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Speed Control of Brushless DC Motor Drives by Using Hybrid Fuzzy Controllers

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Abstract:

This paper aims at the design and simulation of hybrid PI-fuzzy control system for the speed control of a brushless dc motor. The performance of the fuzzy logic controller (FLC) is better under transient conditions, while that of the proportional plus integral (PI) controller is superior near the steady-state condition. The combined advantages of these two controllers can be obtained with hybrid PI -fuzzy speed controller. Both the design of the fuzzy controller and its integration with the proportional-integral (PI) controller is to be done. In this paper, design and implementation of hybrid fuzzy controller is presented and its performance is compared with pi and fuzzy controller to show its capability to track the error and usefulness of hybrid fuzzy controller in control applications.

Index Terms:

Brushless dc (BLDC) servomotor drive, fuzzy controller, modeling, PID controller, transient and steady-state performance.

I. INTRODUCTION:

In recent years, brushless dc (BLDC) machines have gained widespread use in electric drives. These machines are ideal for use in clean, explosive environments such as aeronautics, robotics, electric vehicles, food and chemical industries and dynamic actuation. Using these machines in high-performance drives requires advance and robust control methods. Conventional control techniques require accurate mathematical models describing the dynamics of the system under study. These techniques result in tracking error when the load varies fast and overshoot during transients. In lieu of provisions for robust control design, they also lack consistent performance when changes occur in the system.

If advance control strategies are used instead, the system will perform more accurately or robustly. It is therefore, desired to develop a controller that has the ability to adjust its own parameters and even structure online, according to the environment in which it works to yield satisfactory control performance. An interesting alternative that could be investigated is the use of fuzzy logic control (FLC) methods. In the last decade, FLC has attracted considerable attention as a tool for a novel control approach because of the variety of advantages that it offers over the classical control techniques.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.

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II. MODELING OF BLDC SERVO MOTOR DRIVE SYSTEM:

The BLDC servomotor drive system consisting of BLDC servomotor and IGBT inverter is modeled [1]–[4], [15] based on the assumptions that all the stator phase windings have equal resistance per phase; constant self and mutual inductances; power semiconductor devices are ideal; iron losses are negligible; and the motor is unsaturated.The equivalent circuit of the BLDC servomotor drive system is shown in Fig.1. The line to line voltage equations are expressed in matrix form as

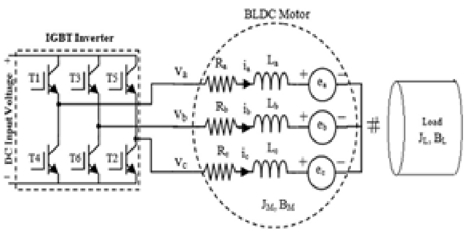

Fig.1. Equivalent circuit of the BLDC servomotor drive system

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \begin{bmatrix} R & -R & 0 \\ 0 & R & -R \\ -R & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & M-L & 0 \\ 0 & L-M & M-L \\ M-L & 0 & L-M \end{bmatrix} \times \frac{di}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a - e_b \\ e_b - e_c \\ e_c - e_a \end{bmatrix}. \quad (1)$$

Since the mutual inductance is negligible as compared to the self-inductance, the aforementioned matrix equation can be rewritten as

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \begin{bmatrix} R & -R & 0 \\ 0 & R & -R \\ -R & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & -L & 0 \\ 0 & L & -L \\ -L & 0 & L \end{bmatrix} \times \frac{di}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a - e_b \\ e_b - e_c \\ e_c - e_a \end{bmatrix} \quad (2)$$

Where Land Mare self-inductance and mutual inductance per phase; R is the stator winding resistance per phase; ea, eb ,and ec are the back EMFs of phases a, b, and c, respectively; ia,ib, And ic are the phase currents of phases a, b, and c, respectively. The electromagnetic torque developed by the motor can be expressed as

$$T_e = (e_a i_a + e_b i_b + e_c i_c)/\omega = K_t I \quad (3)$$

Where $i_a = i_b = i_c = I$, ω is the angular velocity in radians per second, and Kt is the torque constant. Since this electromagnetic torque is utilized to overcome the opposing torques of inertia and load, it can also be written as

$$T_e = T_L + J_M d_\omega/dt + B_M \omega \quad (4)$$

Where T_L is the load torque, J_M is the inertia, and B_M is the friction constant of the BLDC servomotor. The load torque can be expressed in terms of load inertia J_L and friction BL

$$T_L = J_L \frac{d\omega}{dt} + B_L \omega. \quad (5)$$

The output power developed by the motor is

$$P = T_e \omega \quad (6)$$

$$E = e_a = e_b = e_c = K_b \omega \quad (7)$$

Where Kb is back EMF constant, E is back EMF per phase, and ω is the angular velocity in radians per second.The parameters of motor are phase resistance, phase inductance, and inertia and friction of BLDC servomotor and load. It is necessary to determine the parameters of both BLDC servomotor and load so as to design conventional controllers like P, PI, and PID controllers.The parameters that are likely to vary during the working conditions are R, JM,JL, BM, and BL. These parameters can influence the speed response of the BLDC servomotor drive system. Increase in the value of energy storage inertia elements JM and JL will increase the settling time of the speed response or vice versa. The decrease in the values of power consuming friction components BM and BL will increase the deceleration time of the speed response or vice versa. Another parameter, which is likely to vary during working conditions is phase resistance of the BLDC servomotor due to addition of terminal resistance, change in resistance of phase winding, and change in on-state resistance of IGBT switches due to change in temperature. The change in phase resistance can also affect the speed response of the BLDC servomotor drive system. Mixed combination of inertia, friction, and phase resistance of the BLDC servomotor may lead to large overshoots that are undesirable in most of the control applications. Therefore, the BLDC servomotor drive system needs suitable controllers such as PID or Fuzzy controllers to speed up the response, reduce overshoot, and steady-state error to meet up the applications requirements.

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In this paper, PID and Fuzzy controller-based BLDC servomotor drive is developed and their performance is investigated during different operating conditions such as step change in reference speed, different system parameters, and sudden load disturbance.

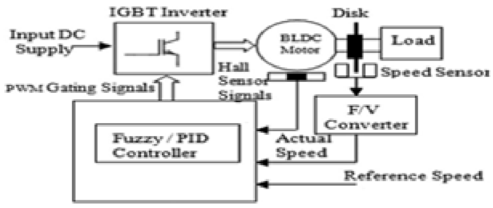

Fig.2. Block diagram of the experimental setup.

III. DESIGN AND IMPLEMENTATION OF PID CONTROLLER:

Proportional-Integral-Derivative controllers [7]–[9] are widely used in industrial control systems as they require only few parameters to be tuned. The PID controllers have the capability of eliminating steady-state error due to integral action and can anticipate output changes due to derivative action when the system is subjected to a step reference input. The most popular PID tuning method is the Ziegler–Nichols method, which relies solely on parameters obtained from the system step response. The block diagram of the experimental set-up used for implementing PID and fuzzy controller is shown in Fig. 2. The specifications of the BLDC servomotor are given in Appendix.The continuous control signal u(t)of the PID controller [19] is given by

$$u(t) = K_P\,(e(t) + (1/T_i)\int e(t)dt + T_d de(t)/dt) \quad (8)$$

where, KP is the proportional gain, Ti is the integral time constant, Td is the derivative time constant, and e(t)is the error signal.

The corresponding discrete equation for the control signal [19] can be written as

$$u(k) = u(k-1) + K_1 \times e(k) + K_2 \times e(k-1) + K_3 \times e(k-2) \quad (9)$$

Where u(k−1)is the previous control output, e(k−1) is the previous error, and e(k−2)is the error preceding e(k−1). The constants K_1,K_2, and $K_3$are given by

$$K_1 = K_P + TK_i/2 + K_d/T \quad (10)$$

$$K_2 = -K_P - 2K_d/T + TK_i/2 \quad (11)$$

$$K_3 = K_d/T \quad (12)$$

$$K_i = K_P/T_i \quad (13)$$

$$K_d = K_P T_d \quad (14)$$

$$T = 1/f \quad (15)$$

Where f is the sampling frequency and T is the sampling rate. In this paper, a simple PID tuning method [8] that is based on system step response is used to determine the controller gains. This method provides a systematic approach to adjust the proportional gain in order to minimize the overshoot.

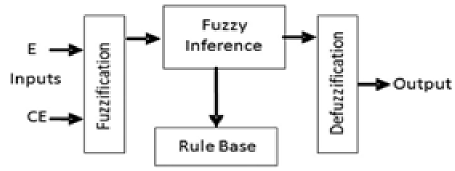

Fig.3. Block diagram of a fuzzy inference system.

It is well known that the conventional PID controllers will yield better transient and steady-state responses, if the system parameters remain unchanged during the operating conditions. But the parameters of the practical systems change during operating conditions. As a result, the PID controllers failed to yield desired performance under nonlinearity, load disturbances, and parameter variations of motor and load. This has resulted in an increase in demand for nonlinear controllers, intelligent and adaptive controllers.

IV. DESIGN AND IMPLEMENTATION OF FUZZY CONTROLLER:

There has been a significant and growing interest in the application of artificial intelligence type control techniques such as neural network and fuzzy logic to control the complex, nonlinear systems. Fuzzy logic is applied in applications like washing machines, subway systems, video cameras, sewing machines, biomedical, and finance. Having understood the general behavior of the system, fuzzy logic enables the designer to describe the general behavior of the system in a linguistic manner by forming IF–THEN rules that are in the form of statements. The great challenge is to design and implement the FLC quickly by framing minimum number of rules based on the knowledge of the system. The general FLC [4], [10]–[12] consists of four parts as illustrated in Fig.3. They are fuzzification, fuzzy rule base, fuzzy inference engine, and defuzzification. The design steps are as follows. Step 1 (Define inputs, outputs, and universe of discourse): The inputs are error E and change in error CE and the output is change in duty cycle ΔDC. The error is defined as the difference between the reference speed

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Nref and actual speed Nact and the change in error is defined as the difference between the present Error e(k)and previous error e(k−1). The output, change in duty cycle ΔDC is the new duty cycle DC new that is used to control the voltage applied across the phase windings. The inputs and new duty cycle are described by

$$E = e(k) = N_{\mathrm{ref}} - N_{\mathrm{act}} \tag{16}$$

$$\mathrm{CE} = e(k) - e(k-1) \tag{17}$$

$$DC_{\mathrm{new}} = \Delta DC. \tag{18}$$

The speed range of the motor is taken as 0–4000 r/min based on the specifications of BLDC servomotor. The possible range of error is from−4000 to+4000 r/min. Therefore, the universe of discourse for error can be defined to span between−4000 and+4000 r/min. Based on the study of PID controller-based BLDC servomotor drive system, the universe of discourse for change in error is chosen as+/−500 r/min.

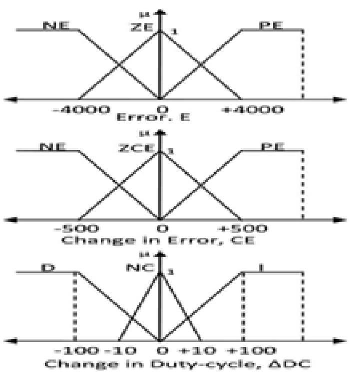

Fig.4. Membership functions for Error E, Change in Error CE, and Change in Duty Cycle ΔDC.

The maximum and minimum value for the change in duty cycle are defined as −100% and+100%, respectively. To easily handle the large values of error and change in error and reduce the computation time so as to achieve faster control action, the inputs and output are normalized.

Step 2 (Defining fuzzy membership functions and rules): To perform fuzzy computation, the inputs must be converted from numerical or crisp value into fuzzy values and the output should be converted from fuzzy value to crisp value. The fuzzy input variables "error" and "change in error" are quantized using the following linguistic terms Negative N, Zero Z, and Positive P.

The fuzzy output variable "change in duty cycle" is quantized using the following linguistic terms Decrease D, No-change NC, and Increase I. Fuzzy membership functions are used as tools to convert crisp values to linguistic terms. A fuzzy variable can contain several fuzzy subsets within, depending on how many linguistic terms are used. Each fuzzy subset represents one linguistic term. Each fuzzy subset allows its members to have different grade of membership; usually the membership value lies in the interval [0, 1]. In order to define fuzzy membership function, the designer can choose many different shapes based on their preference and experience. The popular shapes are triangular and trapezoidal because these shapes are easy to represent designer's ideas and they require less computation time. Therefore, triangular membership functions are used for inputs and output and are shown in Fig.4. In order to fine tune the controller for improving the performance, the adjacent fuzzy subsets are overlapped by about 25% or less. Instead of using mathematical formula, FLC uses fuzzy rules to make a decision and generate the control action. The rules are in the form of IF–THEN statements. There are nine rules framed for this system and they are illustrated in Fig. 5.

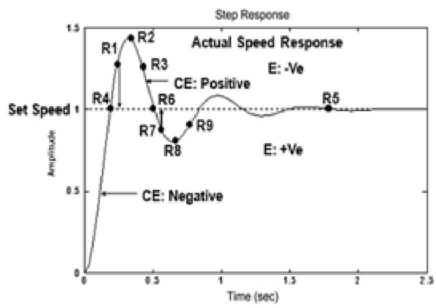

Fig.5. Illustration for the formation of rules for a typical under damped BLDC servomotor drive system.

TABLE I

3 × 3 FAM MATRIX

E / CE	NE	ZE	PE
NCE	D	D	I
ZCE	D	NC	I
PCE	D	I	I

The number of rules to be used to describe the system behavior is entirely based on the designer's experience and the previous knowledge of the system. The performance of the controller can be improved by adjusting the membership function and rules.

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A fuzzy associative memory (FAM) expresses fuzzy logic rules in tabular form. A FAM matrix maps antecedents to consequents and is a collection of IF–THEN rules. Each composition involves three fuzzy variables and each fuzzy variable is further quantized into three. This has resulted in nine possible two inputs and single output FAM rules as illustrated in the Table I. The nine rules formulated for the proposed fuzzy logic control system are listed below.
R1. IF Error E is Negative NE and Change in Error CE is Negative NCE THEN Change in duty-cycle ΔDC is Decrease D.This rule implies that when the system output is at R1, then the actual speed is greater than the reference speed (or set speed) and the motor is accelerating, so the duty cycle of the IGBTs of the Inverter module should be decreased so as to reduce the average voltage applied across the phase windings and bring the actual speed of the system close to the reference speed.

R2. IF E is Negative NE and CE is Zero ZCE THEN ΔDC is Decrease D. R3. IF E is Negative NE and CE is Positive PCE THENΔDC is Decrease D. R4. IF E is Zero ZE and CE is Negative NCE THENΔDC is Decrease D. R5. IF E is Zero ZE and CE is Zero ZCE THENΔDC is No-Change NC. This rule implies that when the system output is at R5, then there should be a no change in the duty cycle as the actual speed has already reached steady state.R6. IF E is Zero ZE and CE is Positive PCE THENΔDC is Increase I. R7. IF E is Positive (PE) and CE is Negative (NCE) THEN ΔDC is Increase (I).This rule implies that when the system output is at R7, then the actual speed is lesser than the reference speed and the motor is decelerating, so the duty cycle of the IGBTs of the Inverter module should be increased so as to increase the average voltage applied across the phase windings and bring the actual speed of the system close to the reference speed.

R8. IF E is Positive PE and CE is Zero ZCE THENΔDC is Increase I.R9. IF E is Positive PE and CE is Positive PCE THENΔDC is Increase I.Finally, the fuzzy output is converted into real value output, i.e., crisp output by the process called defuzzification. Even though many defuzzification methods are available, the most preferred one is centroid method because this method can easily be implemented and requires less computation time when implemented in digital control systems using microcontrollers or DSPs. The formula for the centroid defuzzification method is given by

$$z = \sum_{x=1}^{n} \mu(x)x / \sum_{x=1}^{n} \mu(x) \quad (19)$$

Where z is the defuzzified value and μ(x)is the membership value of memberx. This crisp value is used to control the duty cycle of the switching devices in the power inverter module so as to control the average voltage applied across the phase windings, hence the speed of the motor.

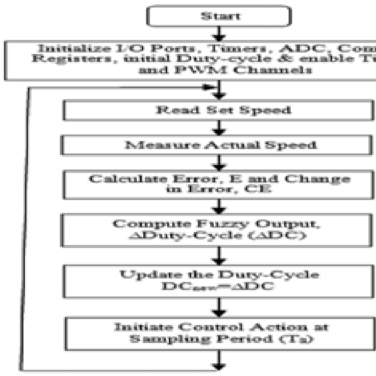

Fig. 6. Flowchart of a fuzzy controller program.

PWM1-PWM6 pins of Event Manager-A (EVA) module are used to generate gating signals. The program is written for DSP using Code Composer Studio 3.0 software and the output file generated is downloaded from personal computer to the DSP.The PWM control technique is used to control the voltage applied across the windings in order to control the speed of the motor. The choice of 20-kHz PWM signal is made because of the absence of acoustic noise during the motor operation. The duty cycle of the 20-kHz signal generated by the DSP is varied to control the average current and average voltage of the phase windings, and hence the torque produced by the motor. The duty cycle of the devices is controlled based on the fuzzy controller output. The expression for the average voltage applied across the winding is given by (20). The dc signal output of F/V converter is given as one of the input to analog-to-digital converter (ADC) of the DSP processor to determine the actual speed of the motor. The reference speed is set through a potentiometer and voltage follower and it is given as another input to the ADC converter to determine the reference speed. The other provisions to set the reference speed are by changing the value of the reference speed in the program or from watch window of code composer studio software. The function of the DSP processor is to compute the error and change in error, store these values, compute the fuzzy controller output, determine the new duty cycle for the switching devices, and perform electronic commutation. The PWM signals are generated for the IGBT switching devices using EVA module components such as timers, PWM channels, etc.

The flowchart for the fuzzy controller program is shown in Fig. 6. The steps involved are: Initialize, ADC to read actual and reference speeds, I/O ports to read hall senor signals and generate commutation signals for IGBT switches, Timer1 to generate control action time and sampling time to measure speed, Timer 2 to generate 20-kHz PWM signal, measure the reference and actual speeds, compute controller output, and initiate control action by changing the duty cycle of the IGBT switches. The control signals for the IGBTs are generated by AND ing commutation signals with PWM signal. The driver circuits are designed to operate at high frequencies. The duty cycle of the IGBTs is varied so as to vary the average voltage applied across the winding, and hence the speed of the motor. The duty cycle is initially set more than 50% so as to allow sufficient current through the motor windings to start and run the motor with load. The time period of the PWM signal is chosen such that it is greater than the time constant of the motor so as to allow sufficient current through the windings and to produce the required torque during the normal operation [3], [4], [17], [18]. The PWM control signal of 20 kHz is generated at PWM1–PWM6 pins of EVA module of DSP processor. The control action is initiated at every 1.5 ms using Timer1

$$V_o(\text{avg}) = \text{Duty} - \text{cycle} \times \; V_{dc} \tag{20}$$

$$\%\ \text{Duty} - \text{cycle} = (t_{on}/T) \times 100 \tag{21}$$

Where ton is turn-on time, T is total time period of PWM signal, Vdc is the dc input voltage applied to the inverter, and Vo (avg) is the average dc voltage applied across the phase windings.

V. Hybrid PI-Fuzzy Controller:

The objective of the hybrid controller is to utilize the best attributes of the PI and fuzzy logic controllers to provide a controller which will produce better response than either the PI or the fuzzy controller. There are two major differences between the tracking ability of the conventional PI controller and the fuzzy logic controller. Both the PI and fuzzy controller produce reasonably good tracking for steady-state or slowly varying operating conditions. However, when there is a step change in any of the operating conditions, such as may occur in the set point or load, the PI controller tends to exhibit some overshoot or oscillations. The fuzzy controller reduces both the overshoot and extent of oscillations under the same operating conditions.

Although the fuzzy controller has a slower response by itself, it reduces both the overshoot and extent of oscillations under the same operating conditions. The desire is that, by combining the two controllers, one can get the quick response of the PI controller while eliminating the overshoot possibly associated with it. Switching Control Strategy the switching between the two controllers needs a reliable basis for determining which controller would be more effective. The answer could be derived by looking at the advantages of each controller.

Both controllers yield good responses to steady-state or slowly changing conditions. To take advantage of the rapid response of the PI controller, one needs to keep the system responding under the PI controller for a majority of the time, and use the fuzzy controller only when the system behavior is oscillatory or tends to overshoot. Thus, after designing the best stand-alone PI and fuzzy controllers, one needs to develop a mechanism for switching from the PI to the fuzzy controllers, based on the following two conditions:

1) Switch when oscillations are detected;
2) Switch when overshoot is detected.

The switching strategy is then simply based on the following conditions: IF the system has an oscillatory behavior THEN fuzzy controller is activated, Otherwise PI controller is operated. IF the system has an overshoot THEN fuzzy controller is activated, Otherwise PI controller is operated. The system under study is considered as having an overshoot when the error is zero and the rate of change in error is any other value than zero. The system is considered oscillatory when the sum of the absolute values of the error taken over time does not equal the absolute values of the sum of the error over the same period of time. Since the system is expected to overshoot during oscillatory behavior, the only switching criterion that needs to be considered is overshoot.

However, in practice, it is more convenient to directly implement the control signal according to the control actions delivered by the controller. Consequently, the fuzzy controller can be designed so that normal behavior (no oscillations or overshoot) results in a null fuzzy action. Accordingly, the switching between the two controllers reduces to using PI if the fuzzy has null value; otherwise, the fuzzy output is used. In particular, the fuzzy controller can be designed so that a normal behavior.

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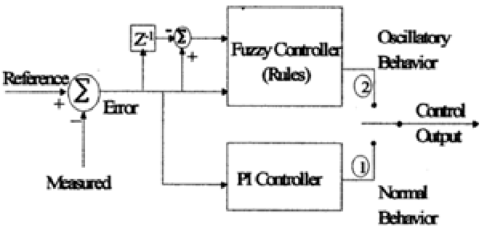

Fig.7 Structure of switching strategy results in a null fuzzy action.

V.MATLAB/SIMULINK RESULTS

Case i: By using PID controllers

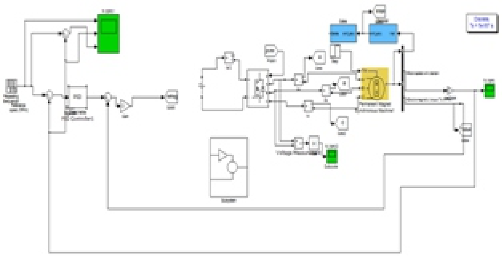

Fig.8. Simulink circuit for bldc drive for step change load by using pid controller

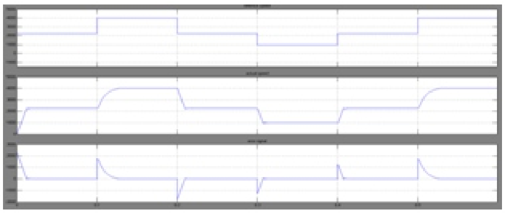

Fig. 9. Simulation results for Speed response of the PID controller-based BLDC servomotor drive for step change in reference speed with system parameters J1, R1 and 100%Load. (a) Reference speed; (b) Actual speed; (c) Error

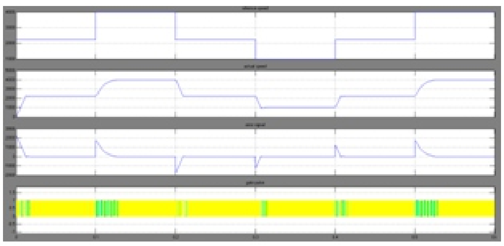

Fig. 5. Speed response of the PID controller-based BLDC servomotor drive for step change in reference speed with system parameters J1, R1 and 20% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) %Duty cycle.

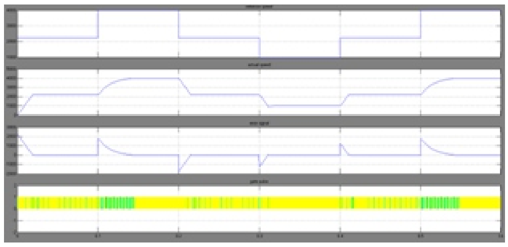

Fig. 7. Speed response of the PID controller-based BLDC servomotor drive for step change in reference speed with system parameters J2, R2, and 100% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) %Duty cycle.

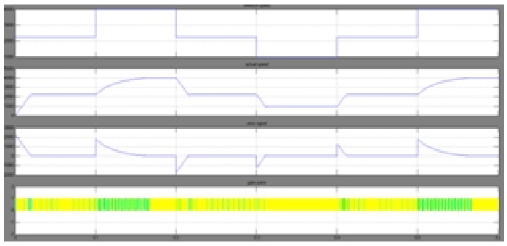

Fig. 6. Speed response of the PID controller-based BLDC servomotor drive for step change in reference speed with system parameters J2, R1, and 100% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) %Duty cycle.

Case ii: By using Fuzzy controllers

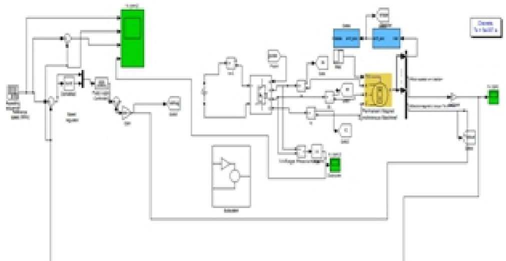

Fig.8. Simulink circuit for bldc drive for step change load by using fuzzy controller

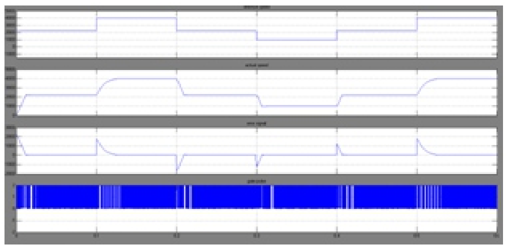

Fig. 5. Speed response of the PID controller-based BLDC servomotor drive for step change in reference speed with system parameters J1, R1 and 100% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) %Duty cycle.

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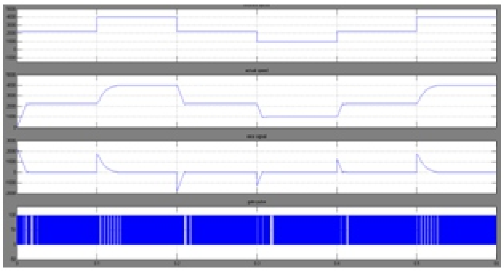

Fig. 5. Speed response of the PID controller-based BLDC servomotor drive for step change in reference speed with system parameters J1, R1 and 20% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) %Duty cycle.

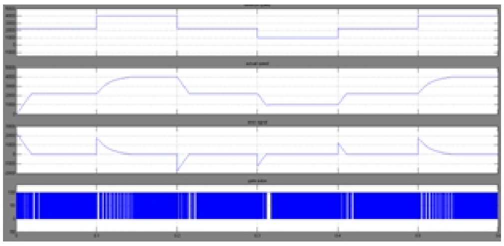

Fig. 7. Speed response of the PID controller-based BLDC servomotor drive for step change in reference speed with system parameters J2, R2, and 100% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) %Duty cycle.

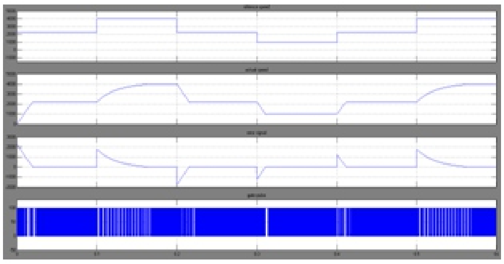

Fig. 6. Speed response of the PID controller-based BLDC servomotor drive for step change in reference speed with system parameters J2, R1, and 100% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) %Duty cycle.

VI.CONCLUSION:

This paper presented the design of a hybrid PI-fuzzy control system for the speed control of a brushless dc motor The performance of the fuzzy logic controller is better under transient conditions, while that of the proportional plus integral controller is superior near the steady state condition. The combined advantages of these two controllers can be obtained with hybrid PI-fuzzy speed controller. Mathematical model of the BLDC motor is studied. Based on this, the modeling and simulation of the proposed control system is done.

The performance of the system using PI controller, fuzzy logic controller and hybrid PI- fuzzy controller are compared. It is shown through extensive simulation that the performance of the Hybrid PI- Fuzzy controller is better than using PI controller and fuzzy controller alone for the speed control of BLDC motor.

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