but still as per today's needs and demands, the parameters further need to be improved. Therefore, this research focuses on the use of hybrid control i.e. conventional PID controller with fuzzy supervisory control.

2. MATHEMATICAL FORMULATION

2.1 Reference Model of IM

Stator Reference Model: Stator reference model presented that, the axis remains staticon d-q axis [14]. In stator reference model stator and reference frame rotate at same speed, i.e. $\omega_c=0$.

Rotor Reference Model: Rotor reference model presented that, the d-q axes moves according to rotor's speed [15-16]. In rotor reference model stator and reference frame rotate at same speed, i.e. $\omega_c = \omega_r$ and $\theta_c = \theta_r$.

Synchronously Rotating Reference Model: Synchronously rotating reference model presented that, the d-q axes rotate with synchronous speed [15-16]. In synchronously rotating reference model stator and reference frame rotate at same speed, i.e. $\omega_c = \omega_r$ and ω_{st}.

$$\begin{bmatrix} V_{qs}^e \\ V_{ds}^e \\ V_{qr}^e \\ V_{dr}^e \end{bmatrix} = \begin{bmatrix} R_s + L_S \frac{d}{dt} & \omega_s L_s i_{ds}^e & L_m \frac{di_{qr}^r}{dt} & \omega_s L_s i_{dr}^r \\ -\omega_s L_s & R_s + L_S \frac{d}{dt} & -\omega_s L_m & L_m \frac{d}{dt} \\ L_m \frac{d}{dt} & (\omega_s - \omega_r) L_s & R_r + L_r \frac{d}{dt} & (\omega_s - \omega_r) L_s \\ -(\omega_s - \omega_r) L_m & L_m \frac{d}{dt} & -(\omega_s - \omega_r) L_r & R_r + L_r \frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{qs}^e \\ i_{ds}^e \\ i_{qr}^e \\ i_{dr}^e \end{bmatrix}$$

In control system, because of the constant variables of the motor, synchronously rotating reference frame is used [15-16].

2.2 Derivation of Transfer Function

To design a speed controller for an IM, we assume the constant rotor flux [14-15] i.e.

λ_r = constant and

$$\frac{d\lambda_r}{dt} = 0$$

As stator voltages are given;

$$V_{qs}^e = \left(R_s + L_s \frac{d}{dt} \right) i_{qs}^e + \omega_s L_s i_{ds}^e + L_m \frac{di_{qr}^e}{dt} + \omega_s L_s i_{dr}^e \tag{2}$$

$$V_{qs}^e = -\omega_s L_s i_{qs}^e + \left(R_s + L_s \frac{d}{dt} \right) i_{ds}^e - \omega_s L_m i_{qr}^e L_m \frac{di_{dr}^e}{dt} \tag{3}$$

Where, $\omega_{sl} = \omega_s - \omega_r$

$$V_{qs}^e = \left(R_s + \sigma L_s \frac{d}{dt} \right) i_{qs}^e + \omega_s i_{ds}^e (\sigma L_s) + \omega_s L_m \tag{4}$$

Similarly,

$$V_{ds}^e = \left(R_s + \sigma L_s \frac{d}{dt} \right) i_{ds}^e - \omega_s i_{ds}^e (\sigma L_s) + \frac{L_m}{L_r} \frac{d}{dt} (\lambda_r) \tag{5}$$

As we know that i_{ds} is constant in steady state and its derivative is zero so,

$$i_{ds}^e = i_f \tag{6}$$

$$\frac{di_{ds}^e}{ss} = 0 \tag{7}$$

Hence, the torque producing component is written in Equations (8-9):

$$i_{qs}^e = i_T \tag{8}$$

$$V_{qs}^e - \omega_r \left(L_s i_f\right) = \left(R_s + \frac{R_r L_s}{L_r} + L_a \frac{d}{dt}\right) i_T \tag{9}$$

We take Laplace transform of the torque producing current component such as:

$$i_T = \frac{V_{qs}^e - \omega_r\left(L_a i_f\right)}{R_a\left(1+\frac{sL_a}{R_a}\right)} \tag{10}$$

Now by substituting $K_a = \frac{1}{R_a}$ and $T_a = \frac{L_a}{R_a}$ and 1 in the above expression:

$$i_T = \frac{K_a}{\left(1+sT_a\right)} V_{qs}^e - \omega_r\left(L_s i_f\right) \tag{11}$$

With the help of voltage signal and speed feedback. The torque can be expressed as [15].

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r} \text{ if } i_T \tag{12}$$

$$K_t = \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r} \text{ if } i_T \tag{13}$$

Now substitute the value of K_t in Equations (12)

$$T_e = K_t i_T \tag{14}$$

The load dynamics is represented in electromagnetic torque and load torque [17].

$$J\frac{d\omega_m}{dt} + B\omega_m = K_t i_T - B_t \omega_m \tag{15}$$

$$T_t = B_t \omega_m \tag{16}$$

Equation (15) can be shown as [12]

$$d\left(\frac{P}{2}\omega_m\right)dt + B\left(\frac{P}{2}\omega_m\right) = \frac{P}{2}K_t i_T - B_t\left(\frac{P}{2}\omega_m\right) \tag{17}$$

$$\omega_r = \frac{P}{2}\omega_m \tag{18}$$

By substituting value of ω_r

$$J\frac{d\omega_r}{dt} + B\omega_r = \frac{P}{2}K_t i_T - B_t \omega_r \tag{19}$$

By taking Laplace transform of above expression

$$Js\omega_r(s) + \left(B + B_t\right)\omega_r(s) = \frac{P}{2}K_t i_T(s) \tag{20}$$

Where, $B + B_1 = B_t$

$$Js\omega_r(s) + B_t\omega_r(s) = \frac{P}{2}K_t i_T(s) \tag{21}$$

$$\omega_r(s)B_t\left(s\frac{J}{B_t}+1\right) = \frac{P}{2}K_t i_T(s) \tag{22}$$

$$\frac{\omega_r(s)}{i_T(s)} = \frac{P}{2}\frac{K_t}{B_t}\frac{1}{\left(s\frac{J}{B_t}+1\right)} \tag{23}$$

The above expression can be written as:

$$\frac{\omega_r(s)}{i_T(s)} = \frac{K_m}{1+sT_m} \tag{24}$$

The Equation (24) shows the relationship between the speed and current produced by the torque in terms of transfer function. The main parameters of the IM are specified in [16] (Table 1)

Once the transfer function is computed then we have find the performance parameters of the IM in terms of settling time, rise time and overshoot.

2.3 Open Loop Response of the System

It is significant to check the open loop response of system by computing the performance of the system and the performance is measured by characteristics like settling time, rise time and overshoot. The output characteristics response of the unit step open loop system is presented below in Fig.1 and Table 2.

TABLE 1. PARAMETER OF IM [16]

Quantity	Magnitude/Symbol
Power (P)	5 Hp
Rated voltage (V)	220 V
Poles (P)	P = 4
Stator resistance (R_s)	R_s=0.277?
Rotor resistance (R_r)	R_r=0.183?
Stator inductance (L_s)	L_s=0.0553H
Rotor inductance (L_r)	L_r=0.0583H
Frequency (f)	f=50 Hz
Mutual inductance (L_m)	L_m=0.0583H
Moment of inertia (J)	J=0.011667Kg-m
Settling time of plant (T_s)	T_S=10s
Time constant of speed filter (T_w)	T_w=0.002
Gain of current transducer (H_c)	H_C=0.333V/A
Steady state field current (i_f)	i_f=6A
Control frequency (F_c)	F_c=2000Hz

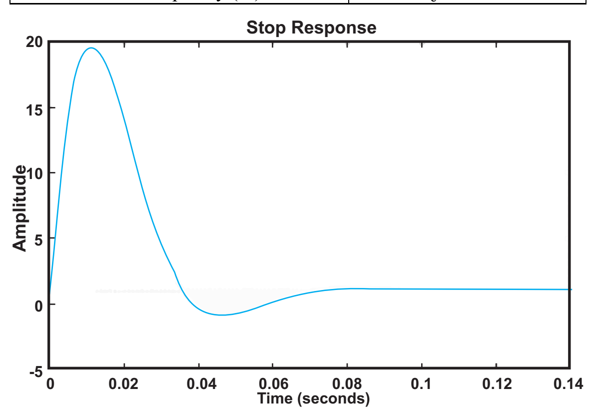

FIG. 1. OPEN LOOP RESPONSE OF THE SYSTEM

TABLE 2. PERFORMANCE PARAMETER OF THE SYSTEM

Performance Parameters	Open Loop Response of System
Rise Time (s)	3.0799e-04
Settling Time (s)	0.0651
Overshoot	1.7896e+03

A very high overshoot has been observed in the open loop response because of the system nonlinearity and harmonics present in the system parameters. As desired performance is described in [15], so the parameters are required to be improved. For that reason, it is important to design a controller.

3. CONVENTIONAL CONTROLLER

Conventional PD along with PID controller helps in controlling of Induction motors. The conventional controller is a feedback controller. The value of error can be calculated by the difference between the measured process value and the desired set point value. It drives the controlled plant to keep the steady state error equal to zero, so here we designed the PD and PID controllers to check the performance of IM. The conventional feedback controller block diagram is shown in Fig. 2.

3.1 Proportional Derivative Controller

PD controller is also used for the speed control of IM, the pros of using this controller is to reduce the settling time, rise time and the overshoot, significantly. Therefore, it increases the bandwidth of the system. But due to the derivative operation, the noise also get amplified resulting in a system which is suspicious to noise i.e. error, which may cause a system to be unstable. Here, we have designed the PD controller for the IM and following are the gain parameters of designed PD controller; K_p = 66101 and K_d = 2.2863. The response and performance parameters are given in Fig. 3 and Table 3.

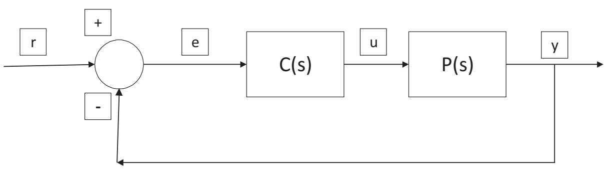

FIG. 2. FEEDBACK CONTROLLED SYSTEM BLOCK DIAGRAM [18]

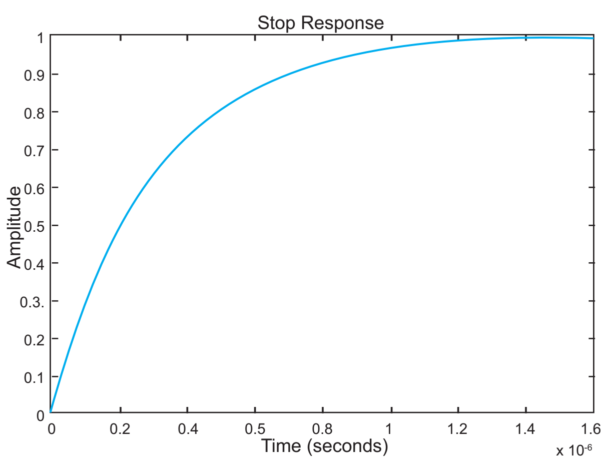

FIG. 3. STEP RESPONSE OF PD CONTROLLER

TABLE 3. PERFORMANCE PARAMETER OF THE PD CONTROLLER	
Performance Parameters	With PD Controller
Rise time (s)	6.6101e-07
Settling time (s)	1.1600e-06
Overshoot	0.0735

3.2 Proportional Integral Derivative Controller

PID controller is mostly applicable in control system of industries. PID controller has all basic features i.e. **D** controller shows fast reaction when the controller input changes. **I** controller increases the control signal which lead error towards the zero. **P** controller helps to eliminate the oscillations. Derivative mode improves the stability of system and enables increase in gain, $\mathbf{K_P}$ which increases speed of the controller response. The output of PID depends on the main three terms which are error signal, error integral and error derivative. The mathematical form is shown in Equation (25):

$$u(t) = K_P e(t) + K_I \int_0^t e(\tau)d\tau + K_D \frac{de(t)}{dt}$$

Where K_P, K_i and K_d are PI and Derivative gains respectively. It combines proportional, derivative and integral of the error signal which determine command signal 'u' for the system. In our case 'u' represents the T^*_e torque of the vector control drive for the induction motor.

The response and performance parameters of PID Controller are given below in the Fig.4 and Table 4.

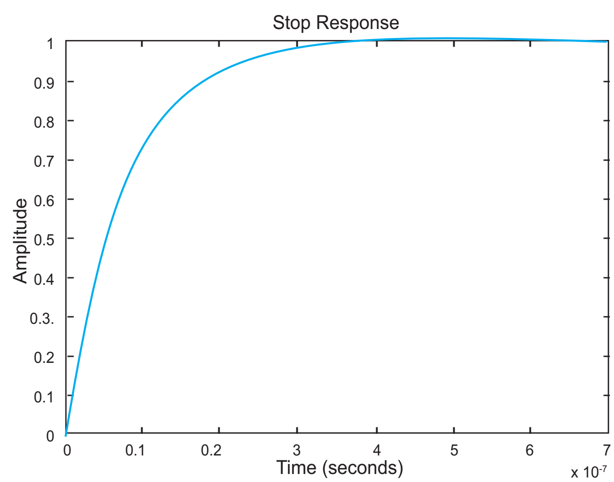

FIG. 4. STEP RESPONSE OF THE PID CONTROLLER

TABLE 4. PERFORMANCE PARAMETER OF THE PID CONTROLLER	
Performance Parameters	With PID Controller
Rise Time (s)	1.6668e-07
Settling Time (s)	2.9750e-07
Overshoot	0

It is necessary to mention that the performance degradation is the main drawback in PID controller because of parameter variations and this matter mostly arises because of fixed gain of the controller that influences on speed performance.

4. FUZZY CONTROLLER

Fuzzy control is basically applied through "if-then" statement for control process. The variables showed the antecedent (the if-part of the statement) and the consequent (the then-part of the statement). Thus, the non-linear system can be relied in this statement. Mamdani inference engine is used to map the input to their corresponding output. It is preferred over sugeno inference engine because it is more flexible and deal with the both MIMO (Multiple-Input and Multiple-Output) and MISO system Flow chart shown in Fig. 5, describes the methodology to search the solution using FLC system.

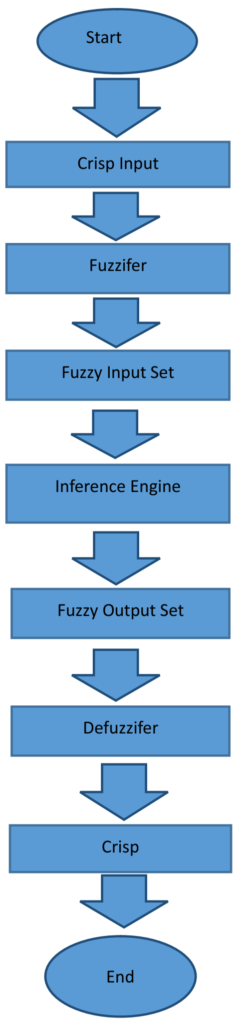

FIG. 5. FLOW CHART METHODOLOGY OF FUZZY LOGIC CONTROL

5. HYBRID FUZZY GAIN SCHEDULING OF PID CONTROLLER

Hybrid controller is designed with the incorporation of different controller. Here in our case, we have designed FGS-PID controller. In this way, we used the simple PID controller with the fuzzy controller to signify both overshoot and undershoot of the PID, which provides the optimized domino effects with the implementation of this model. Also with the help of hybrid model, it provides the increased levels of stability under different load variations.

To get the best optimized results, conventional controller is combined with the FC, hybridization of both controllers is proposed. In our proposed technique, hybrid controller works as the single controller for the speed control of the IM. In this technique, there are two input signals which are the error of the signal (E) and change in the error signal (CE) that is derivative of the error. A new error signal which is the output of the FC which is fed to the PID controller.

5.1 Inputs of Fuzzy Controller

Fuzzy controller uses "error" and "rate of change of error" as inputs. "Error" is the estimated difference between observed and true values of torque producing current

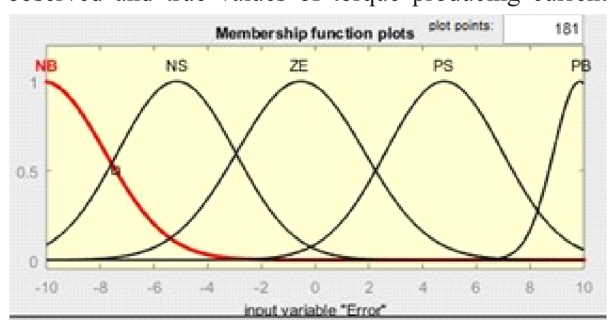

FIG. 6. MEMBERSHIP FUNCTION PLOT FOR ERROR

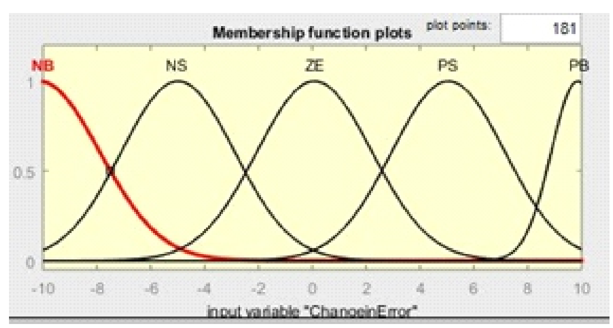

FIG. 7. MEMBERSHIP FUNCTION PLOT FOR CHANGE IN ERROR

TABLE 5.RULES BASE FOR THE FUZZY CONTROLLER

ECE	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PS	PB	PB

component of IM. These ranges have been partitioned as shown in Figs. 6-7. Here we use the ranges of "error" and "rate of change of error" are NL (Negative Large), NS (Negative Small), ZE (Zero), PS (Positive Small) and PL (Positive Large). There are different types of membership function i.e. triangular, Gaussian, trapezoidal. Here we use Gaussian membership function due to their smoothness and concise natures.

5.2 Rules Base for the Fuzzy Controller

The rules for the FLC is followed in this paper are given in Table 5.

5.3 Outputs of the Fuzzy Logic Controller

FLC output is the value of gain parameter for PID controller i.e. $\mathbf{K_p}$, $\mathbf{K_i}$ and $\mathbf{K_d}$. Fuzzy controller automatically adjusts the values of the gain parameters according to the load variations. The universe of discourse for these three gains have been selected after performing extensive simulations. The membership function corresponding to the controller outputs are as shown in Figs. 8-10.

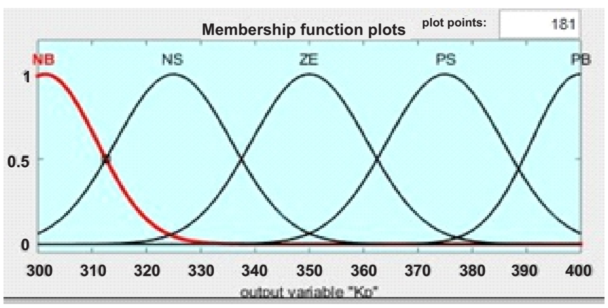

FIG. 8. MEMBERSHIP FUNCTION PLOT FOR K_p

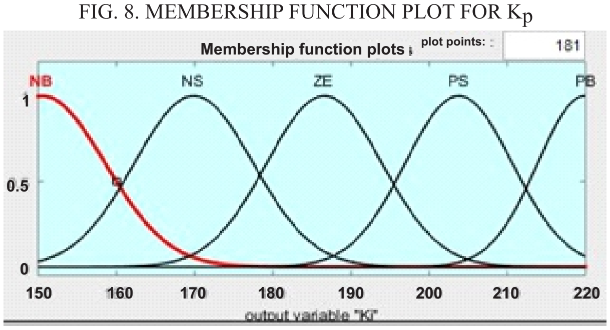

FIG. 9. MEMBERSHIP FUNCTION PLOT FOR K_i

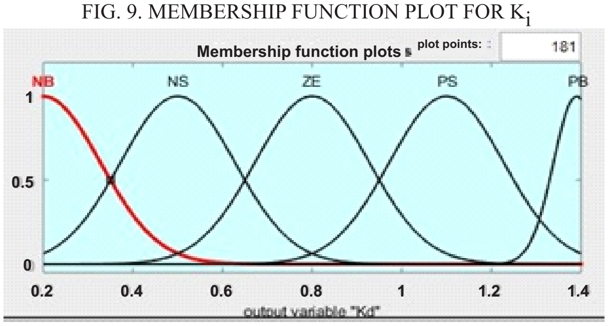

FIG. 10. MEMBERSHIP FUNCTION PLOT FOR K_d

The 3D surface view for the rules of $\mathbf{K_p}$ while considering the error and rate of change of error is shown in the Fig 11.

6. RESULTS AND DISCUSSIONS

As we have discussed earlier that our main aim is to control the speed control of IM as a purpose, we have designed the conventional controller i.e. PD and PID controller. By using these controllers, the system response become fast, as shown in Table 6. In Table 6, we do the comparison of open loop response of the system with the closed loop PD and PID control responses of the system.

The analysis indicates that overshoot value has decreased from, $1.7896\text{x}10^{3}$% to 0.0735% in PD and $1.7896\text{x}10^{3}$% to 0% in PID. Rise time improved from $3.0799\text{x}10^{-4}$s to $6.6101\text{x}10^{-7}$s in PD and $3.0799\text{x}10^{-4}$s to $1.6668\text{x}10^{-7}$s in PID. Settling time has improved from 0.0651s to $1.1600\text{x}10^{-6}$s in PD and 0.0651s to $2.9750\ \text{x}10^{-7}$s in PID. So the system response become fast.

Due to the limitations of the conventional controllers we designed FGS-PID controller. The results of FGS-PID controller are presented in Table 7. Considering, a case in which we change the load and according to the load variation the values of error and change in error become [-7 7] then the value of K_p, K_i and K_d are automatically updated at the values of error and change in error as shown in Fig. 12 and the step response is given in Fig. 13 respectively. At this stage, the PI and derivative gains will be 341,180 and 0.69 respectively. If we change the error values, gains will change accordingly as shown in Figs. 12-13 and Table 7.

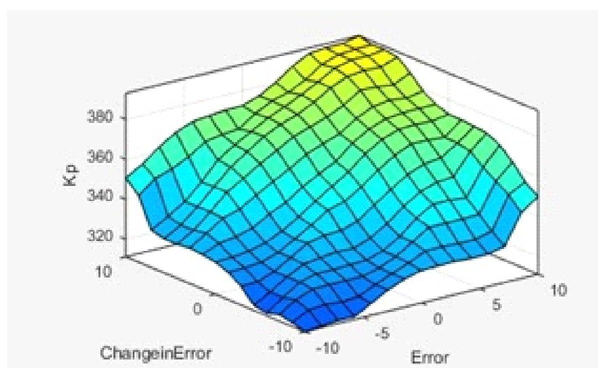

FIG. 11. 3D SURFACE VIEW

TABLE 6. COMPARISON BETWEEN ALL THE CONVENTIONAL

Performance Parameters	Step Response of System	With PD Controller	With PID Controller
Rise time (s)	3.0799e-04	6.6101e-07	1.6668e-07
Settling time (s)	0.0651	1.1600e-06	2.9750e-07
Overshoot	1.7896e+03	0.0735	0

We demonstrated from Table 7 that the FGS-PID for the IM has better performance over the conventional controller. The results in Table 7 show that if the values of "error" and "rate of change of error" is in between the designed (-10 to 10) values, the FGS set the gain values for PID controller to get the better results.

7. CONCLUSION

In this paper, our primary focus is to design a fuzzy supervisory controller to tune the classical PID controller and compare the performance of PID, PD controller and Fuzzy supervisory controller. In the first stage, we designed the PID and PD controller. The analysis indicates that the system response become fast. Conventional PID controller is extensively used but it has constant parameters, due to any change in the parameters, the controller has to re-adjust its gain values, so it is unreliable in case of noise, so to deal with this uncertainty FGS-PID controller is designed. In order to design a control system having fuzzy logic, various input and output ranges were assumed. Two different inputs were assumed for the controller which are "error" and "rate of change of error" for the following outputs i.e. K_p, K_i and K_d. Gaussian membership functions were used for the conversion of the crisp values into their respective fuzzy values. Rules were designed after repeated simulations and to map the input to their corresponding output Mamdani's Inference Engine is used. MATLAB plays a vital role in performing all these simulations and steps. Performance of FGS-PID controller have been assessed under different operating conditions, performance of the IM is evaluated by the control parameters i.e. peak overshoot, settling time and rise time, we demonstrated that the FGS-PID controller for the IM has improved performance above the PID controller. From the results it is cleared that if the "error" and "rate of change of error" is in between the designed (-10 to 10 unit), the FGS adjusts the gain values for PID controller to get desired performance. On the basis of the simulated results, the dynamic response takes less time to meet the steady state and controller shows better response under the quick load changes as compared with the other conventional PD and PID controller.

TABLE 7. GAIN VALUES AT RANDOM VALUES OF "ERROR" AND "CHANGE IN ERROR"

[Error, Change in Error]	K_p	K_i	K_d	Rise Time (s)	Settling Time (s)	Over Shoot
[0,0]	351	187	0.809	3.2904e-09	5.8594e-09	0
[0,0.5]	351	187	0.814	3.2740e-09	5.8300e-09	0
[0.5,0]	352	188	0.828	3.2184e-09	5.7311e-09	0
[-7,7]	341	180	0.69	3.8587e-09	6.8712e-09	0
[0,10]	373	202	1.07	2.4880e-09	4.4304e-09	0
[-10,0]	327	171	0.528	5.0451e-09	8.9842e-09	0
[-10,10]	351	187	0.808	3.2972e-09	5.8713e-09	0

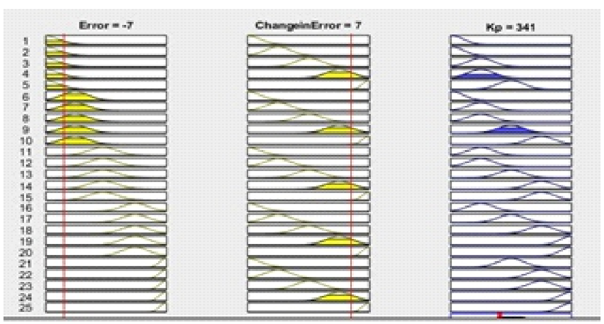

FIG. 12. VALUE OF Kp AT [-7 7]

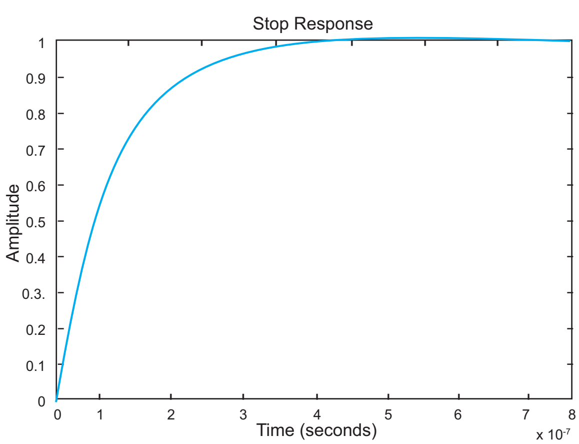

FIG. 13. FGS-PID CONTROLLER OUTPUT AT [-7 7]

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