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A COMPARATIVE STUDY OF FUZZY LOGIC CONTROLLERS FOR BLDC MOTOR DRIVE

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ABSTRACT

The development of high performance variable speed brushless dc motor drive is very important in all industrial applications. Generally, a high performance BLDC motor drive system must have good dynamic speed response, reference speed command tracking capability and load regulating response. Conventional controller such as PI, PID does not provide good dynamic response due to the problem of non-linearity, difficulty in the tuning of controller parameters. With the fast growing of intelligent controllers for precise motor speed control, fuzzy logic controllers are taken in this paper. This paper demonstrates a comparative study of PI, fuzzy logic, hybrid fuzzy PID controllers using MATLAB/SIMULINK environment.

Keywords: BLDC motor, fuzzy logic, PI, hybrid fuzzy PID controller, back EMFs, speed control.

1. INTRODUCTION

Brushless D.C (BLDC) synchronous motors have been used in various fields of industrial applications for their high power/weight, high torque, high efficiency, long operating life, noiseless operation, high speed ranges and ease of drive control [1]. Permanent Magnet Brushless DC (PMBLDC) motor is defined as a permanent magnet synchronous motor with a trapezoidal Back EMF waveform [2]. BLDC motors do not have brushes for commutation. They are electronically commutated [3]. For the variable speed applications of BLDC motor, Proportional, Integral and Derivative (PID) motor control is commonly used control [4].Because; it has simple design and ease of control. However, its performance depends on proportional, integral and derivative gains [5-6]. When the operating condition changes, the re-tuning process of control gains is necessary for dynamically minimize the total controller error. The various algorithms are used to find optimal PID controller parameters such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) [7-10].Particle Swarm Optimization (PSO) and genetic algorithm (GA) is given based on population size, generation number, selection method, and crossover and mutation probabilities. There is no guarantee for finding optimal solutions for controllers within a finite amount of time. To overcome the problems in PID controller, fuzzy logic controller and hybrid fuzzy PID controllers can be designed for the speed control of BLDC motor. In this proposed research work, the speed control of BLDC motor was analyzed and its performance has been observed by using fuzzy logic controller and hybrid fuzzy PID [11-13].The simulation results of two methods are studied and compared with conventional PI controller by using MATLAB/SIMULINK computational software. The simulation results of proposed controllers are used to show the abilities and shortcomings of conventional PI controller.

2. CLOSED LOOP MODEL OF BLDC MOTOR

The BLDC motor drive system consists of permanent magnet synchronous motor fed by a three-phase inverter.Figure1 shows the overall closed loop system configuration of three phase BLDC motor drive.
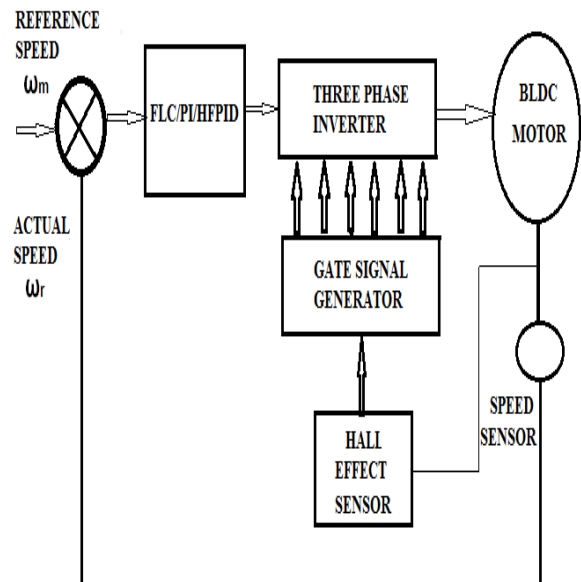

Figure-1. Block diagram of PMBLDC drive.

In the inner loop, Hall Effect sensor provides position information for gate signal generator is given in the form of table as shown in Figure-2. Gate signal generator generates the commutating gate triggering signals for three phase inverter with back EMFs coming from particular rotor position of motor. Gate signal generator consists of back EMFs generator and gate logic decoder. Back EMF generator gives back EMF logic signals to the hall signals of BLDC motor. Gate logic decoder determines the switching sequence of the six

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power transistors to give the power to the two BLDC motor phases concurrently. Outer loop controls the speed of the motor by supplying regulating D.C power to three phase inverter with any one of the controllers.

Hall sensor A	Hall sensor B	Hall sensor c	EMF A	EMF B	EMF C
0	0	0	0	0	0
0	0	1	0	-1	1
0	1	0	-1	1	0
0	1	1	-1	0	1
1	0	0	1	0	-1
1	0	1	1	-1	0
1	1	0	0	1	-1
1	1	1	0	0	0

Figure-1. Back EMF logic with hall sensor signals.

3. SPEED CONTROLLERS

A. Fuzzy logic controller

Fuzzy logic controller is a rule-based logic controller. Fuzzy logic controller designs the general behaviors of the control system in a linguistic manner by forming IF-THEN rules [14]. The fuzzy rules are in the form of no of statements. The general structure of fuzzy logic controller consists of four functional parts as shown in Figure-3. They are given as fuzzification, fuzzy rule-base, fuzzy inference engine and defuzzification. The design steps in fuzzy logic controller are i) Define the inputs and output variables ii) Define universe of discourse iii) Define fuzzy membership functions and fuzzy set rules. In this fuzzy logic controller structure, E (error) and IE (integrative error) are taken as two inputs and gives controlled output (u) to the BLDC motor. A fuzzy logic controller with a fuzzy rule viewer block is used to control the output of BLDC motor. Different membership functions for fuzzy variables are selected to control the output. Fuzzy Interference System (FIS) file is saved which includes all input and output membership functions and fuzzy rules.
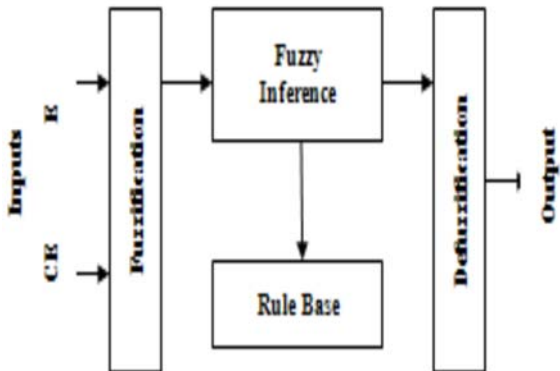

Figure-3. General Fuzzy logic controller.

Fuzzy Associative Memories (FAM) in FLC is a transformation matrix which map no of fuzzy sets. A FAM consists of collection of IF-THEN rules. These rules are given in forty nine possible two inputs and single output FAM rules as illustrated in Table as shown in Figure-4. The fuzzy output is converted into real value as the crisp output by the process called defuzzification. Even though various defuzzification methods are available, the most preferred method is centroid. It can be easily implemented in all digital control systems with less computation time. Final crisp value is the control value for the applied voltage across the armature winding and hence the speed of the motor.

E \ IE	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

Figure-4. 7*7 Fuzzy rules FAM matrix.

Each universe of discourse can be divided into seven fuzzy sets as followings; [14] NB: Negative Big PB: Positive Big Z: Nearer Zero NM: Negative Medium PS: Positive Small PM: Positive Medium NS: Negative Small. Triangular membership functions are selected for NB, NM, NS, ZE, PS, PM and PB fuzzy sets. The fuzzy set rules are given by,

If error is NB and integrative of error is NB then output signal is NB

If error is NB and integrative of error is NM then output signal is NB

Finally, all forty-nine fuzzy rules are summarized in the form of a FAM matrix is given in the form of table as shown in Figure-4. MATLAB/Fuzzy Logic Toolbox and BLDC overall simulink block are combined into FIS file to simulate the result.

B. Hybrid fuzzy PID controller

The basic control structure of the proposed Hybrid Fuzzy PID Controller (HFPIDC) is shown in Figure5.The HFPIDC has more advantages with combination of classical PI, PID controller along with fuzzy control action[11].The proportional (K4, K1), integral (K5), and derivative (K6) control gains in the HFPIDC are selected for reducing peak overshoot and oscillations[12].

Triangular membership functions are selected for NB, NM, NS, ZE, PS, PM and PB fuzzy sets [16]. The fuzzy rule matrix for computing the output Δu is given in table as shown in Figure-6. The simulation of speed control of trapezoidal back EMF BLDC motor drive for HFPIDC controller is done by using MATLAB/SIMULINK software package [13].
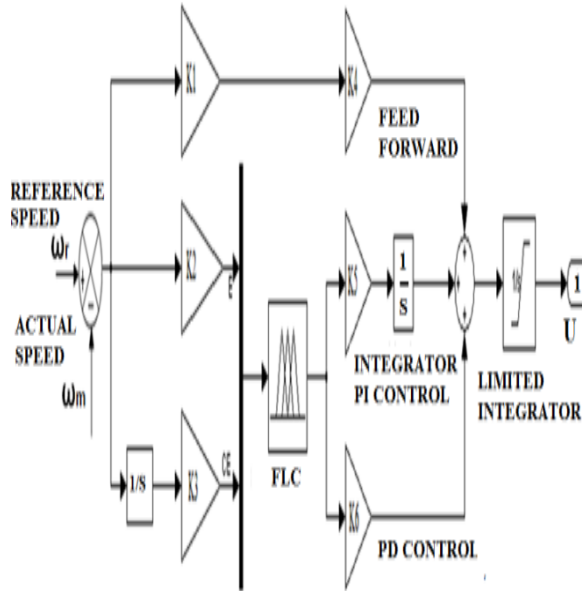

Figure-2. Block diagram of hybrid fuzzy PID.

Figure-3. Fuzzy rules matrix of hybrid fuzzy PID.

C. PI controller

The PID controller is the most common and very useful controller for any plant. In a plant the feedback loops are mainly controlled by the PID controller. The error signal is passed through the PID controller and plant then output signal is given as feedback signal to the set input signal. The proportional (P), integral (I), and derivative (D) control parameters are arranged in a cascade order which is shown in below Figure 7. PID controller gains are K_p, K_i and K_d will be varied either by

manual method or Ziegler Nichols method to get output response with less rise time and overshoot.
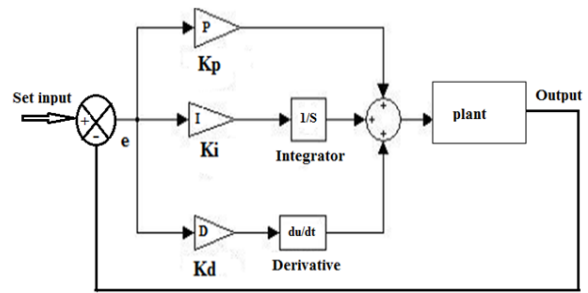

Figure-4. Basic PID controller module.

4. SIMULATION RESULTS

The simulation of the BLDC motor is done by using MATLAB/SIMULINK technical computing software package [15]. Its speed and torque waveforms are analyzed. A PI controller and fuzzy controller have been employed for speed control of BLDC motor. Through the simulations of all controllers, it is confirmed that the proposed hybrid fuzzy PID and fuzzy logic controllers provide a good response to the successive changes in reference speed and load torque. The results obtained by simulation show the feasibility and ability of the proposed fuzzy controllers strategy. The HFPID and Fuzzy logic controllers provide more efficient speed control technique for BLDC motor with good dynamic response characteristics such as rise time, peak overshoot, steady state error and settling time. Moreover, it generates less speed and torque ripples.
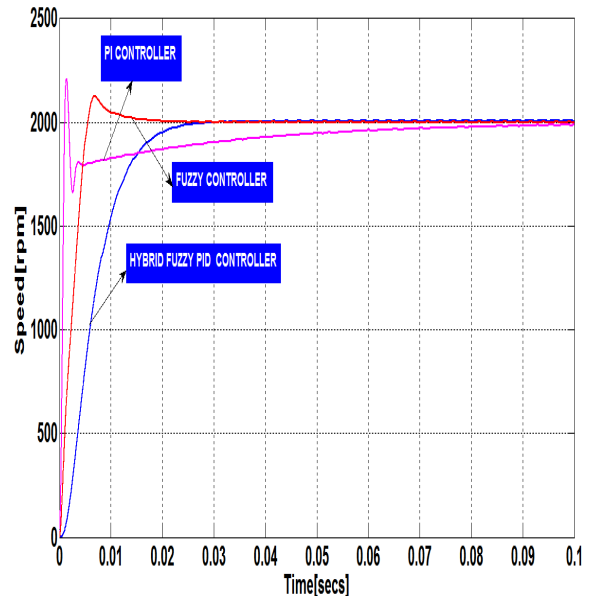

Figure-5. No load performance of the fuzzy, conventional PI and hybrid fuzzy PID controllers at reference speed of 2000 rpm.
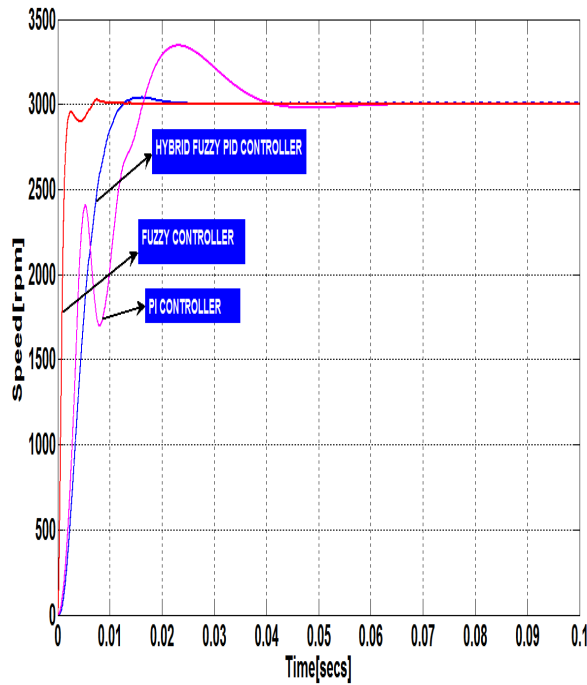
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Figure-6. No load performance of the fuzzy, conventional PI and hybrid fuzzy PID controllers at reference speed of 3000 rpm.
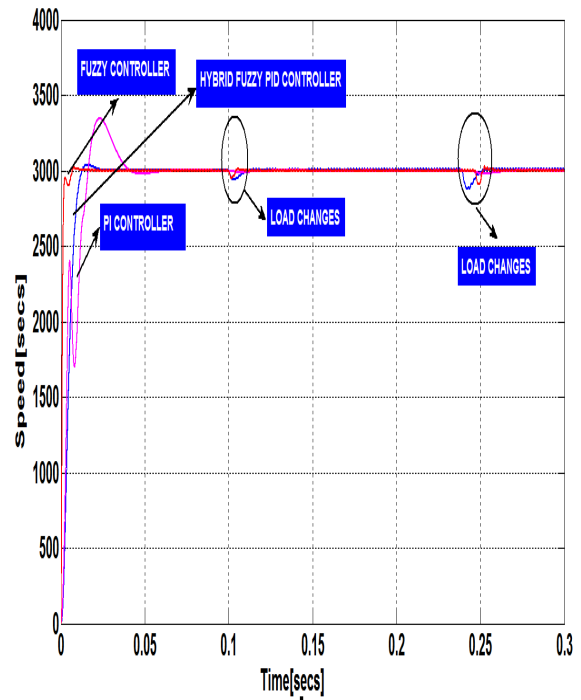

Figure-8. The performance of fuzzy, hybrid fuzzy PID and conventional PI controllers of BLDC motor on speed of 3000rpm with load changes from 0.1Nw-m to 0.2Nw-m.
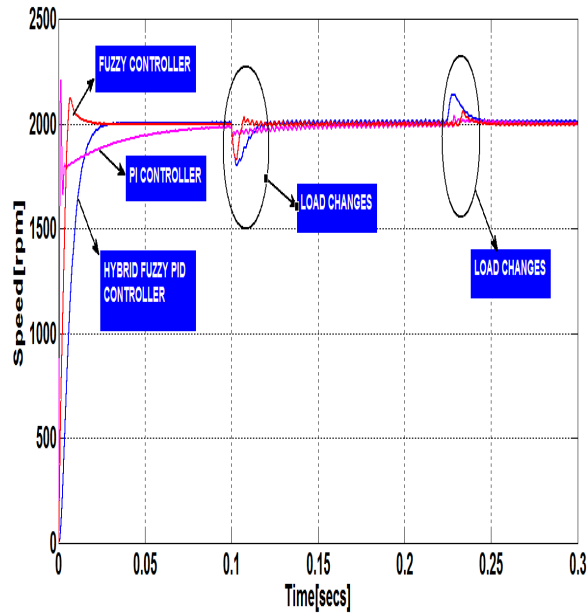

Figure-7. The performance of fuzzy, hybrid fuzzy PID and conventional PI controllers of BLDC motor on speed of 2000rpm with load changes from 0.2Nw-m to 0.1Nw-m.
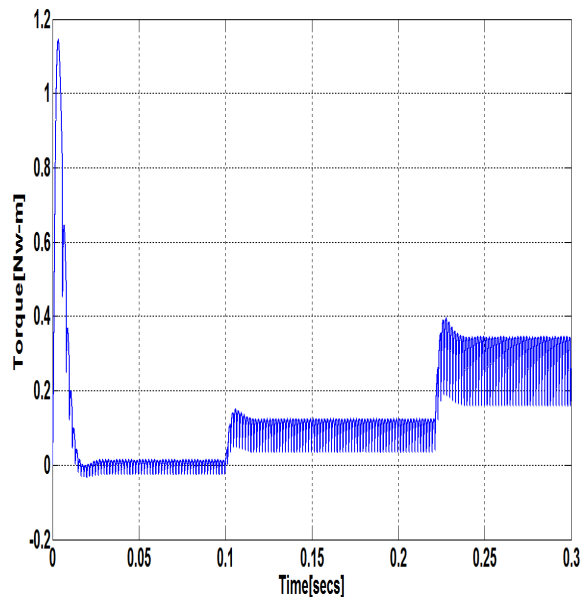

Figure-9. The load torque performance of hybrid fuzzy PID controller of BLDC motor on speed of 3000rpm with load changes from 0.1Nw-m to 0.3Nw-m.
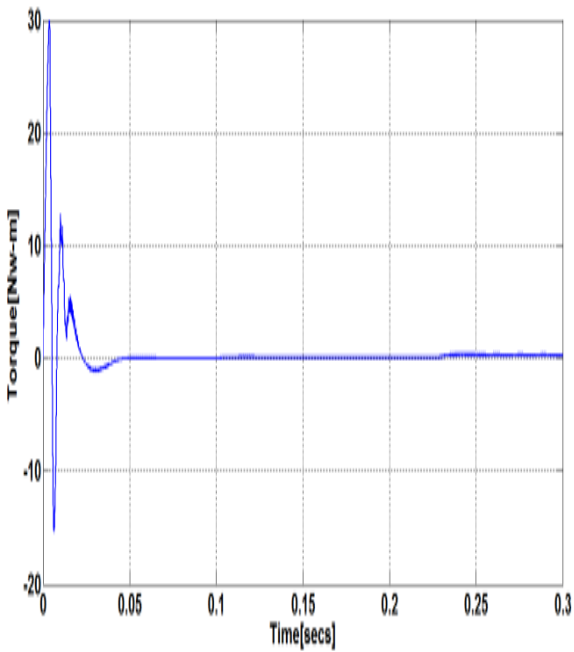
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Figure-10. The load torque performance of conventional PIcontroller of BLDC motor on speed of 3000rpm with load changes from 0.1Nw-m to 0.3Nw-m.
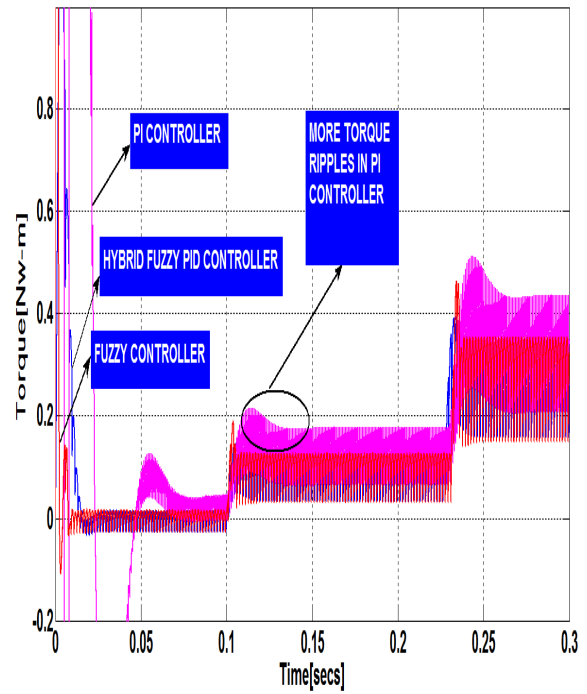

Figure-12. The load torque performance of fuzzy, conventional PI and hybrid fuzzy PID controllers of BLDC motor on speed of 3000rpm with load changes from 0.1Nw-m to 0.3Nw-m in expanded view.
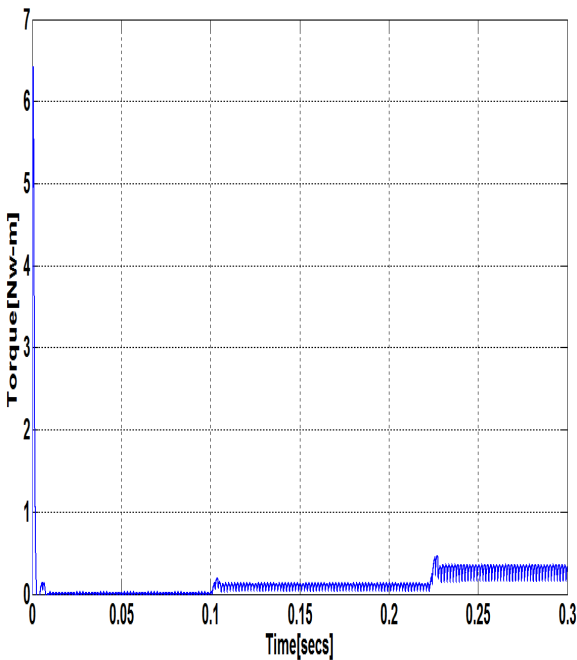

Figure-11. The load torque performance of fuzzy controller of BLDC motor on speed of 3000rpm with load changes from 0.1Nw-m to 0.3Nw-m.
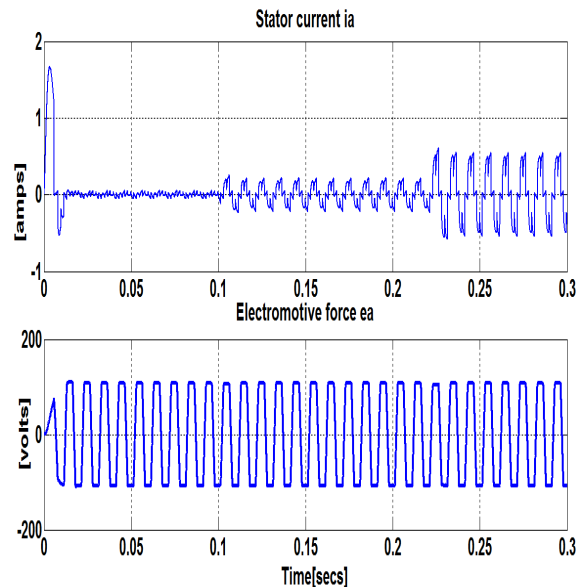

Figure-13. The stator current and back EMF waveforms of hybrid fuzzy PID controller of BLDC motor on speed of 2000rpm.
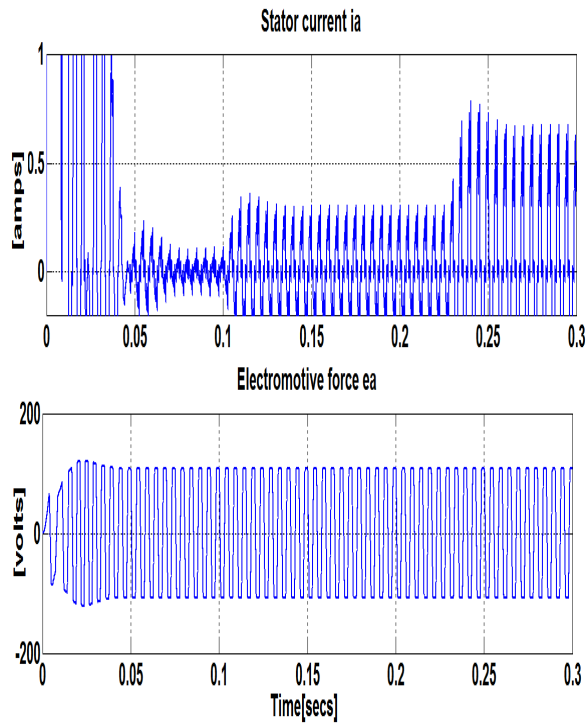
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Figure-14. The stator current and back EMF waveforms of conventional PI controller of BLDC motor on speed of 2000rpm.
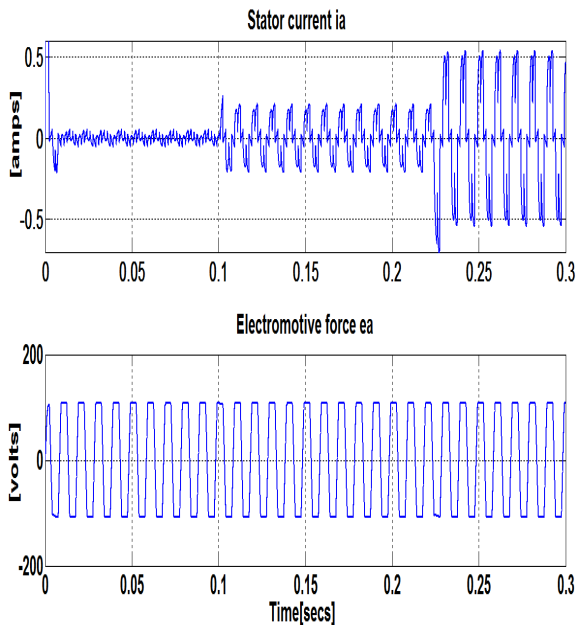

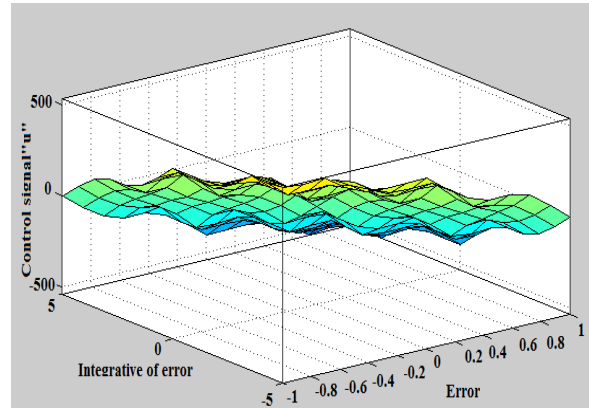**Figure-15.** The stator current and back EMF waveforms of fuzzy controller of BLDC motor on speed of 2000rpm.

Figure-16. Fuzzy logic controller surface viewer.
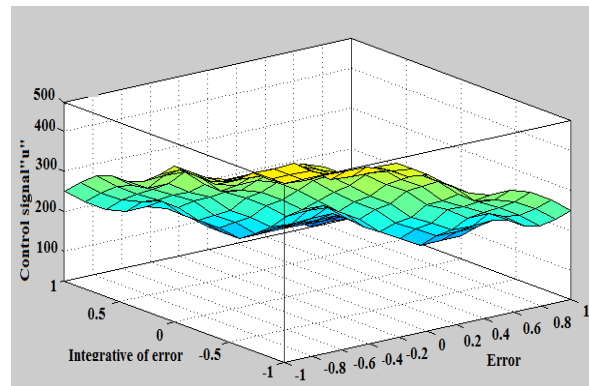

Figure-17. Hybrid fuzzy PID controller surface viewer.

Figure-8 shows the performance of the fuzzy, conventional PI and hybrid fuzzy PID controllers of BLDC motor on reference speed of 2000rpm with no load condition. Figure-9 shows the performance of the fuzzy, conventional PI and hybrid fuzzy PID controller of BLDC motor on reference speed of 3000rpm with no load condition.

Figure-10 shows the performance of fuzzy, hybrid fuzzy PID and conventional PI controller of BLDC motor on speed of 2000rpm with load torque changes from 0.2Nw-m to 0.1Nw-m. Figure-11 shows the performance of fuzzy, hybrid fuzzy PID and conventional PI controller of BLDC motor on speed of 3000rpm load torque changes from 0.1Nw-m to 0.2Nw-m. Figure-12, Figure-13 and Figure-14 shows the load torque performance of fuzzy, conventional PI and hybrid fuzzy PID controllers of BLDC motor on speed of 2000rpm with load changes from 0.2Nw-m to 0.1Nw-m respectively. Figure 15 shows the load torque performance of fuzzy, conventional PI and hybrid fuzzy PID controllers of BLDC Motor on speed of 3000rpm with load torque changes from 0.1Nw-m to 0.3Nw-m.

Figure-16, Figure-17 and Figure-18 shows stator current and back EMF waveforms of conventional PI, fuzzy and hybrid fuzzy PID controllers of BLDC Motor on speed of 2000rpm respectively.

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Figure-19 shows surface viewer for fuzzy logic controller. Mamdani type of FIS is used. All membership functions of the FLC inputs, error (E) and integrative of error (IE) are given on the normalized domain form (-1, 1), (-5, 5). Output (u) is given as (-500, 500) normalized form.

Figure-20 shows surface viewer for hybrid fuzzy PID controller. Mamdani type of FIS is used. All membership functions of proposed HFPIDC inputs, error (E) and integrative of error (IE) are given on the normalized domain form (-1, 1), (-1, 1). Output (u) is given as (0, 500) normalized form. The performance results of conventional PI, fuzzy and hybrid fuzzy PID controllers of BLDC motor is shown in Table-1 and Table-2. The performance parameters of rise time (TR), peak overshoot (rpm), settling time (ts), steady state error (%) speed ripples (%), torque ripples (%) of BLDC motor drive controllers are analyzed. From the performance results, hybrid fuzzy PID and fuzzy controllers have better control performance than the conventional PI controller.

Table-1. The performance results of conventional PI, fuzzy and hybrid fuzzy PID controllers for 1000 rpm with no-load at 0.3secs.

Speed with load torque	1000 rpm with no-load		
	PI controller	**Fuzzy logic controller**	**Hybrid Fuzzy PID controller**
Rise time (tr in secs)	0.036	0.0093	0.0319
Settling time (ts in secs)	0.045	0.018	0.028
Peak overshoot (%)	16.67	0.50	--------
Steady state error (%)	0.3	0.15	0.2
Torque ripples (%)	1.6	1.1	1.0
Speed ripples (%)	0.2	0.1	0.1

Table-2. The performance results of conventional PI, fuzzy and hybrid fuzzy PID controllers for 3000 rpm with no-load at 0.3secs.

Speed with load torque	3000 rpm with no-load		
	PI controller	**Fuzzy logic controller**	**Hybrid Fuzzy PID controller**
Rise time (tr in secs)	0.016	1.582e-3	0.0123
Settling time (ts in secs)	0.090	0.020	0.023
Peak overshoot (%)	11.66	0.8667	1.33
Steady state error (%)	0.270	0.0667	0.2667
Torque ripples (%)	1.5	1.2	1.1
Speed ripples (%)	0.2	0.1	0.1

Table-3. The performance results of conventional PI, fuzzy and hybrid fuzzy
PID controllers for 2000 rpm with 0.3 Nw-m load at 0.3secs.

Speed with load torque	2000rpm with 0.3 Nw-m load		
	PI controller	Fuzzy logic controller	Hybrid Fuzzy PID controller
Rise time (tr in secs)	0.0333	4.6e-3	0.0170
Settling time (ts in secs)	0.155	0.115	0.120
Peak overshoot (%)	10.60	7.0	----------
Steady state error (%)	1.0	0.95	0.90
Torque ripples (%)	23.0	18.60	17.50
Speed ripples (%)	1.11	1.0	1.0

Table-4. The performance results of conventional PI, fuzzy and hybrid fuzzy
PID controller's for 3000 rpm with 0. 1 Nw-m load at 0.3secs.

Speed with load torque	3000rpm with 0. 1 Nw-m load		
	PI controller	Fuzzy logic controller	Hybrid Fuzzy PID controller
Rise time (tr in secs)	0.015	2e-3	0.01
Settling time (ts in secs)	0.10	0.03	0.035
Peak overshoot (%)	11.67	0.933	1.30
Steady state error (%)	0.24	0.06	0.23
Torque ripples (%)	15.0	13.5	10.0
Speed ripples (%)	0.533	0.50	0.50

From the results of analysis of controllers, it is clear that HFPID controller has to provide better results with less torque ripples compared to other controllers. But, FLC gives good speed response with less rise time and settling time than HFPID and PI controllers. Speed ripples for HFPIDC and FLC will be the same and less than PI controller.

5. CONCLUSIONS
This paper presents comparative simulation study of conventional PI, fuzzy and hybrid fuzzy PID controllers of three phases BLDC Motor. In conventional PI control, parameters of PI controller are fixed as the reference speed and torque changes. With the results of simulations, it is clear that the BLDC speed control using hybrid fuzzy PID and fuzzy logic controllers give better performance than the conventional PI controller. The motor speed response is better when the load is varied from low to high or high to low values.

APPENDIX A
Parameters of PID Controller
Proportional gain K_P = 16.61
Integral gain K_I = 0.5

APPENDIX B
BLDC motor parameters

Rated speed: 3000 rpm
Rated voltage: 300 V dc
Number of poles: 2
Type of connection: star
Self & Mutual inductance/phase: 8.5e-3H
Moment of inertia: 2.26e-005 kg-m^2
Voltage constant: 71.9215 V/rpm
Rated Torque: 0.8 Nw-m
Resistance/phase: 18.7ohms
Torque constant: 0.6868Nw-m/amp

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