A Methodological Comparison of Adaptive Fuzzy PI On-Line and Off-Line Controllers of BLDC Motor Drive System for High Speed Range Industry Application

N.Jayamary Sujatha*[1], M.Saravanan[2]

[1]Electronics and Communication Engineering, [1]University College of Engineering,
[1]Anna University, [1]Ramanathapuram-623513, [1]Tamilnadu, [1] India
[2]Electrical and Electronics Engineering, [2]Thiagarajar College of Engineering,
[2]Madurai-625015, [2]Tamilnadu, [2]India
Corresponding Author: *jayamary_sujatha@rediffmail.com, jayamary_sujatha@hotmail.com

Abstract: BLDC motors are being designed and presently used in high speed range of industrial applications such as power steering, engine cooling fan speed control, fuel/water pump speed control, air-conditioning compressor control, air-conditioning blower motor control. Commonly, many controllers have been developed to enhance high control performance of the BLDC drive under transient and steady state conditions. They are conventional proportional-integral-derivative controller and intelligent controller using neural network and fuzzy logic technique. As the both conventional controllers and intelligent controllers controllers have many drawbacks and limited for high speed range of industrial applications. This paper focuses the development of controllers by the combination of both conventional proportional-integral and intelligent controller using fuzzy logic technique. This paper provides design of proposed hybrid intelligent controllers such as adaptive fuzzy proportional integral on-line controller, adaptive fuzzy proportional-integral-derivative off-line controller, fuzzy proportional- derivative and integral on-line controller and fuzzy proportional-integral on-line controller. This paper presents the comparison of transient response and steady state analysis all proposed hybrid intelligent controllers. The simulations results derived in this paper are presented to show the ability of all proposed fuzzy on-line controllers for high speed range of industry applications.

Keywords: BLDC motor, adaptive fuzzy proportional integral on-line controller, adaptive fuzzy proportional-integral-derivative off-line controller, fuzzy proportional- derivative and integral on-line controller, fuzzy proportional-integral on-line controller

1. Introduction

Brushless direct current (BLDC) trapezoidal back EMF motors are largely used in definite important industrial applications such as servo drives, air compressor, and electric vehicles due to their elongated operating life, high power density, soundless operation, high speed ranges, high motor efficiency, enhanced dynamic response, and easier motor's parameter control [1]. BLDC motor is customarily named as a permanent magnet brushless direct current (PMBLDC) motor with a trapezoidal shape of back EMF [2]. BLDC motors do not embrace the brushes for commutation. They are electronic commutation control. In recent times, high performance BLDC motor drives are frequently used for variable speed drive systems of convinced specific industrial applications. In practice, the general design of the BLDC motor drive system occupies a complex process such as modelling of motor, selection of control method, simulation of characteristics, controller parameters tuning etc. Recently, various modern type control solutions are proposed for the speed control design of BLDC motor [3] [4] [5].

They are conventional proportional (P), proportional-integral (PI), proportional-integral-derivative PID speed control systems [6] [7] [8] [9]. However, conventional PID controller algorithm used for BLDC motor is very simple, stable operation, easy control adjustment, and high consistency of operation. But, the most of the industrial processes are nonlinear operation; parameter inconsistency of control and uncertainty in the design of mathematical model of the system, tuning PID of control parameters are very difficult. Hence, conventional PID controllers generally do not perform well for non-linear systems, higher order time-delayed linear systems. Design of PID controller requires mathematical model of the under transient and steady state conditions. These problems are eliminated by designing fuzzy logic controllers, which do not consider entire mathematical model of the motor drive system and are mostly based on linguistic rules obtained from the understanding of the system knowledge of human operator. But the performance of the fuzzy logic controller are compared with PI controller is superior only under transient condition if the controller gains are assorted with the input error signal and the limits of the gains have to be created manually [10] [11] [12][13].

In this paper, an adaptive fuzzy PI on-line controller is introduced in speed regulation system of BLDC motor. Load torque, speed variations of motor can be adjusted in real time under improved adaptive fuzzy PI on-line control. The performance of the adaptive fuzzy PI on-line control system is designed by defining appropriate values of integral, proportional gains, number of inputs and membership functions. The individual set of rules is created for each K_p, K_i. By means of individual set of rules, the controller can be adapting to any change of parameter. The main aim of this paper is to show the dynamic response of system for keeping the motor speed to be constant when the load varies. The simulation result shows that the performance of adaptive fuzzy PI on-line controller has better for load variation than all fuzzy logic off-line and on-line controllers.

2. Closed loop model of BLDC motor

The brushless DC motor (BLDCM) offers a trapezoidal back Electro Motive Force (EMF) and rectangular stator currents are needed to generate a constant smooth electromagnetic torque. A brushless dc motor is mostly defined as a trapezoidal permanent magnet synchronous motor with rotor position feedback signal. It is generally controlled by using a three phase power semiconductor inverter bridge. For this, it requires a rotor position sensor for starting the motor with proper commutation sequence to turn on the power switches in three phase's inverter bridge. Based on the rotor rotation, the power switches are commutated sequentially every 60 degrees. *Fig.1.* Shows general block diagram of PMBLDC motor drive. In the inner loop of control mechanism, Hall Effect sensor provides position information for gate signal generator. Gate signal generator logic consists of back EMFs generator and gate logic decoder for BLDC drive. Gate signal generator generates the commutating gate triggering pulses for three phase's inverter bridge with proper back EMF signals coming from particular rotor position.

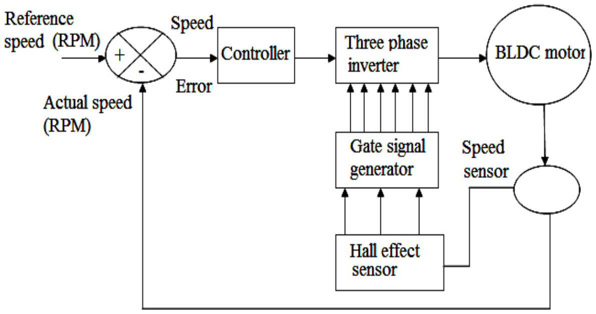

Fig.1. *Block diagram of PMBLDC motor drive*

Table 1 Back EMF generator with hall sensor signals

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

Gate logic decoder is given in the form of table as shown in Table 2. Back EMF generator generates the back EMF logic signals for the hall sensor signals of BLDC motor. Back EMF generator is given in the form of table as shown in Table 1. Gate logic decoder functional block determines the switching sequence of the six power transistors. The power transistors within the inverter circuit used to energize the two BLDC motor phases concurrently. Outer loop control logic controls the speed of the motor by supplying proper value of regulating D.C power supply to three phase inverter of motor by using any one of the controllers.

Table 2 Gate logic decoder for BLDC drive

EMF A	EMF B	EMF C	Q1	Q2	Q3	Q4	Q5	Q6
0	0	0	0	0	0	0	0	0
0	-1	1	0	0	0	1	1	0
-1	1	0	0	1	1	0	0	0
-1	0	1	0	1	0	0	1	0
1	0	-1	1	0	0	0	0	1
1	-1	0	1	0	0	1	0	0
0	1	-1	0	0	1	0	0	1

3. Speed Controllers

3.1 Adaptive Fuzzy PID off-line controller

Fuzzy logic has rapidly appeared to the one of the the majority powerful tools of today's technology for developing sophisticated control system. Fuzzy logic is a logical system which is an extension of multi valued logic systems and synonymous with the theory of fuzzy sets. Fuzzy logic set theory is formerly introduced by Lotfi Zadeh in the 1960's is actually looks like a approximate reasoning by the use of approximate information and uncertainty to provide decisions.

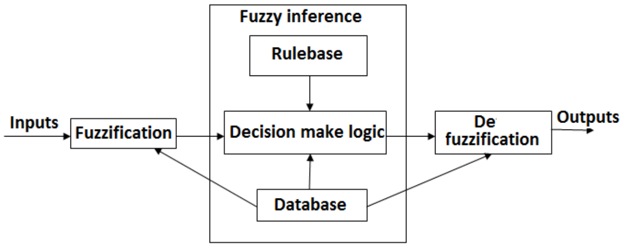

Fig.2. *General Fuzzy logic controller*

Table 3 7*7 Fuzzy rule matrix for fuzzy logic controller 1

IE E	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

The fuzzy logic controller has to provide three main components,

1. Fuzzification
2. Fuzzy inference
3. De-fuzzification

The functions of Fuzzification are; 1) Multiple measured crisp inputs are mapped into fuzzy membership function 2) Performs a scale mapping function that transfers the range of values of input variables into corresponding its universes of discourses 3) Converts all input data into another suitable linguistic values which may be viewed as labels of fuzzy set[14].

Fuzzy logic linguistic terms are always expressed in the form of logical implication, such as if--then fuzzy rules [15]. These rules are used to form a definition for the range of values known as fuzzy member ship functions. Fuzzy membership functions are in the form of a triangular, a trapezoidal, a bell or other appropriate forms.

The inputs of the fuzzy logic controller are distinct in various linguistic levels. They are articulated as positive-big (PB) value, positive-medium (PM) value, positive-small (PS) value, negative-small (NS) value, negative-medium (NM) value, negative-big (NB) value or in other levels. Each level is described by fuzzy set. Triangular membership functions are chosen for NB, NM, NS, ZE, PS, PM and PB fuzzy sets.

Fuzzy inference within the fuzzy logic controller is provided for forming the process of formulating and mapping of a given input to an output using fuzzy logic. The mapping thus provides a common basis from which all decisions can be made or patterns are discerned.

There are two types of Fuzzy Inference Systems (FIS) are generally implemented in the Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type. These two types of inference systems gives variation somewhat in the way of outputs determined. Mamdani fuzzy inference system is the most commonly seen fuzzy inference methodology. Mamdani method was the first control logic built using fuzzy set theory.

The second phase of the fuzzy logic controller in fuzzy inference is the knowledge base and data base. The rule base and data base form the knowledge base. The data base defines the description of input and output variables for fuzzy logic control. The decision making logic in fuzzy system determines all control rules. The fuzzy rule based logic can be developed to relate the output action of the controller to the obtained inputs.

The output of the fuzzy inference mechanism is fuzzy output variables. The fuzzy logic controller converts its internal fuzzy output variables into final crisp values so that the actual system can use all these variables. This type of conversion process is called de-fuzzification. This operation is performed in several ways. The most commonly used control in de-fuzzification strategy is centroid method. The fuzzy rule matrix for computing the output control signal is given in the Table 3. The fuzzy set rules are given by,

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

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

Finally, all forty-nine fuzzy rules are produced in the form of a Fuzzy Associate Memory Matrix (FAM).This is in the form of table as shown in Table 3.Matlab fuzzy toolbox and BLDC motor overall simulink block are combined into FIS file to simulate the result.

In this paper, [16] adaptive fuzzy PID off-line (AFPIDOFFL) controller used is based on two inputs and three outputs as shown *Fig.3.* The overall structure of AFPIDOFFL controller is shown in *Fig.3.*

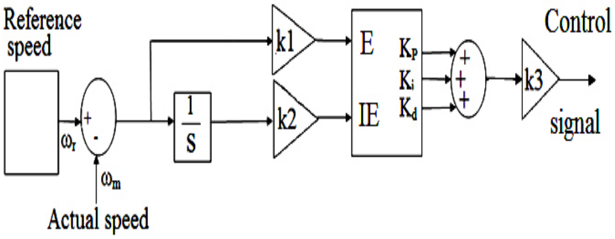

Fig.3.*Overall structure of Adaptive Fuzzy PID off-line controller*

In adaptive fuzzy PID off-line controller K_p, K_i and K_d are obtained as three outputs as shown in *Fig.4.* Error speed (E) and Integrative of error in speed (IE) are given as fuzzy logic controller1 inputs and outputs are taken as K_p,K_i, k_d are calculated by using equations (1),(2),(3) are given in *Fig.4*.

$$\Delta K_p = K_{p\,*}\Delta K_p{}' \tag{1}$$

$$\Delta K_i = K_{i\,*}\Delta K_i{}' \tag{2}$$

$$\Delta K_d = K_{d\,*}\Delta K_d{}' \tag{3}$$

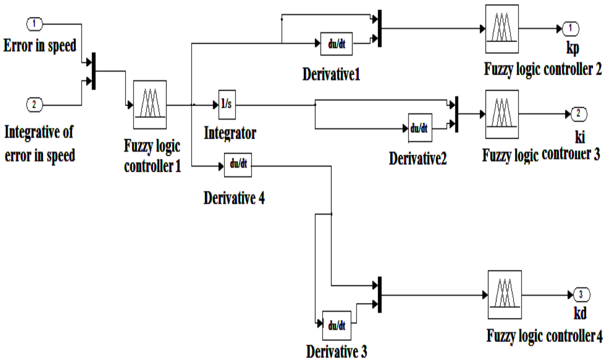

Fig.4.*Block diagram of Adaptive Fuzzy PID off-line controller*

A linguistic variable implies the inputs and outputs have been classified as: NB NM, NS, Z, PS, PM, PB. The fuzzy linguistic variable of adjusted parameter K_p, K_i and K_d in the required ranges are also articulated. The triangle membership function is selected to yield good dynamic response than the trapezoidal membership function for AFPIDOFFL controller.

The fuzzy rule matrix for computing proportional gain K_p (Fuzzy logic controller 2), integral gain K_i (Fuzzy logic controller 3) and derivative gain K_d (Fuzzy logic controller 4) is in the form of table is shown in Table 4, Table 5 and Table 6. Fuzzy logic controller1 in AFPIDOFFL was implemented by using fuzzy rule matrix is given in Table 3.

3.2 Adaptive Fuzzy PI on-line controller

The basic control structure of the proposed adaptive fuzzy PI on-line controller (AFPIONLC) is shown in *Fig.5.* The AFPIONLC has more advantages with proper selection of proportional gain fuzzy rule matrix, integral gain fuzzy rule matrix for producing good dynamic and transient response characteristics of control action [17].The fuzzy rule matrix for computing proportional gain K_{fp}, integral gain K_{fi} is given in the form of table as shown in Table.4, Table.5.

The general structure diagram of BLDC motor drive control system based on adaptive Fuzzy PI on-line control is given in *Fig.5*. In this general structure, fuzzy logic controller provides correct gain values of K_{fp}, K_{fi} adaptively to the PI controller for efficient control action. The simulation model of closed loop block diagram of AFPIONLC is shown in *Fig.6*. The PI parameters are tuned by using AFPIONLC fuzzy inference structure which provides a nonlinear mapping from the error (E) and derivation of error (DE) to PI parameters.The simulation of internal block diagram of closed loop diagram of AFPIONLC is shown in *Fig.6*. AFPIONLC continuously add the values of K_{fp}, K_{fi} with K_p=0.8 and K_i=10 during the online motor running condition. So that fuzzy controller can tune the conventional PI parameters online in order to adapt the dynamic changes in the motor drive system. *Fig.7* shows internal block diagram of adaptive fuzzy PI on-line controller.

AFPIONLC can be expressed with the following equation:

$$u(t) = (K_p + K_{fp})e(t) + (K_i + K_{fi}) \int e(t)dt \qquad (4)$$

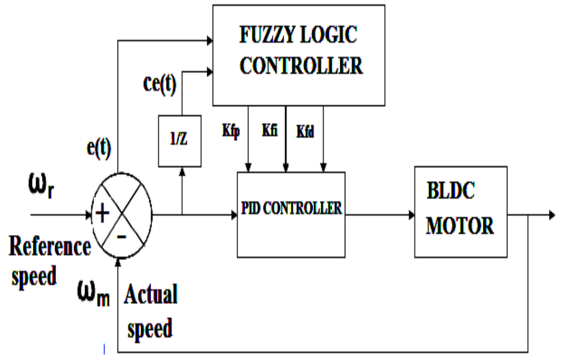

Fig.5. *The structure diagram of BLDCM drive control system based on adaptive Fuzzy PI on-line control*

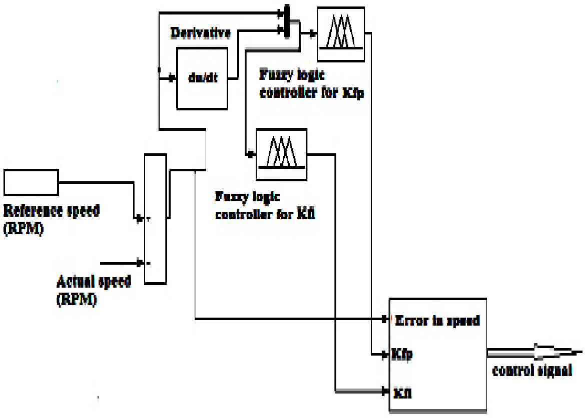

Fig.6. *Closed loop block diagram of BLDCM with AFPIONLC module*

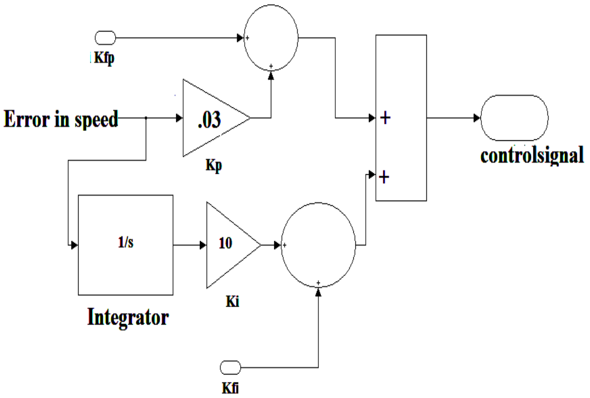

Fig.7.*Internal block diagram of adaptive fuzzy PI on-line controller*

Table 4 Fuzzy rule matrix for derivative gain

DE E	NB	Z	PB
NB	NS	NM	NM
NS	NS	NM	NS
Z	NS	Z	Z
PS	NS	Z	PS
PB	NM	NS	PM

Table 5 Fuzzy rule matrix for integral gain

DE E	NB	Z	PB
NB	NS	NM	NM
NS	NS	NM	NS
Z	NS	Z	Z
PS	NS	Z	PS
PB	NM	NS	PM

Table 6 Fuzzy rule matrix for derivative gain

DE E	NB	Z	PB
NB	PS	PM	PS
NS	PS	PS	PS
Z	Z	PS	PS
PS	NS	PS	PM
PB	NM	NS	PM

3.3 Fuzzy PD and I on-line controller

The basic block diagram of the proposed adaptive fuzzy PD and I on-line controller (FPDIONLC) is shown in *Fig.8.* The FPDIONLC is designed for on-line variation of motor parameters with high degree of accuracy for lager values of constant motor speed operation [18]. Fuzzy rule matrix for PD and I controller has less no of rules compared with other types of fuzzy controllers as given in Table.7.

Integral gain and all other gains in FPDIONLC is properly selected to obtain the good on-line variation of steady state and transient response characteristics of control action. The general structure diagram of BLDC motor control system based on fuzzy PD and I on-line controller is given in *Fig.8*. In this general structure, fuzzy logic PD controller output is added with I controller output to obtain the correct control output. The simulation model of closed loop block diagram of FPDIONLC with error (E) and derivation of error (DE) as the input parameters is shown in *Fig.9*.

In this paper, the clarification of all fuzzy variables is realized by using the weighted average method. The weighted average value of membership function may be calculated according to the following equation.

$$u = \frac{\sum_{i=1}^{m} \mu(u_i).u_i}{\sum_{i=1}^{m} \mu(u_i)} \qquad (5)$$

Where u_i is the elements for domain, μ (u_i) is the membership grade of u_i.

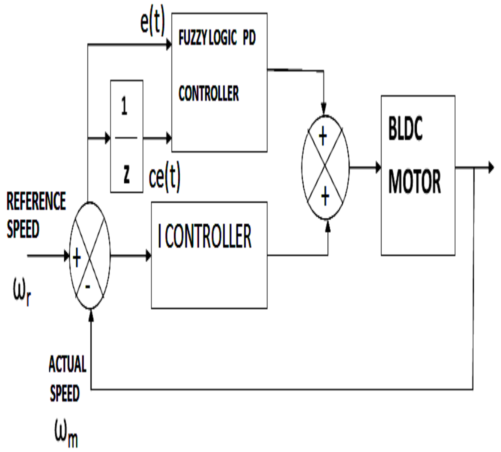

Fig.8._Block diagram of fuzzy PD and I on-line controller_

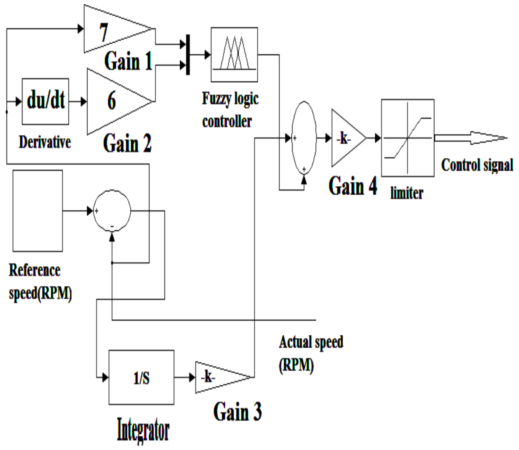

Fig.9_.Simulink diagram of fuzzy PD and I on-line controller_

Table 7 Fuzzy rule matrix for Fuzzy PD Controller

DE E	Negative	Positive
Negative	Negative	Zero
Positive	Zero	Positive

3.4 Fuzzy PI on-line controller

The basic control structure of the proposed fuzzy PI on-line controller (FPIONLC) is shown in _Fig.10_. The FPIONLC has more advantages with combination of classical PI controller along with fuzzy control action. The proportional (K2, K1), integral (K4) control gains in the FPIONLC are selected for reducing peak overshoot and oscillations [20] [21].

Triangular membership functions are chosen for NB, NM, NS, ZE, PS, PM and PB fuzzy sets [18]. The fuzzy rule matrix for computing the output (U) is given in the form of table as shown in Table.8.The simulation of speed control of trapezoidal back EMF BLDC motor drive for FPIONLC controller is done by using MATLAB/SIMULINK software package [19] as shown in _Fig.11_. Gain1, Gain2, Gain3, Gain4, Gain5 are correctly selected for producing good accurate control signal. The gain values are fixed for online parameter variations. Any parameter variation of motor does not alter the controller gains during dynamic and transient response of motor running condition.

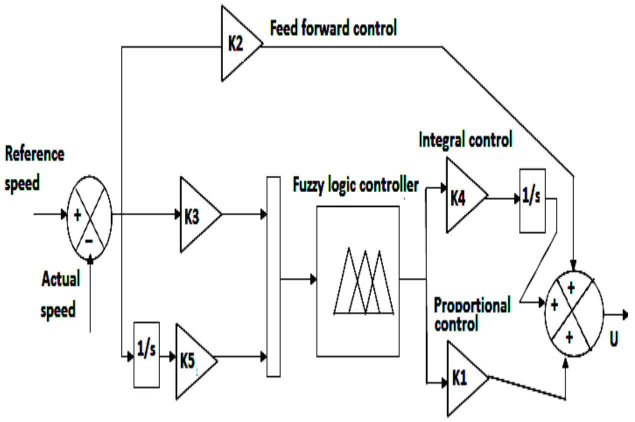

Fig.10._Block diagram of Fuzzy PI controller for BLDCM_

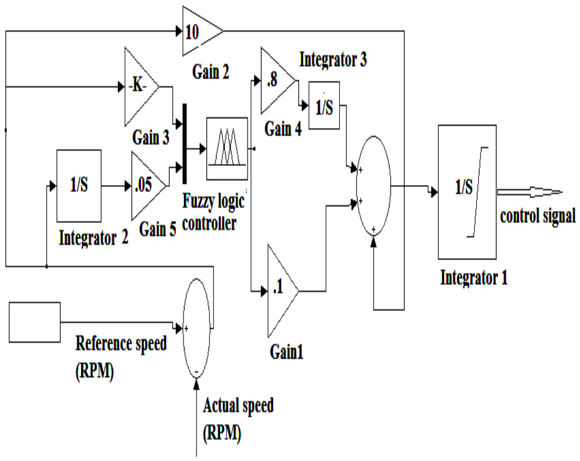

Fig.11._Simulation diagram of Fuzzy PI controller for BLDCM_

Table 8 Fuzzy rule matrix for fuzzy logic controller

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

The simulation study of this paper consists of various type of action of controller. Each type of action is simulated in separate cases [20], [21], [22]. The simulation of BLDC motor is carried out for parameters of BLDC motor is given in Appendix.6-A.When the speed of motor is running at 5000 RPM with no-load condition for AFPIDOFFL, FPDIONL, FPIONL, and AFPIONL controllers are simulated is shown in *Fig.12*.All controllers are regulating the speed with less upper overshoot. When the motor is running at loaded torque of 0.1N-M with constant speed of 5000 RPM for AFPIDOFFL, FPDIONL, FPIONL, and AFPIONL controllers are simulated is shown in *Fig.13*.

When the motor is running at loaded torque of 0.1N-M at 0.1 sec and 0.2N-M at 0.2 sec with constant speed of 5000 RPM for AFPIDOFFL, FPDIONL, FPIONL, and AFPIONL controllers are simulated is shown in *Fig.14*. When the motor is running at loaded torque of 0.2N-M at 0.2 sec and 0.3N-M at 0.3 sec with constant speed of 5000 RPM for AFPIDOFFL, FPDIONL, FPIONL, and AFPIONL controllers are simulated is shown in *Fig.15.* When the motor is running at loaded torque 0.3 N-M at 0.1 sec, 0.2 N-M at 0.2 sec and 0.1 N-M at 0.3 sec with constant speed of 5000 RPM for AFPIDOFFL, FPDIONL, FPIONL, and AFPIONL controllers are simulated is shown in *Fig.16. Fig.17*.shows the speed curve of BLDC motor runs with step down speed of 3000RPM- 5000RPM from 0.2 sec to 0.25sec and load of 0.2N-M at 0.2 sec for AFPIDOFFL, FPDIONL, FPIONL, and AFPIONL controllers. *Fig.18*. shows the speed curve of BLDC motor runs with step down speed of 5000RPM-2000RPM from 0.2 sec to 0.25sec and load of 0.1N-M from 0.2 sec to 0.25sec for AFPIDOFFL, FPDIONL, FPIONL, and AFPIONL controllers.

Load torque response of BLDC motor for AFPIDOFFL, FPIONL, AFPIONL, and FPDIONL controllers with load torque changes from 0.3 N-M at 0.1 sec, 0.2 N-M at 0.2 sec and 0.1 N-M at 0.3 sec with a speed of 5000 RPM are given from *Fig.19* *t*o *Fig.22* respectively. Stator current and back EMF waveforms response of BLDC motor for AFPIDOFFL, FPIONL, AFPIONL, and FPDIONL controllers with load torque changes from 0.3 N-M at 0.1 sec, 0.2 N-M at 0.2 sec and 0.1 N-M at 0.3 sec with a speed of 5000 RPM are given from *Fig.23* to *Fig.26* respectively. Load torque response of BLDC motor for AFPIDOFFL, FPIONL, AFPIONL, and FPDIONL controllers with step down speed of 5000RPM-2000RPM from 0.2 sec to 0.25sec and load of 0.1N-M at 0.2 sec are given from *Fig.27*to *Fig.30* respectively.

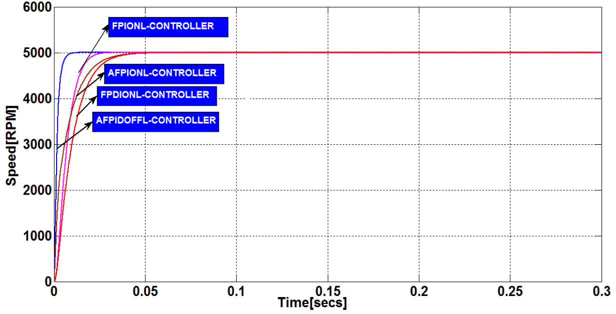

Fig.12.*The speed curve of BLDC motor runs at no-load condition with constant speed of 5000 RPM*

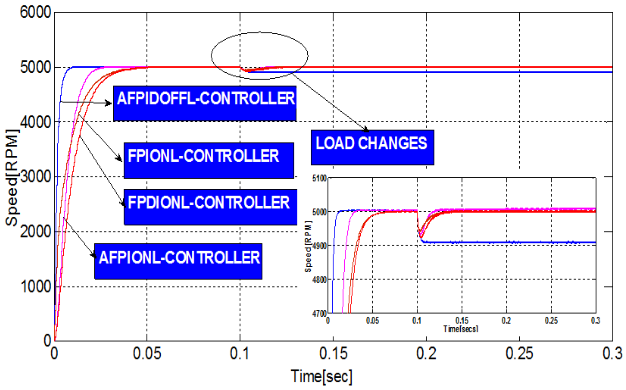

Fig.13. *The speed curve of BLDC motor runs at load torque of 0.1N-M with constant speed of 5000 RPM*

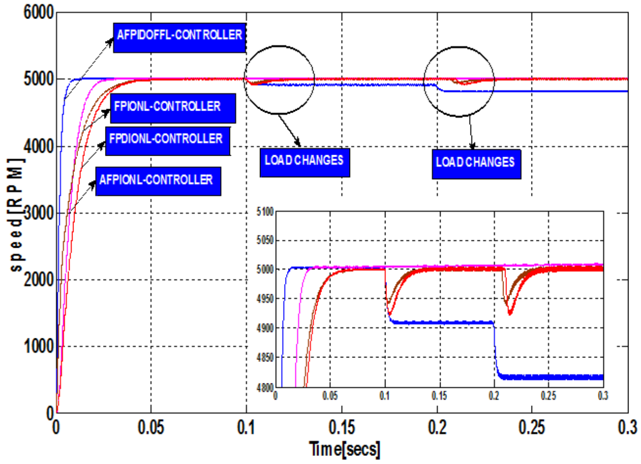

Fig.14. *The speed curve of BLDC motor runs at a step change of load from 0.1N-M at 0.1 sec and 0.2N-M at 0.2 sec with constant speed of 5000 RPM*

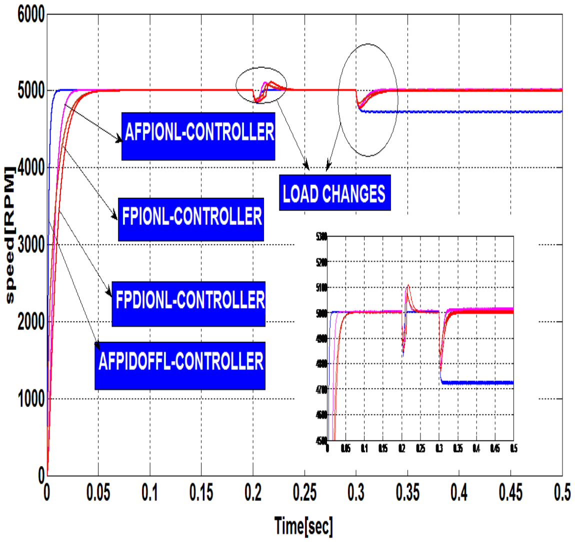

Fig.15. *The speed curve of BLDC motor runs at a step change of load from 0.2N-M at 0.2 sec and 0.3N-M at 0.3 sec with constant speed of 5000 RPM*

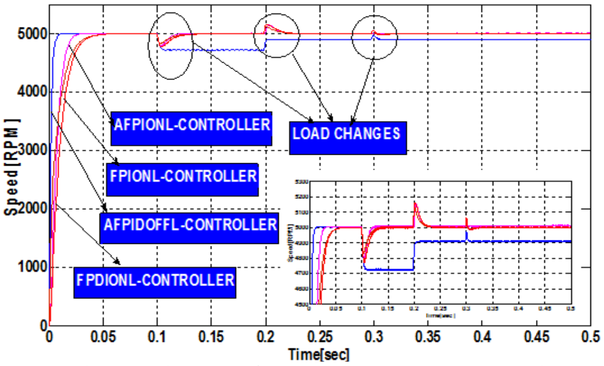

Fig.16.The speed curve of BLDC motor runs at step change of load changes from 0.3 N-M at 0.1 sec, 0.2 N-M at 0.2 sec and 0.1 N-M at 0.3 sec with constant speed of 5000 RPM

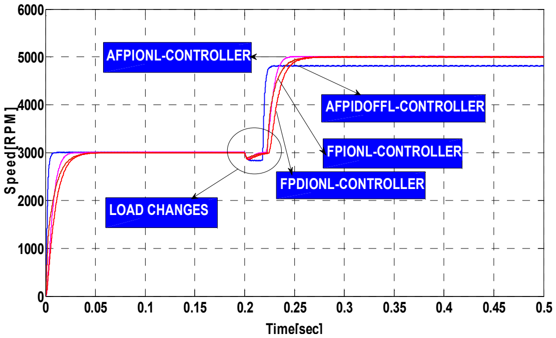

Fig.17.The speed curve of BLDC motor runs with step down speed of 3000RPM- 5000RPM at 0.2 sec to 0.25sec and load of 0.2N-M at 0.2 sec

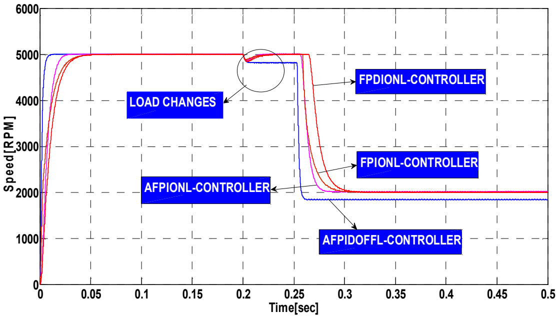

Fig.18. The speed curve of BLDC motor runs at no-load with step down speed of 5000RPM- 2000RPM at 0.2 sec to 0.25 sec and load of 0.1N-M at 0.2 sec

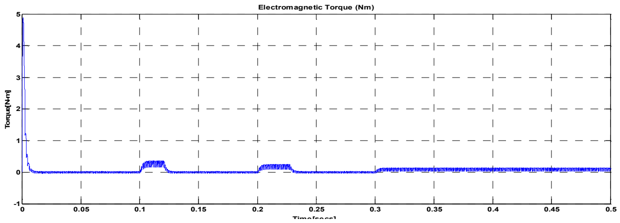

Fig.19. Load torque response of BLDC motor for AFPIDOFFL controller with load torque changes from 0.3 N-M at 0.1 sec, 0.2 N-M at 0.2 sec and 0.1 N-M at 0.3 sec with a speed of 5000 RPM

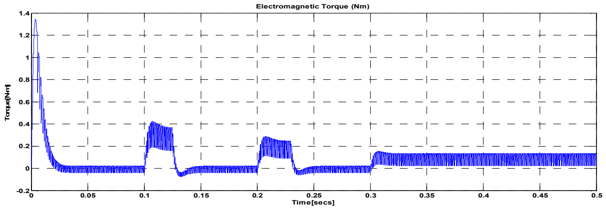

Fig.20.Load torque response of BLDC motor for FPIONL controller with load torque changes from 0.3 N-M at 0.1 sec, 0.2 N-M at 0.2 sec and 0.1 N-M at 0.3 sec with a speed of 5000 RPM

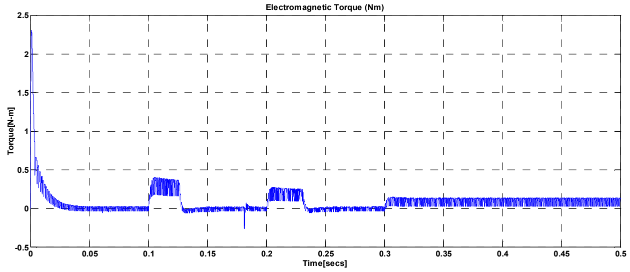

Fig.21. Load torque response of BLDC motor for AFPIONL controller with load torque changes from 0.3 N-M at 0.1 sec, 0.2 N-M at 0.2 sec and 0.1 N-M at 0.3 sec with a speed of 5000 RPM

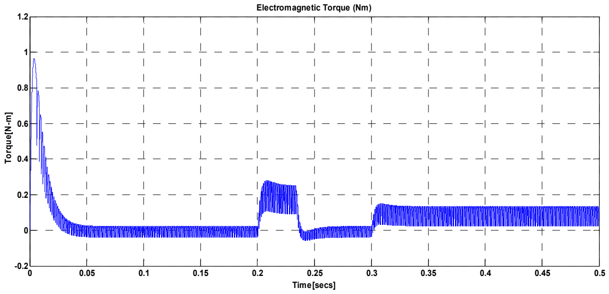

Fig.22. Load torque response of BLDC motor for FPDIONL controller with load torque changes from 0.3 N-M at 0.1 sec, 0.2 N-M at 0.2 sec and 0.1 N-M at 0.3 sec with a speed of 5000 RPM

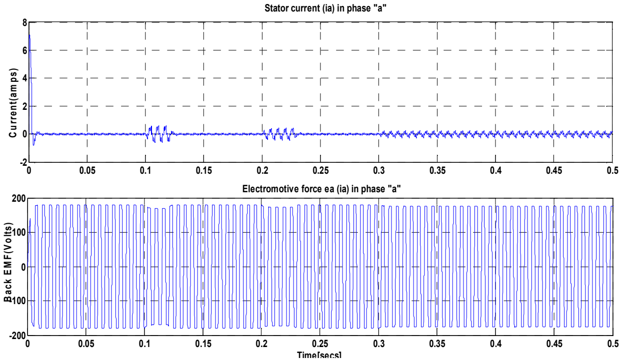

Fig.23.BLDC motor stator current and back EMF waveforms for AFPIDOFFL controller with load torque of at *0.3 N-M at 0.1 sec, 0.2 N-M at 0.2 sec and 0.1 N-M at 0.3 sec for 5000 RPM*

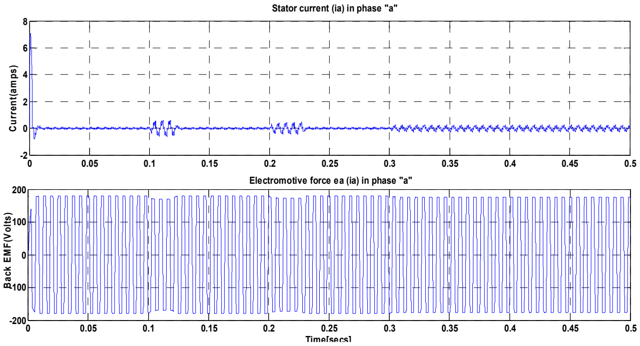

Fig.24.*BLDC motor stator current and back EMF waveforms for FPIONL controller with load torque of* at *0.3 N-M at 0.1 sec, 0.2 N-M at 0.2 sec and 0.1 N-M at 0.3 sec for 5000 RPM*

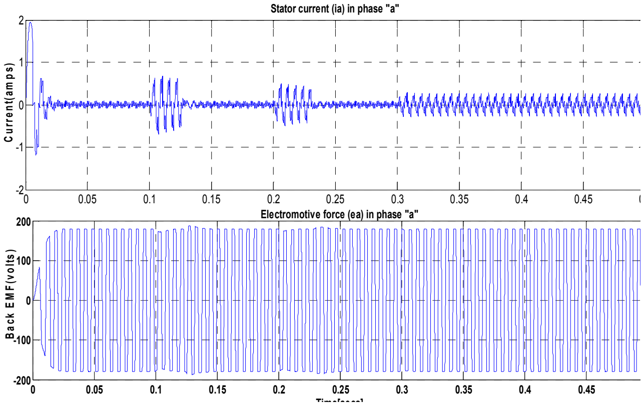

Fig.25.*BLDC motor stator current and back EMF waveforms for AFPIONL controller with load torque of* at *0.3 N-M at 0.1 sec, 0.2 N-M at 0.2 sec and 0.1 N-M at 0.3 sec for 5000 RPM*

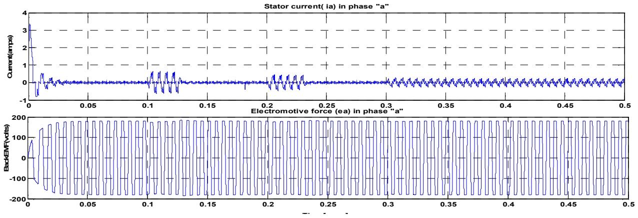

Fig.26.*BLDC motor stator current and back EMF waveforms for FPDIONL controller with load torque of* at *0.3 N-M at 0.1 sec, 0.2 N-M at 0.2 sec and 0.1 N-M at 0.3 sec for 5000 RPM*

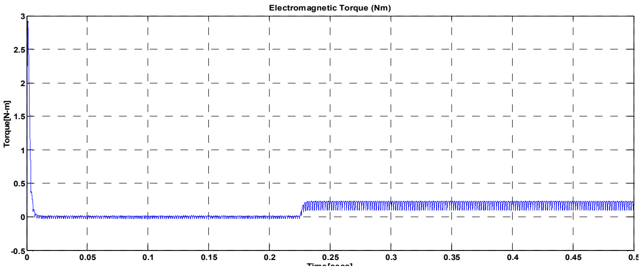

Fig.27.*Load torque response of BLDC motor for AFPIDOFFL controller with step down speed of 3000RPM-5000RPM from 0.2 sec to 0.25 sec and load torque of 0.2N-M*

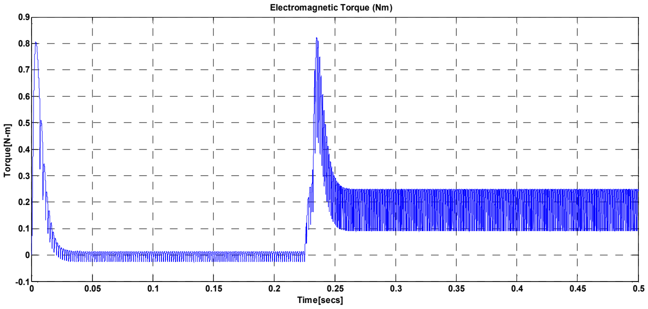

Fig.28.*Load torque response of BLDC motor for FPIONL controller with step down speed of 3000RPM- 5000RPM from 0.2 sec to 0.25 sec and load torque of 0.2N-M*

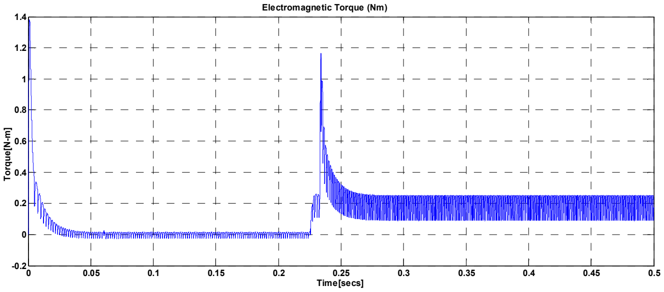

Fig.29.*Load torque response of BLDC motor for AFPIONL controller with step down speed of 3000RPM- 5000RPM from 0.2 sec to 0.25 sec and load torque of 0.2N-M*

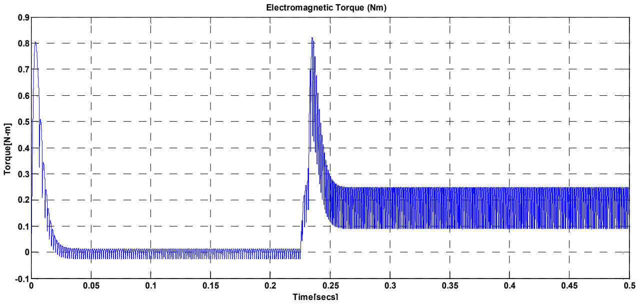

Fig.30.*Load torque response of BLDC motor for FPDIONC controller with step down speed of 3000RPM- 5000RPM from 0.2 sec to 0.25 sec and load torque of 0.2N-M*

4. Results and discussion

Performance measuring parameters of different controllers are produced in Table.9.The performance indices selected for in this discussion are settling time, peak over shoot, steady state error, dip in speed when 0.2 N-M load torque applied. The integral of the absolute value of the error (IAE), the integral of the squared error (ISE), the integral of the time-weighted value of absolute error (ITAE) and the integral of time-weighted value of squared error (ITSE) values are also calculated and given in Table.9.The observations of results are given for both transient and steady state response of the BLDC motor for the set speeds of 5000 rpm, 6000rpm, 7000 rpm. The steady state error, settling time, torque ripples are low for AFPIDOFFL controller as compared with other all types of online controllers

In practice, for the real time and on-line parameter variations, improved performance of BLDC motor is obtained by minimizing the torque ripples present in the transient response, reducing steady state error and settling time using the AFPIONL .In this way, AFPIONL controller gives minimum load torque variation at transient condition among all controllers. Even if the starting torque is high for AFPIDOFFL controller, starting torque is high for AFPIONL controller among all on-line controllers.

From the analysis of various types of error such as %MSE, %ISE, %IAE, %ITSE, %IASE are given in Table 9. AFPIONL controller gives negligibly small value for all type of error as compared with all controllers. From the plots of *Fig.31* and *Fig.32*, it is clear that AFPIDOFFL controller gives highest considerable error among all types of online controllers. Finally, for real time on-line parameter variation, AFPIONL controller is very suitable than all controllers discussed in this paper. Reduction of reference speed for the variation of load torque is found negligibly small along with a desirable reduction in settling time for the AFPIONLC. The speed response of controller is smooth and no oscillations in the case of AFPIONLC. This is due to robust and accurate control structure AFPIONLC *Fig.31* shows the performance of controllers for %MSE for 5000 rpm, 6000rpm and 7000 rpm. *Fig.32* shows the performance of controllers for %ISE for 5000 rpm, 6000rpm, and 7000 rpm. From *Fig.31* and *Fig.32* FPIONL, AFPIONL, FPDIONL controllers produce negligible values of %MSE, %ISE compared with AFPIDOFFL controllers.

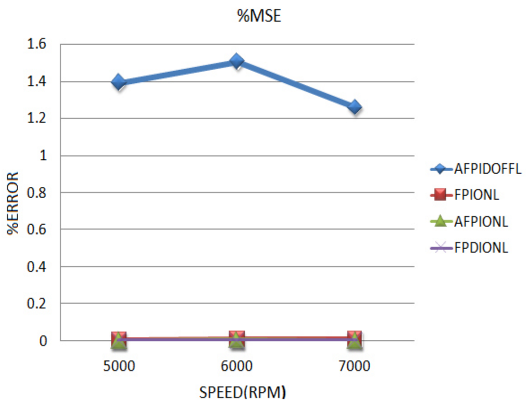

Fig.31.*Performance of controllers for %MSE*

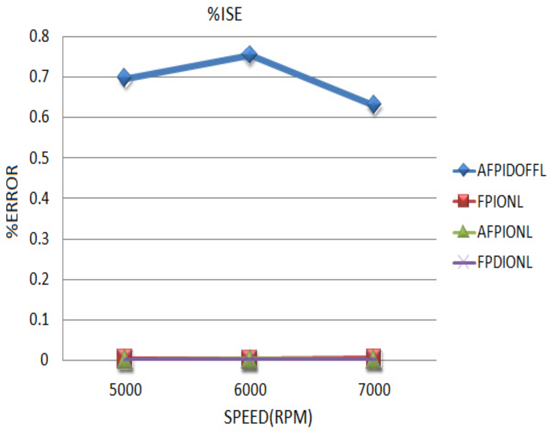

Fig.32.*Performance of controllers for %ISE*

Table.9 Performance measurement parameters of different controllers

	5000 RPM with load torque of 0.2 N-M for 0.5 sec				**6000 RPM with load torque of 0.2 N-M for 0.5 sec**			
Parameters / Type of Controller	AFPIDOFFL	FPIONL	AFPIONL	FPDIONL	AFPIDOFFL	FPIONL	AFPIONL	FPDIONL
Settling time(sec)	0.012	0.0200	0.045	0.048	0.01235	0.0250	0.046	0.047
Steady state error (%)	0.12	0.080	0.04	0.04	0.016	0.0833	0.0333	0.0333
Peak overshoot (%)	----	----	----	----	----	----	----	----
Torque ripples (%)	15.75	15.89	16.10	16.00	16.40	16.45	16.44	16.50
Dip in speed(RPM)	190	140	115	150	200	144.5	120	155
Starting Torque(N-M)	4.8773	1.343	2.3065	0.9662	5.820	1.60	2.768	1.16
MSE (%)	1.392	0.004292	0.0003378	0.0004018	1.505	0.007118	0.002364	0.0001558
ISE (%)	0.696	0.002136	0.0001589	0.0001909	0.7526	0.0003548	0.001172	0.00006788
IAE (%)	-0.00373	0.0002066	-0.00005638	0.0000618	-0.00388	0.0002664	0.0002667	0.00006417
ITAE (%)	-0.001845	0.0001233	-0.00000818	0.0000109	-0.00192	0.0001532	0.0001533	0.0000121
ITSE (%)	0.348	0.001088	-0.00009946	0.0001155	0.3762	0.001794	0.0006058	0.00005394

5. Conclusion

This paper focuses the merits and de-merits of different fuzzy on-line and off –line controllers. All controllers are well designed by taking the action of conventional PI, PID, PD, I controller and fuzzy control action. The hybrid techniques of fuzzy and conventional controllers are accurately designed for eliminating all problems when they are acting individually. The fuzzy logic control rules are formed in various natures for reducing upper shoot problems with minimum torque ripples. Adaptive parameter variations of BLDC motor during on-line and off-line modes are clearly given under different load torque and speed variations. Finally, the results in this paper show the ability of AFPIONL controller is well suited for high speed industry applications.

Appendix-6-A

BLDC MOTOR PARAMETERS

BLDC motor parameter	**Rating with unit**
Rated speed	3000 RPM
Rated voltage	300 V (D.C)
Number of poles	2
Rated torque	0.8 N-M
Stator Resistance/phase	18.7 Ohms
Stator Inductance/phase	8.5e-3 Henry
Voltage constant	71.9215V/RPM
Torque constant	0.6868(N-M/RPM)
Inertia constant	2.26e-005(Kg-m^2)

Appendix-6-B

THREE PHASE INVERTER PARAMETERS

Parameter	**Rating with unit**
Snubber Resistance	5000 ohms
Snubber Capacitance	1e-6 Farad
Number of bridge arms	3
Power Electronics device	IGBT/Diodes

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