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PID and PID-Fuzzy controllers for BLDC motor in Electric Vehicles

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Abstract: In present days to obtain the desired characteristics in Electric vehicles, the speed control of electric motor is necessary. This paper mainly concentrates on the fuzzy logic based closed loop speed control of BLDC motor. As due to the many advantages of BLDC motor like electronic commutation, high torque production, wide speed range, longer life, less maintenance, etc gained popularity and been used in Electric vehicles and many industrial process. The BLDC motor drive with non linear characteristics requires a non linear controller like fuzzy logic controller to tune the PID controller. The speed of the BLDC motor can be controlled under dynamic load conditions and varying set speed or reference speed using fuzzy tuned PID controller. The PID-Fuzzy controller shows better performance than conventional PID controller and fuzzy controller minimizes the drawbacks of conventional PID controller. The results are compared between conventional PID controller with PID-Fuzzy controller by carrying out the simulation process using MATLAB/SIMULINK software.

Keywords: Electric vehicle (EV), Brushless DC (BLDC) motor, Proportional-Integral-Derivative (PID) controller, Fuzzy logic controller (FLC).

I. INTRODUCTION

In recent trends Permanent Magnet motors are widely been used in electric vehicle (EV), particularly BLDC motor is the one mostly used due to its various beneficial factors. BLDC motors also have applications in Robotics, Aerospace, Industries, Automotive and many more. Due to the ease of speed control and availability of wide speed range the Conventional DC motor are used in electric vehicles but there is problem with brushes like electric erosion and friction. Hence there is an option for switching to Brushless DC motors which are low in maintenance, electronically commutated, wide speed ranges, high torque and high efficiency, etc.

The conventional PID controller provides conventional method for the speed control of BLDC motor which has non-linear characteristics [1]. We can implement PID controller with simple algorithms and it is robust and are likely used where we require control on stability [2]. Expertise knowledge is required in order to tune the gains of PID controller for system control to obtain better performance. On the other hand modelling of BLDC motor and control technique selection is very difficult and plays the major role in speed control process.

Exact mathematical model of system is not necessary to implement the fuzzy logic and PID controller gains can be adjusted according to the requirement [5].

By using PID controller we can control the system only after the error occurrence but not instantly. In sensor less systems, the control becomes very complex and difficult, also has poor transient response and speed range is very narrow. Even though the cost of system is very less for the sensor less control it is not preferred in many of the systems due to its drawbacks. Hence the three phases of BLDC motor are excited by the inverter based on the rotor position which is sensed by the Hall Effect sensors available on the stator of BLDC motor.

The PID control can be replaced with fuzzy logic controller (FLC) [3][4] due to its simplicity and it provides better efficiency, but it also have demerits like lack of dimensionality and robustness of the system. With the combination of PID and fuzzy logic controller, both the merits can be combined such as speed error can be rectified, manual interference can be avoided, robustness of the system, etc. For a particular speed range using conventional PID controller we can have the speed control by fixed values of K_P, K_D and K_I gains. For wide speed range it is not possible to fix these gain values. Hence there is need of

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adjusting gains based on the motor speed variation in order to obtain a better performance. This can be achieved by implanting PID-Fuzzy controller in a system. Now without any manual interference the control gains K_P, K_D and K_I can be updated by using the PID-Fuzzy controller in order to get and optimised response.

II. Block Diagram For Speed Control Of BLDC Motor

The block diagram below shows that it has two loops, the outer loop and the inner loop. The outer loop is used for speed control and the inner loop is used to provide hall sensors communication to the inverter circuit. By varying the inverter output, the input to the motor can be varied and the speed can be controlled. The block diagram for speed control process is shown in Fig 1.

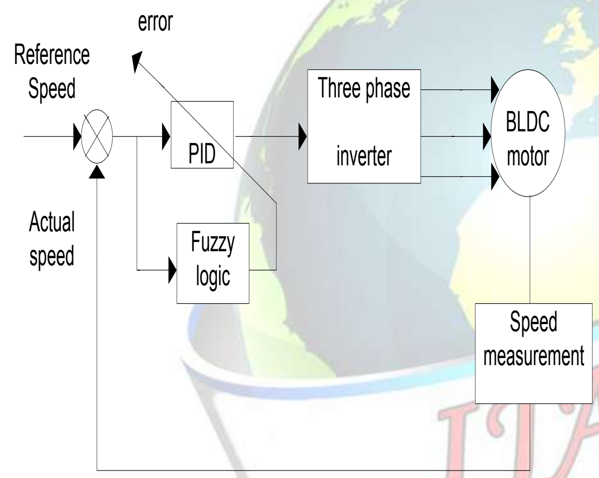

Fig 1. Block diagram indicating speed control of BLDC motor

The position and the speed of the rotor is sensed by the hall sensors which are available on the stator of BLDC motor. The rotor position is sensed and this information is used to provide the sequence for turn ON and OFF of the inverter switches and inverter supplies to the BLDC motor. The rotor starts rotating when coils on the stator are energized by the supply provided by the inverter to the motor which intern produces the required magnetic field. The speed error can be obtained by comparing the motor speed from hall sensors with the reference speed.

In this speed control process the inverter is controlled by Back EMF zero crossing detection method. Here the hall sensors which are 120 degrees apart on the stator give the rotor position. By combining the reference current from the current generator and the rotor position information, the EMF signals are generated by the decoder block. Table I shows the logic followed by the Back EMF zero crossing points. After detecting EMF zero crossing points, these signals are again passed through another logic circuit for the generation of the pulses. These pulses are given to the six switching devices of the inverter in order to control the inverter output. Table II shows the generation of pulses.

TABLE I BACK EMF ZERO CROSSING POINTS DETECTION

TABLE II SEQUENCE OF INVERTER SWITCHES

Switching states of six switches					
Q1	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**
0	0	0	0	0	0
0	0	0	1	1	0
0	1	1	0	0	0
0	1	0	0	1	0
1	0	0	0	0	1
1	0	0	1	0	0
0	0	1	0	0	1
0	0	0	0	0	0

Sequence No	Hall signals at Back-EMF zero crossing points					
	Hall signals			Back-emf		
	Ha	**Hb**	**Hc**	**Ea**	**Eb**	**Ec**
1	0	0	0	0	0	0
2	0	0	1	0	-1	+1
3	0	1	0	-1	+1	0
4	0	1	1	-1	0	+1
5	1	0	0	+1	0	-1
6	1	0	1	+1	-1	0
7	1	1	0	0	+1	-1
8	1	1	1	0	0	0

III. Mathematical Modelling Of BLDC Motor

The motor with permanent magnet rotor which has flat toped trapezoidal back EMF wave form is called as Brushless DC motor. BLDC motor is supplied by the inverter which has six switches. The inverter supplies for any of the two phases of the motor at a time while leaving

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the third phase inactive. The hall sensors which are provided on the stator gives the rotor position in order to provide information to the inverter circuit about switching sequence of the transistors. The hall sensors are placed 120 degrees apart on the stator of the BLDC motor.

The following assumptions are made while modelling the BLDC motor. Considering the inverter switches as ideal, stator is Y connected, the inductance and resistance of all the phases are equal and not considering the hysteresis losses and the core losses [6].

The electrical equivalent circuit of BLDC motor is shown in Fig 2.

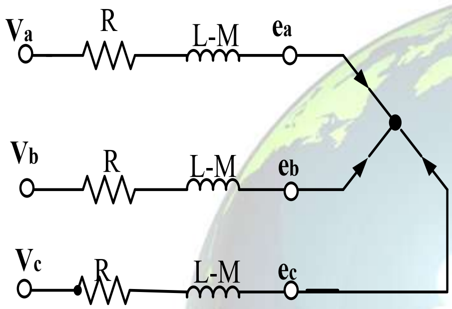

Fig 2. Electrical equivalent circuit of BLDC motor

Representation of electrical and mechanical systems in form of equations is shown below

$$V_a = Ri_a + (L-M)\frac{di_a}{dt} + e_a \quad (1)$$

$$V_b = Ri_b + (L-M)\frac{di_b}{dt} + e_b \quad (2)$$

$$V_c = Ri_c + (L-M)\frac{di_c}{dt} + e_c \quad (3)$$

EMF equations for each phases is given below

$$e_a = K_e\omega_m F(\theta_e) \quad (4)$$

$$e_b = K_e\omega_m F(\theta_e - 2\pi/3) \quad (5)$$

$$e_c = K_e\omega_m F(\theta_e + 2\pi/3) \quad (6)$$

The electromagnetic torque given by three phases is

$$T_a = K_t i_a F(\theta_e) \quad (7)$$

$$T_b = K_t i_b F(\theta_e - 2\pi/3) \quad (8)$$

$$T_c = K_t i_c F(\theta_e + 2\pi/3) \quad (9)$$

Total effective torque is given as

$$T_e = T_a + T_b + T_c \quad (10)$$

The complete electromechanical system with representation as equation is given as

$$T_e - T_l = J\frac{d^2\theta_m}{dt^2} + \beta\frac{d\theta_m}{dt} \quad (11)$$

$$\theta_e = p/2\,\theta_m \quad (12)$$

$$\omega_m = \frac{d\theta_m}{dt} \quad (13)$$

From equations (1), (2), (3) and (7)

$$V_{ab} = R(i_a - i_b) + (L-M)\frac{d(i_a - i_b)}{dt} + e_{ab} \quad (14)$$

$$V_{bc} = R(i_b - i_c) + (L-M)\frac{d(i_b - i_c)}{dt} + e_{bc} \quad (15)$$

Ignoring the mutual inductances and, $i_a+i_b+i_c=0$ the above equations can be rewritten as,

$$\frac{di_a}{dt} = -\frac{R}{L}i_a + \frac{2}{3L}(V_{ab} - e_{ab}) + \frac{1}{3L}(V_{bc} - e_{bc}) \quad (16)$$

$$\frac{di_b}{dt} = -\frac{R}{L}i_b - \frac{1}{3L}(V_{ab} - e_{ab}) + \frac{1}{3L}(V_{bc} - e_{bc}) \quad (17)$$

Where K= a, b, c
V_k= voltage of Kth phase of BLDC motor
i_k= current of Kth phase of BLDC motor
e_k= back Emf of Kth phase
T_k= torque produced by the Kth phase
R= resistance per phase of BLDC motor
L= inductance per phase of BLDC motor
M= mutual inductance between phases
T_e= electromagnetic torque produced by motor
K_e= Emf constant
K_t= torque constant
ω_m= angular speed of rotor
θ_m= mechanical angle of rotor
θ_e= electrical angle of rotor
J= moment of inertia of the mechanical system
β= damping coefficient

TABLE III which indicates the specifications of the BLDC motor used in this experiment.

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TABLE III SPECIFICATIONS OF BLDC MOTOR

BLDC Motor model	23F-2
Wattage	60W
DC Voltage	24V
Speed	1500RPM
Stator phase resistance	2.875Ohm
Stator phase inductance	8.5Mh
Torque constant	1.4 N-M/A
Rotor inertia	$0.8*10^{-3}Kg\text{-}m^2$
Friction constant	$1*10^{-3}$

IV. Speed Controller Design

Controller returns the actual speed of the motor to the reference speed, even though the reference speed is changing continuously. This part of the paper deals with the design of PID and PID-Fuzzy controllers.

A. Proportional-Integral-Derivative controller

In order to meet required performance of the system, PID controllers are made with different combinations of Proportional, Integral and derivative controllers. They can be used in single number or multiple. Here the parallel integration of individual P, I, D controllers is considered.

The characteristics of Proportional, Integral and Derivative controllers are applicable to the Fig 3. PID controller has the transfer function c(s), given below

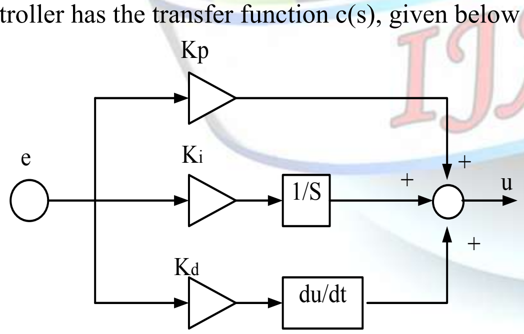

Fig 3. Block diagram of basic PID controller

$$C(s) = K_p + \frac{K_i}{s} + K_D s \quad (18)$$

$$C(s) = \frac{K_D S^2 + K_p s + K_i}{s} \quad (19)$$

Here K_P, K_D and K_I are called the Proportional, Integral and Derivative gain constants respectively, u is called control signal.

The control signal can be given as summation of K_P time of the error, K_D times of the derivative of the error and K_I times of the integral of the error. PID controllers are used where the simplicity of the controller is required. K_P, K_D and K_I are calculated using Zigler-Nicholos method.

K_p	K_i	K_d
2.35	666.7	0.0015

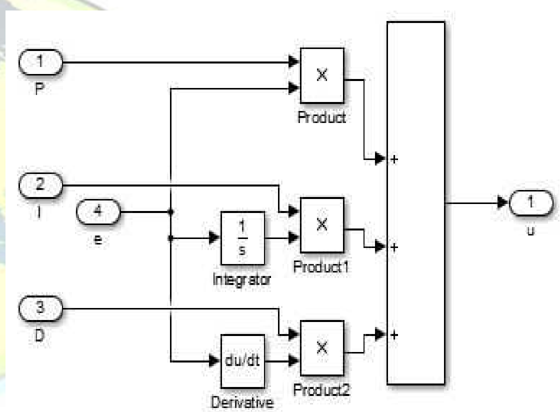

Fig 4. PID controller Simulink model

B. Fuzzy logic controller

When the system set point and load are dynamic the fuzzy logic controller helps to provide optimised output using PID controller. Based on the varying reference speed the fuzzy logic updates the K_P, K_D and K_I values to get the effective output, hence the gain values are determined by the fuzzy logic controller. There are two inputs to the Fuzzy-PID controller those are error and change in error and has three variable output K_P, K_D and α, where K_I is given by α. The gains K_P, K_D are normalised between 0 and 1 and α has the range of 1 to 5. The overall simulation model of closed loop speed control of BLDC motor is shown in Fig 5.

In this paper Mamdani fuzzy inference system is considered. Where a set of fuzzy rules are determined, the two inputs are fuzzified using the membership functions at the input side, establishing the rule strength by mixing created fuzzy rules with fuzzified inputs, the rule strength and the output membership functions are brought together to

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get consequences, after getting all the consequences the output distribution is defined and there by defuzzifying the output distribution. The Fig 6 shows the process involved in Mamdani fuzzy inference systems. The output value of Mamdani type is given in the equation (20).

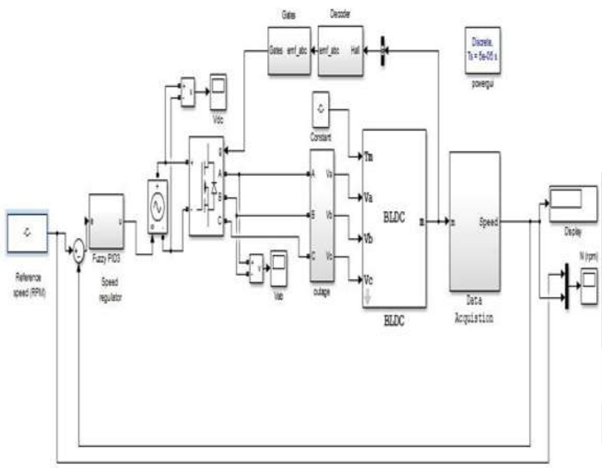

Fig 5. Overall Simulation model of closed loop speed control of BLDC motor using PID-Fuzzy controller

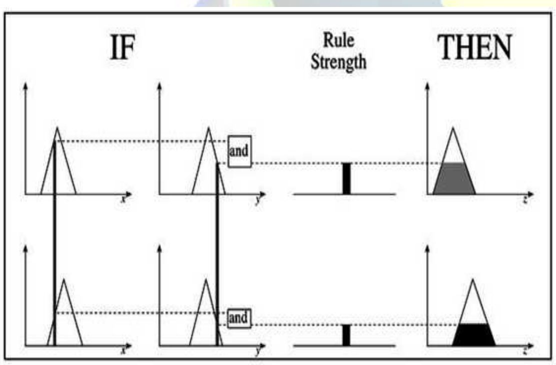

Fig 6. Illustration of Mamdani type defuzzification

$$y = \frac{\int u_Y(y).ydy}{\int u_Y(y)dy} \quad (20)$$

$$K_i = K_p^2/\alpha K_d \quad (21)$$

As discussed the Mamdani fuzzy type has two inputs. The different linguistic variables of the fuzzy logic set are PB, PM, PS, Z NB, NM, NS i,e Positive Big, Positive Medium, Positive Small, Zero, Negative Big, Negative Medium, Negative Small are used in input membership functions which are shown in Table IV, Table V and S, B i,e Small and Big are used in output membership functions.

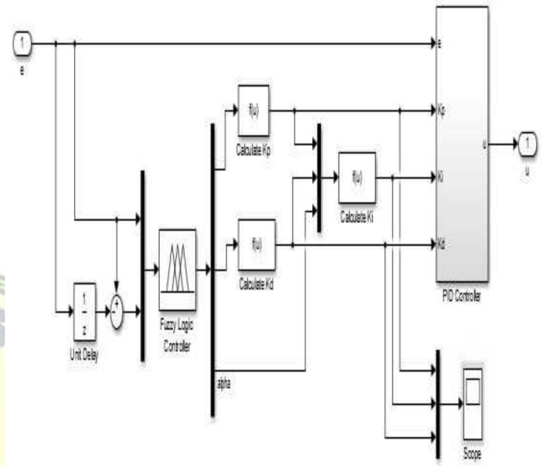

Fig 7. Subsystem of PID-Fuzzy controller

TABLE IV FUZZY RULES FOR K_P

		Δe(k)						
		NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
e(k)	**NB**	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
	ZO	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

TABLE V FUZZY RULES FOR K_D

		Δe(k)						
		NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
e(k)	**NB**	S	S	S	S	S	S	S
	NM	B	B	S	S	S	B	B
	NS	B	B	B	S	B	B	B
	ZO	B	B	B	B	B	B	B
	PS	B	B	B	S	B	B	B
	PM	B	B	S	S	S	B	B
	PB	S	S	S	S	S	S	S

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TABLE VI FUZZY RULES FOR α

		Δe(k)						
		NB	NM	NS	ZO	PS	PM	PB
e(k)	NB	2	2	2	2	2	2	2
	NM	3	3	2	2	2	3	3
	NS	4	3	3	2	3	3	4
	ZO	5	4	3	3	3	4	5
	PS	4	3	3	2	3	3	4
	PM	3	3	2	2	2	3	3
	PB	2	2	2	2	2	2	2

The output membership functions for K_P, K_D and α are shown in the Fig10, Fig 11, Fig 12. The gains K_P, K_D and K_I can be obtained by the system tuning based on Ziegler Nichols method as the fuzzy controller output. The input membership functions are shown in Fig 8 and Fig 9.

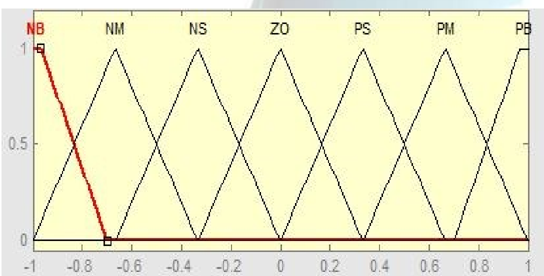

Fig 8. Membership function for input e(t)

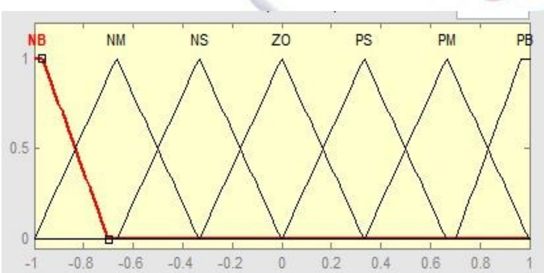

Fig 9. Membership function for input Δe(t)

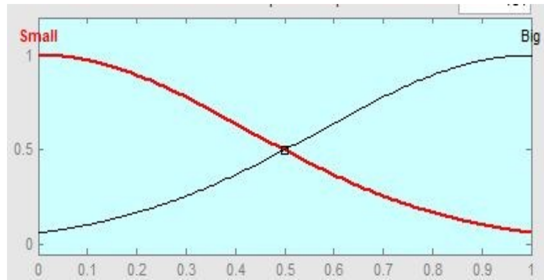

Fig 10. Membership function for output K_P

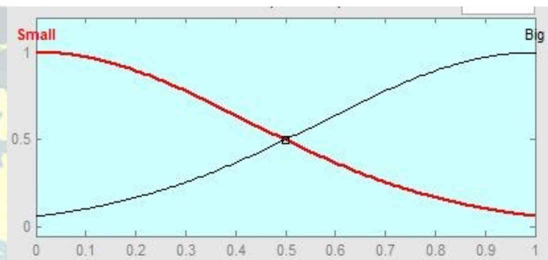

Fig 11. Membership function for output K_D

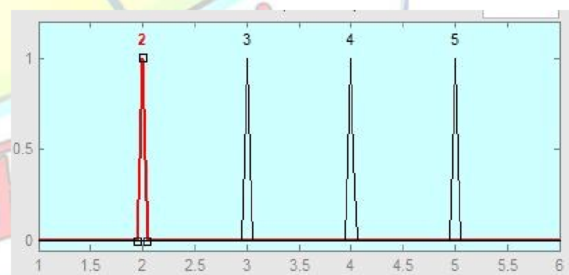

Fig 12. Membership function for output α

V. Simulation Results And Discussion

A set of measurements are carried out in order to conduct the performance analysis on the system. The comparison between the conventional PID controller and PID-Fuzzy controller for the speed control of BLDC motor is evaluated and the performance is analysed, shown in Table VII. The rise time (t_r), settling time (t_s) and overshoot (M_p) are the different characteristic parameters to be considered.

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TABLE VII PERFORMANCE ANALYSIS

controller	Load(N-m)	Ref-speed	T_s(msec)	T_r(msec)	M_p
PID	3	1000	154	15	2.8
	3	1500	158	20	2.9
	5	1000	230	28	2.8
	5	1500	220	33	3.2
PID-Fuzzy	3	1000	38	21	4.7
	3	1500	59	31	3.2
	5	1000	48	30	4.4
	5	1500	90	41	3.6

A 3-Ph, 24V, 60W BLDC motor with a rated speed of 1500rpm is considered and simulation is carried out. The results are compared between PID and PID-Fuzzy controllers for speed control of BLDC motor under conditions like varying reference speed and change in load. The Back EMF wave form and stator currents for three phases are shown in Fig 13 and Fig 14, when the motor is running at 3N-m with a speed of 1000rpm.

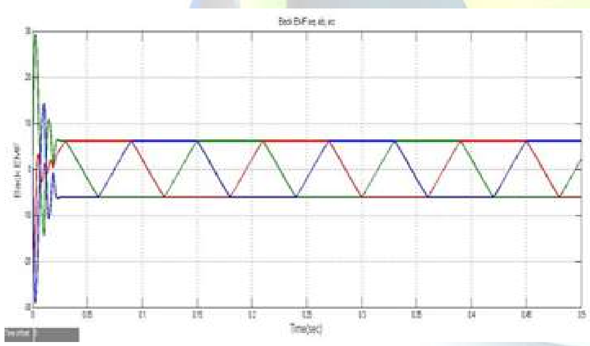

Fig 13. Back EMF wave forms for three phases

Under the loaded condition from the Fig 15, Fig 16, the speed response using PID controller has rise time of 15msec and settling time of 154msec at 1000rpm and 3N-m. On the other hand the speed response using PID-Fuzzy controller has rise time of 21msec and settling time of 38msec at 1000rpm and 3N-m load, which shows the better performance than conventional PID controller.

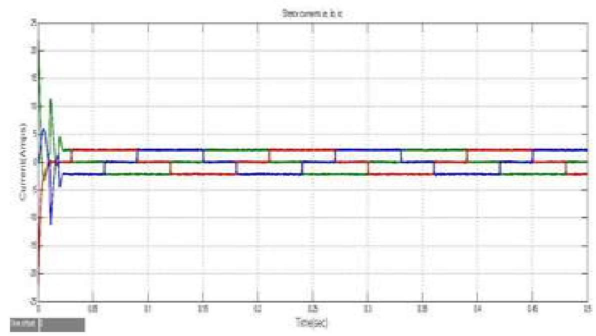

Fig 14. Stator currents for three phases

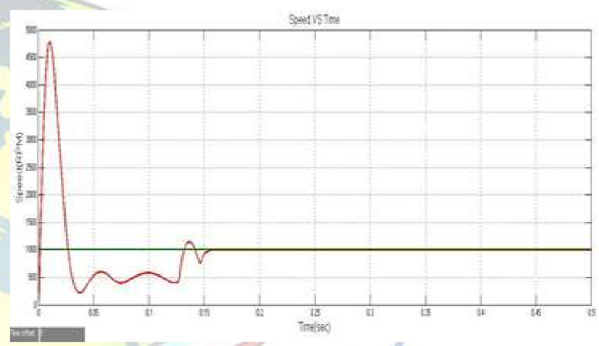

Fig 15. Speed response using PID at 1000rpm, 3N-m

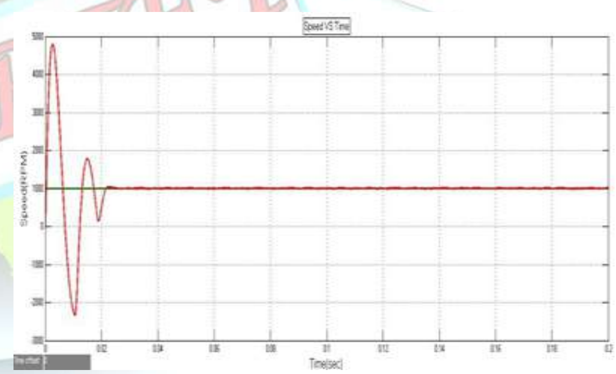

Fig 16. Speed response using PID-Fuzzy at 1000rpm, 3N-m

Now the reference speed is changed to 1500rpm and load at 3N-m, the speed response using PID controller has rise time of 20msec and settling time of 158msec. On the other hand the speed response using PID-Fuzzy controller has rise time of 31msec and settling time of 59msec, the response is shown in Fig 17 and Fig 18.

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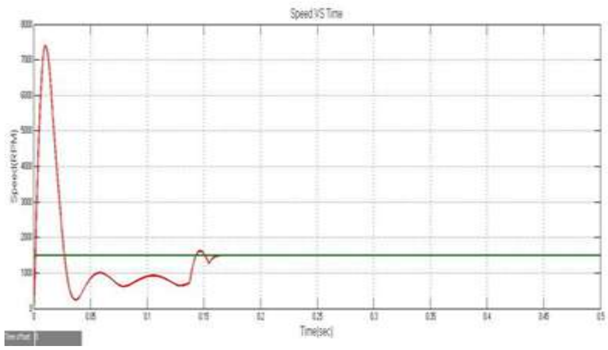

Fig 17. Speed response using PID at 1500rpm, 3N-m

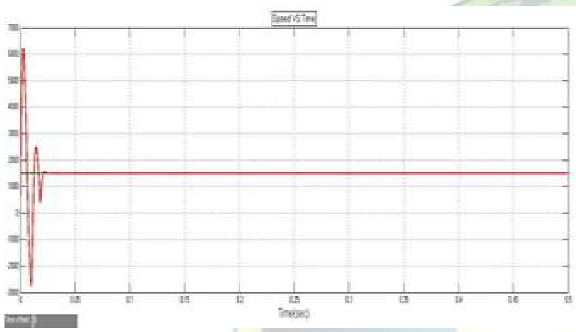

Fig 18. Speed response using PID-Fuzzy at 1500rpm, 3N-m

Here the reference speed is again changed to 1000rpm and load to 5N-m, the speed response using PID controller has rise time of 28msec and settling time of 230msec and the speed response using PID-Fuzzy controller has rise time of 30msec and settling time of 48msec, the response is shown in Fig 19 and Fig 20.

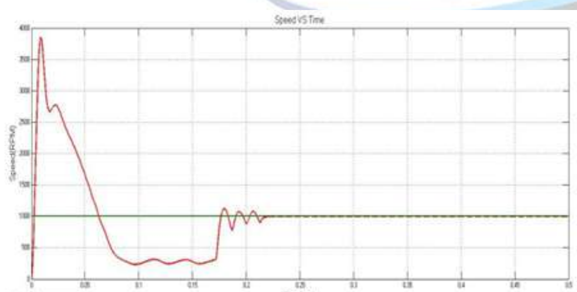

Fig 19. Speed response using PID at 1000rpm, 5N-m

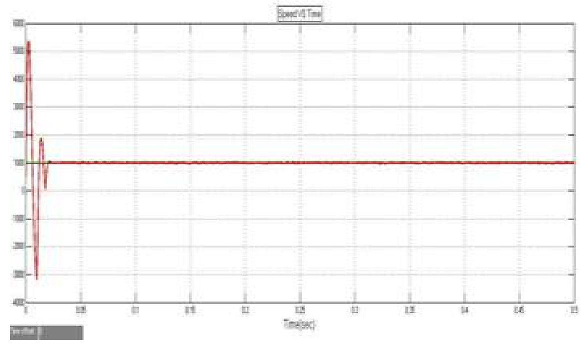

Fig 20. Speed response using PID-Fuzzy at 1000rpm, 5N-m

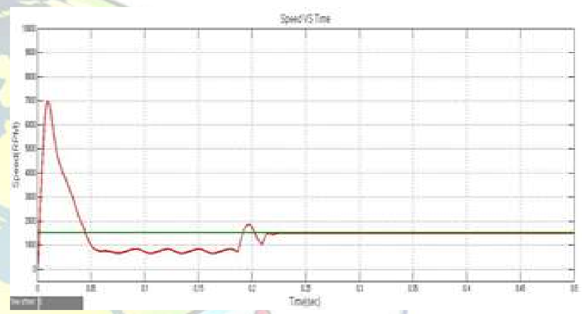

Fig 21. Speed response using PID at 1500rpm, 5N-m

Now the reference speed is changes to 1500rpm and load at 5N-m, the speed response using PID controller has rise time of 33msec and settling time of 220msec and the speed response using PID-Fuzzy controller has rise time of 41msec and settling time of 90msec, the response is shown in Fig 21 and Fig 22.

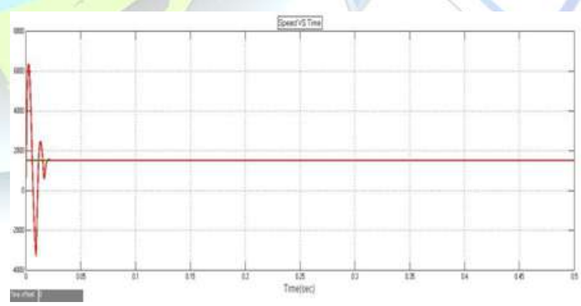

Fig 22. Speed response using PID-Fuzzy at 1500rpm, 5N-m

This shows that PID-Fuzzy controller speed response is superior to that of conventional PID controller response and the steady state can be achieved fast by using Fuzzy tuned PID controller

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VI. CONCLUSION

This paper resulted the simulation of closed loop speed control of BLDC motor using PID and PID-Fuzzy controllers. Under the condition of varying set point and dynamic load, the speed of BLDC motor is controlled by the PID controller whose gains are continuously been updated by Fuzzy controller for improved performance. By comparing the simulation results of speed control using conventional PID controller and the Fuzzy tuned PID controller, it is observed that the response can reach steady state faster and the system has less settling time by using the PID-Fuzzy controller.

REFERENCES

[1]. Vinod KR Singh Patel, A.K.Pandey "Modeling and Performance Analysis of PID Controlled BLDC Motor and Different Schemes of PWM Controlled BLDC Motor"International Journal of Scientific and Research Publications, Volume.

[2]. Atef Saleh Othman Al-Mashakbeh,(2009) " Proportional Integral and Derivative Control of Brushless DC Motor", European Journal of Scientific Research,(ISSN 1450-216X Vol.35 No.2, pp.198-203).

[3]. ChuenChien Lee, "Fuzzy Logic in Control Systems:Fuzzy Logic controller–Part1"1990 IEEE. 4. huenChien Lee, "Fuzzy Logic in Control Systems : Fuzzy Logic controller Part 2" 1990 IEEE

[4]. A.Kiruthika, A.Albert Rajan, P.Rajalakshmi "Mathematical modelling and Speed control of a Sensored Brushless DC motor using Intelligent controller" 2013 IEEE International Conference on Emerging Trends in Computing, Communication and Nanotechnology (ICECCN2013)

[5]. Zhen-Yu Zhao, Masayoshi Tomizuka, and Satoru Isaka, " Fuzzy Gain Scheduling of PID Controllers" IEEE TRANSACTIONS On Systems, Man and Cybernetics. Vol. 23, No. 5. September/october 1993.

[6]. R. Krishnan, "Electric Motor Drives : Modeling, Analysis, and Control," Prentice Hall, 2001, pp. 577-580.

[7]. T.Saarulatha,V.Yaknapriya,T.Muthukumar3, S.Saravanan, "Proportional Integral &Derivative Controller For BLDC Motor" (IJAER) 2014, Vol. No. 8, Issue No. V, November.

[8]. Vikas Maske, Mithlesh Kumar Yadav, Abhay Halmare, "Mathematical Modeling and Simulation of BLDC motor for Performance Analysis Using MATLAB/SIMULINK" (IJEREEE) Vol 4, Issue 3, March 2018.

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