Implementation and Performance Analysis of Digital Controllers for Brushless DC Motor Drives

R. Shanmugasundram, *Member, IEEE*, K. Muhammad Zakariah, and N. Yadaiah, *Senior Member, IEEE*

***Abstract*—This paper presents design and digital implementation of a fuzzy controller for achieving improved performance of Brushless dc (BLDC) servomotor drive. The performance of fuzzy and PID controller-based BLDC servomotor drives is investigated under different operating conditions such as change in reference speed, parameter variations, load disturbance, etc. BLDC servomotors are used in aerospace, instrumentation systems, space vehicles, electric vehicles, robotics, and industrial control applications. In such applications, conventional controllers like P, PI, and PID are being used with the BLDC servomotor drive control systems to achieve satisfactory transient and steady-state responses. However, the major problem associated with the conventional PID controller is that the tuned gain parameters obtained for such BLDC servomotor drive control systems do not yield better transient and steady-state responses under different operating conditions such as parameter variations, load disturbances, etc. In this paper, design and implementation of fuzzy controller is presented and its performance is compared with PID controller to show its capability to track the error and usefulness of 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) servomotor drives have been widely used in aeronautics, electric vehicles, robotics, and food and chemical industries. The conventional controllers like P, PI, and PID are being used for control applications over few decades. It is essential to know the exact mathematical model of the system or response of the system for designing these controllers but in practical applications, systems are found to be nonlinear and complex; so they are approximated as linear systems to obtain their mathematical model. The controller designed for such systems can only give satisfactory transient and steady-state responses but not optimum responses. In most of the literature, it has been assumed that the system parameters never change during operating conditions, but in practical applications the mechanical load parameters such as inertia and friction may change due to coupling or decoupling inertia elements, and change in load. The phase resistance of the BLDC servomotor may also slightly change due to addition of terminal resistance, change in winding resistance, and on-state resistance of the semiconductor switches due to change in temperature during operating conditions. It has been found that the ratio of no load to full load friction is 1:15 and the change in moment of inertia [20], [24], [29] is up to 10–20 times due to coupling or decoupling inertia elements for typical automation, motion control, and positioning applications. The main disadvantage of the conventional controllers is that they can provide better transient and steady-state responses only when the system parameters for which they are designed remain unchanged. But in most of the practical systems, parameters of the system change during operation. In this paper, design and implementation of fuzzy controller-based BLDC servomotor drive using TMS320LF2407A digital signal processor (DSP) is described and experimental results are presented to compare its performance with the PID controller-based BLDC servomotor drive. The performance of these controllers and their suitability for wide range speed control of BLDC servomotor drive are investigated under different operating conditions such as change in reference speed, parameter variations, and load disturbance.

The information referred from various literatures for carrying out this study is as follows. The modeling of BLDC motor, estimation of parameters, and control schemes are discussed in [1]–[4], [15], [23], [25], [26]. The effect of change in motor parameters on the performance of the BLDC drive system is discussed in [5], [6], [20], [24], [29], [30]. Several tuning methods for the PID controllers are described in [7]–[9]. The tuning method suggested in [8] is found to yield desired results, and hence this method is adopted for determining PID controller gain parameters. Design, implementation, and performance analysis of fuzzy logic controllers (FLCs) for various applications such as dc servomotor, BLDC motor, gas-turbine plant, servo systems, etc., are presented in [4], [10]–[12], [27], [28]. The genetic algorithm-based method for the determination of the PID controller parameters for achieving improved performance is discussed in [13]. The robust adaptive and optimal control scheme to compensate for parametric and dynamic uncertainties in the BLDC motor drives is investigated in [14], [25], and [30]. The design of BLDC motor controller for electric vehicle application and BLDC motor drives is described in [15] and [16]. The pulsewidth modulated (PWM) and digital control schemes for the BLDC motor drives are discussed in [17] and [18]. Design and implementation of adaptive controllers

Manuscript received January 4, 2012; revised August 15, 2012; accepted October 7, 2012. Date of publication November 30, 2012; date of current version January 17, 2014. Recommended by Technical Editor J. M. Berg.

R. Shanmugasundram is with the Department of Electrical and Electronics Engineering, Sri Ramakrishna Engineering College, Coimbatore 641022, India (e-mail: rss_is@ yahoo.com).

K. M. Zakariah was with the Department of Electronics and Communication Engineering, SNS College of Technology, Coimbatore 641 035, India. He is now a Consultant in Coimbatore, India (e-mail: kmzakariah@yahoo.co.in).

N. Yadaiah is with the Department of Electrical and Electronics Engineering, JNTUH College of Engineering (Autonomous), Hyderabad 500085, India (e-mail: svpnarri@yahoo.com).

Digital Object Identifier 10.1109/TMECH.2012.2226469

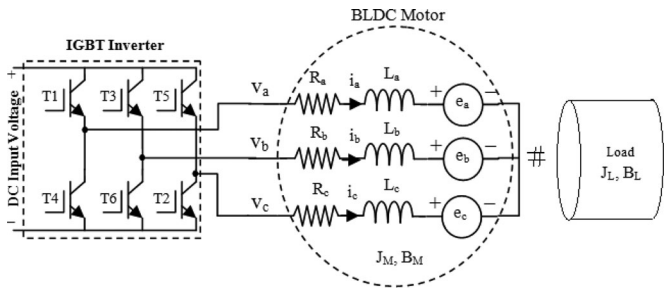

Fig. 1. Equivalent circuit of the BLDC servomotor drive system.

for improving the performance of dc motors and BLDC drives under different operating conditions are discussed in [20]–[22].

This paper is organized into five sections. In Section II, modeling of BLDC servomotor drive is presented; Section III, design and implementation of PID controller are described; Section IV, design and implementation of fuzzy controller are presented, and finally conclusion is presented in Section V.

II. Modeling of BLDC Servomotor 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

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

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

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

where L and M are self-inductance and mutual inductance per phase; R is the stator winding resistance per phase; e_a, e_b, and e_c are the back EMFs of phases a, b, and c, respectively; i_a, i_b, and i_c 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 $i_a = i_b = i_c = I, \omega$ is the angular velocity in radians per second, and K_t 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 B_L components as

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

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 K_b 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, J_M, J_L, B_M, and B_L. These parameters can influence the speed response of the BLDC servomotor drive system. Increase in the value of energy storage inertia elements J_M and J_L will increase the settling time of the speed response or vice versa. The decrease in the values of power consuming friction components B_M and B_L 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. 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.

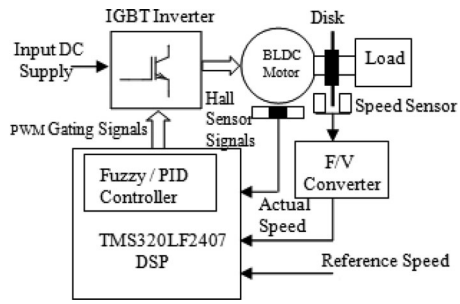

Fig. 2. Block diagram of the experimental setup.

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

$$u(t) = K_P\left(e(t) + (1/T_i)\int e(t)dt + T_d de(t)/dt\right) \tag{8}$$

where, K_P is the proportional gain, T_i is the integral time constant, T_d 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

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

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

$$K_1 = K_P + TK_i/2 + K_d/T \tag{10}$$

$$K_2 = -K_P - 2K_d/T + TK_i/2 \tag{11}$$

$$K_3 = K_d/T \tag{12}$$

$$K_i = K_P/T_i \tag{13}$$

$$K_d = K_P T_d \tag{14}$$

$$T = 1/f \tag{15}$$

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. The PID controller gains determined are $K_p = 11$, $K_i = 5$, and $K_d = 0.1$ for the BLDC servomotor drive system with effective inertia of motor and load $J = 350\text{e-}6$ kg-m^2, total friction coefficient of motor and load $B = 1\text{e-}4$ N·m/(rad/s), resistance per phase $R = 0.57\ \Omega$, and inductance per phase $L = 1.5$ mH.

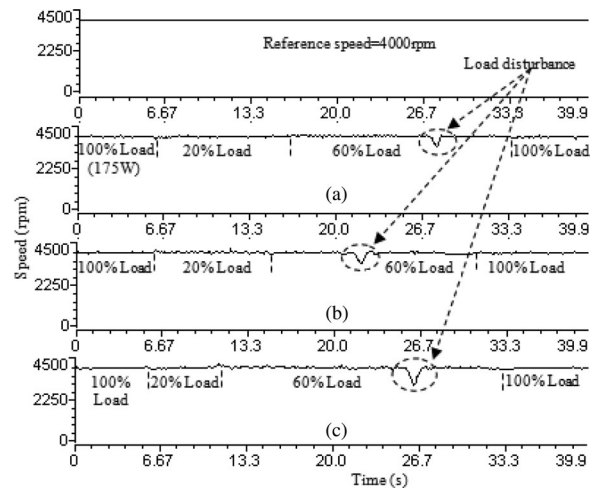

Fig. 3. Speed response of PID controller-based BLDC servomotor drive for a particular load pattern and load disturbance with different system parameters: (a) J_1, R_1; (b) J_2, R_1; (c) J_2, R_2.

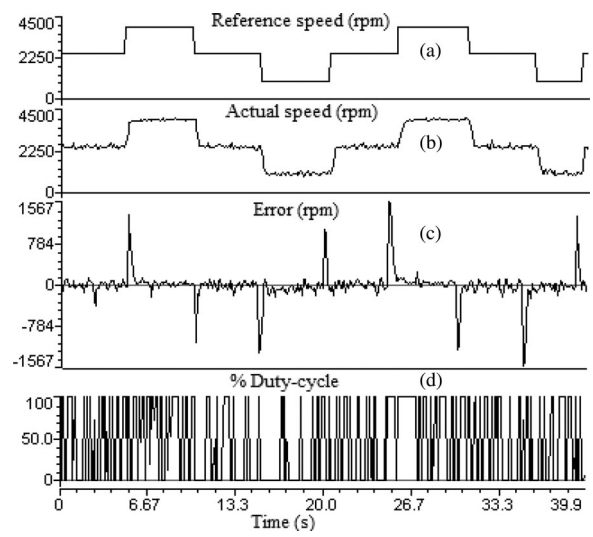

Fig. 4. Speed response of the PID controller-based BLDC servomotor drive for step change in reference speed with system parameters J_1, R_1 and 100% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) %Duty cycle.

The PID control algorithm is implemented using a DSP, TMS320LF2407A. This system is tested under different operating conditions such as parameters variations, change in reference speed, and load disturbance. The results are presented in the following section.

A. Results and Discussion

The system responses are obtained for different operating conditions such as change in reference speed, load disturbance, different inertia of the system, and different phase resistance of BLDC servomotor and shown in Figs. 3–7. The PID controller-based BLDC servomotor drive system is tested 1) by changing

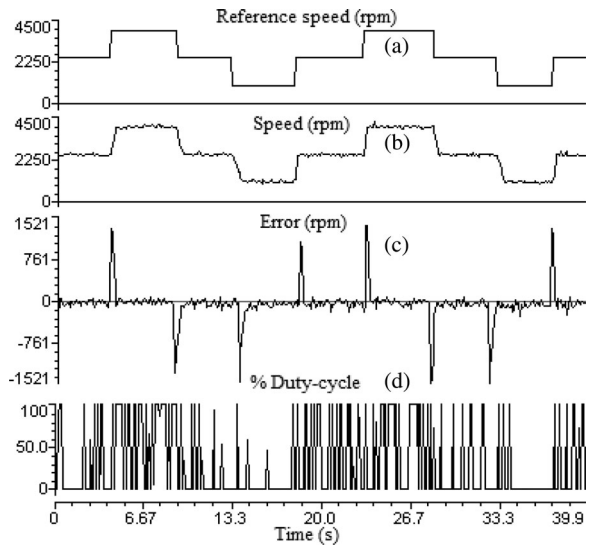

Fig. 5. Speed response of the PID controller-based BLDC servomotor drive for step change in reference speed with system parameters J_1, R_1 and 20% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) %Duty cycle.

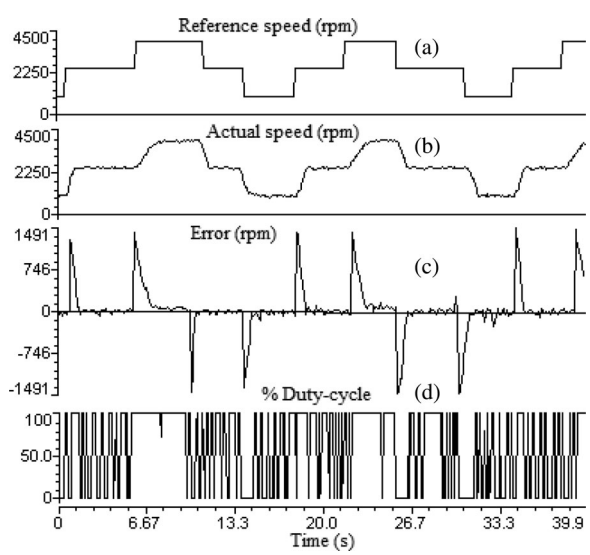

Fig. 6. Speed response of the PID controller-based BLDC servomotor drive for step change in reference speed with system parameters J_2, R_1, and 100% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) %Duty cycle.

the reference speed in steps from 1000–2500–4000–2500–1000 r/min; 2) for two different inertia of the system $J_1 =$ 350e-6 kg-m^2 and $J_2 =$ 560e-6 kg-m^2; 3) for two different phase resistance of the BLDC servomotor $R_1 = 0.57\ \Omega$, $R_2 = 1.14\ \Omega$; 4) applying load disturbance; and 5) changing load. A cylindrical iron piece has to be attached to the rotor shaft to increase the system inertia and external resistance has to be included in series with each phase winding to increase the per phase resistance of the BLDC servomotor. Fig. 3 shows the speed responses of the system for a particular change in load pattern from 100–20–60–100% with load disturbance, reference speed = 4000 r/min, different system inertia J_1 and J_2, and different phase resistance of the BLDC servomotor R_1 and R_2.

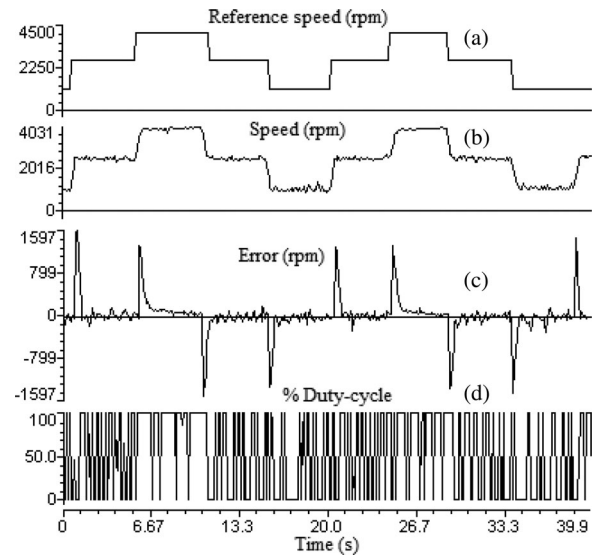

Fig. 7. Speed response of the PID controller-based BLDC servomotor drive for step change in reference speed with system parameters J_2, R_2, and 100% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) %Duty cycle.

The speed responses obtained for three different combinations of system parameters: 1) J_1 and R_1; 2) J_2 and R_1; and 3) J_2 and R_2 with 100% load applied to the BLDC servomotor and the reference speed of 4000 r/min are shown in Fig. 3(a)–(c). It is inferred from the speed responses that the PID controller-based BLDC servomotor drive system can track the speed error and quickly bring the actual speed close to the reference speed whenever there is a change in load or load disturbance. When load is suddenly decreased or increased, the speed response momentarily oscillates before settling at the reference speed. When only the system inertia is increased from $J_1 \rightarrow J_2$, the speed response takes more time to reach the steady speed. If both the phase resistance and system inertia are increased from $R_1 \rightarrow R_2$ and $J_1 \rightarrow J_2$, respectively, the speed response takes slightly more time to reach the steady speed as compared to the speed response obtained with system parameters J_1 and R_1, and takes less time to reach the steady speed as compared to the speed response obtained with system parameters J_2 and R_1. Therefore, the settling time and rise time of the speed response are found to be increasing for the system parameters from $J_1, R_1 \rightarrow J_2, R_2 \rightarrow J_2, R_1$.

The speed response, its corresponding error, and percent change in duty cycle of the IGBT switches due to step change in reference speed from 1000–2500–4000–2500–1000 r/min and with system parameters J_1 and R_1, and 100% load applied to the BLDC motor are shown in Fig. 4. It is inferred from the speed response that this system tracks the change in reference speed and maintains actual speed within ± 60 r/min or $\pm 1.5\%$ of maximum speed of BLDC motor. The value of error is found to increase whenever the reference speed is suddenly increased or decreased. The duty cycle of IGBT switches is found to vary proportional to error. The duty cycle varies between 0% and 100% due to variation in error. The duty cycle becomes 100% so as to apply maximum voltage to the BLDC servomotor when the error reaches or exceeds 36 which is the maximum

supply voltage applied to the BLDC servomotor. The duty cycle becomes 0% to apply zero voltage to the BLDC servomotor when the error reaches zero or becomes negative. The increase in duty cycle of the IGBT switches accelerates the BLDC servomotor and decrease in duty cycle of the switches decelerates the BLDC servomotor. In the PWM control technique, the duty cycle is adjusted to produce the required average phase voltage and average phase current so as to supply the required power to the BLDC servomotor to drive the load, produce a sufficient torque, and maintain the speed. The duty cycle is found to be close to 100%, when maximum load is applied to the BLDC motor and it is running at a maximum speed 4000 r/min. The settling time, rise time, steady-state error, and deceleration time of the speed response are found to be 300, 250 ms, ±60 r/min, and 200 ms, respectively.

The speed response, its corresponding error, and percent change in duty cycle of the IGBT switches due to step change in reference speed from 1000–2500–4000–2500–1000 r/min with system parameters J_1 and R_1 and 20% load applied to the BLDC motor are shown in Fig. 5. The settling time, rise time, steady-state error, and deceleration time of the speed response are found to be 300, 250 ms, ±60 r/min, and 350 ms, respectively.

The system is found to track the speed error and maintain an actual speed close to the reference speed. The duty cycle of the IGBT switches is found to vary according to speed error. The decelerating time is found to increase with decrease in load applied to the BLDC servomotor. Since the load applied to the BLDC motor is 20%, the average current drawn by the BLDC servomotor is 1 A and the torque developed by the BLDC servomotor is 0.084 N·m at speed 4000 r/min.

The speed response, its corresponding error, and percent change in duty cycle of the IGBT switches due to step change in reference speed from 1000–2500–4000–2500–1000 r/min and with system parameters J_2 and R_1, and 100% load applied to the BLDC servomotor are shown in Fig. 6. The settling time, rise time, steady-state error, and deceleration time of the speed response are found to be 900, 700 ms, ±60 r/min, and 400 ms, respectively. The speed response takes more time to reach steady speed due to increase in system inertia from $J_1 \rightarrow J_2$. The decelerating time is also found to increase due to increase in system inertia and with 100% load. The decelerating time is found to further increase to 500 ms when the load is reduced to 20%. The experimental results of PID controller-based BLDC servomotor drive are given in Table II.

The speed response, its corresponding error, and percent change in duty cycle of the IGBT switches due to step change in reference speed from 1000–2500–4000–2500–1000 r/min and with system parameters J_2 and R_2, and 100% load applied to the BLDC servomotor are shown in Fig. 7. The settling time, rise time, steady-state error, and deceleration time of the speed response are found to be 400, 300 ms, ±60 r/min, and 250 ms, respectively. The settling time of speed response is reduced due to increase in both inertia of the system from $J_1 \rightarrow J_2$ and phase resistance of the BLDC servomotor from $R_1 \rightarrow R_2$, as compared to the speed response obtained with parameters J_2 and R_1. The decelerating time is found to be 250 ms at 100% load and 400 ms at 20%.

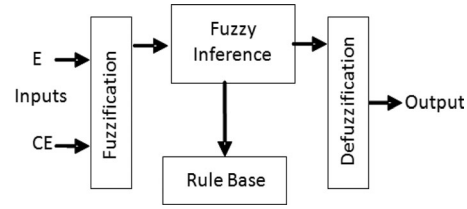

Fig. 8. Block diagram of a fuzzy inference system.

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. 8. 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 N_{ref} and actual speed N_{act} 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. The maximum and

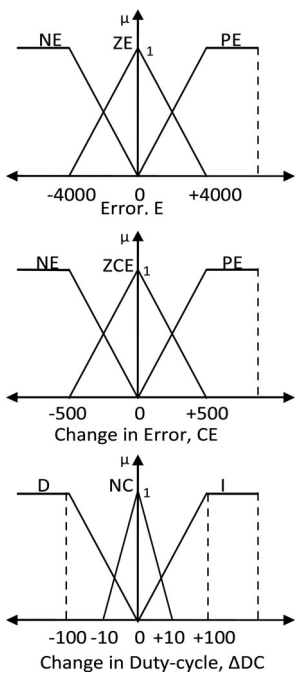

Fig. 9. Membership functions for Error E, Change in Error CE, and Change in Duty Cycle ΔDC.

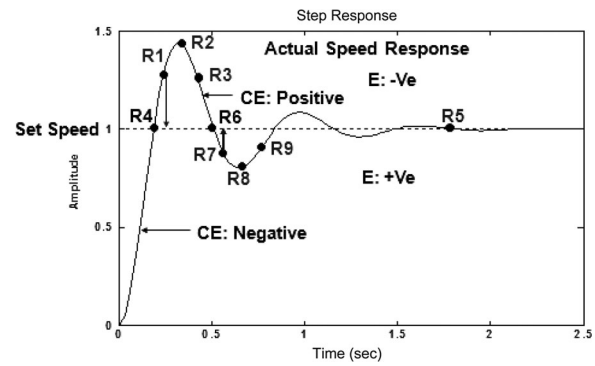

Fig. 10. Illustration for the formation of rules for a typical underdamped BLDC servomotor drive system.

TABLE I
3 × 3 FAM MATRIX

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

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. 9. 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. 10. 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. 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 THEN ΔDC is Decrease D.

R4. IF E is Zero ZE and CE is Negative NCE THEN ΔDC is Decrease D.

R5. IF E is Zero ZE and CE is Zero ZCE THEN ΔDC 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 THEN ΔDC 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 THEN ΔDC is Increase I.

R9. IF E is Positive PE and CE is Positive PCE THEN ΔDC 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

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

where z is the defuzzified value and $\mu(x)$ is the membership value of member x. 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.

A. Experimental Setup

The block diagram of the experimental setup is shown is Fig. 2. The experimental setup consists of four major components. They are IGBT power inverter, BLDC servomotor with loading arrangement, speed, phase voltage and phase current sensing circuits, and TMS320LF2407A DSP. The BLDC servomotor is an electronically commutated motor. The built-in hall sensors generate three signals according to the rotor position. These signals are decoded to identify the rotor position and energize the appropriate windings by switching the appropriate switches in the IGBT power inverter.

The low cost, reliable power hybrid IC "IRMAY20UP60B" [3] that is designed for motor drive applications by the International Rectifiers is used as a power inverter to perform electronic commutation and control the phase voltages of the BLDC servomotor. This power hybrid IC is integrated with high-speed driver, thermal overload, and short-circuit current limit protection circuits. The hybrid power module IC replaces the conventional bulky and expensive MOSFET/IGBT inverter and associated isolation and driver circuits. This IC requires low voltage nearly 3 and 0 V to turn OFF and turn ON, respectively. Moreover, the effects of electromagnetic interference and noise signal are completely eliminated. The high-speed digital buffer IC 74HCT244 is used to interface DSP with hybrid power module IC and hall sensor circuit. The hall sensor signals are applied as input to the DSP through buffer IC. The gating signals generated by the DSP for the IGBT switches are also applied through buffer IC.

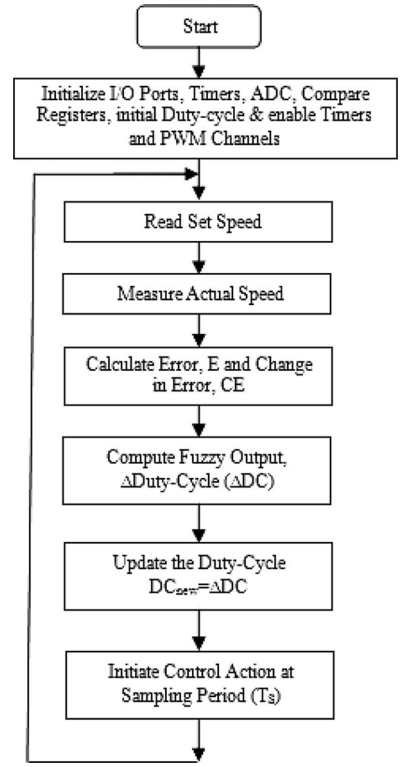

Fig. 11. Flowchart of a fuzzy controller program.

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. 11. The steps involved are: Initialize, ADC to

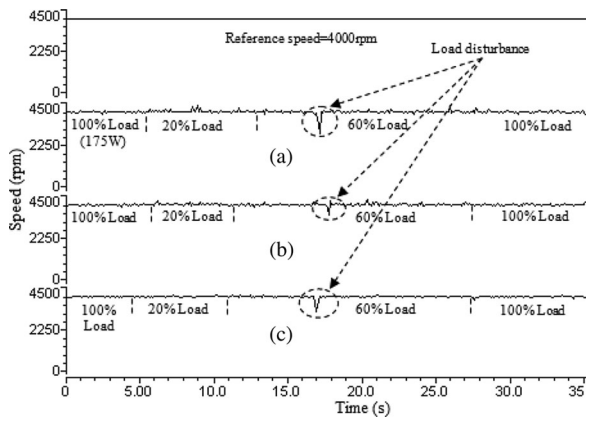

Fig. 12. Speed response of the Fuzzy controller-based BLDC servomotor drive for a particular load pattern with different system parameters: (a) J_1, R_1; (b) J_2, R_1; (c) J_2, R_2.

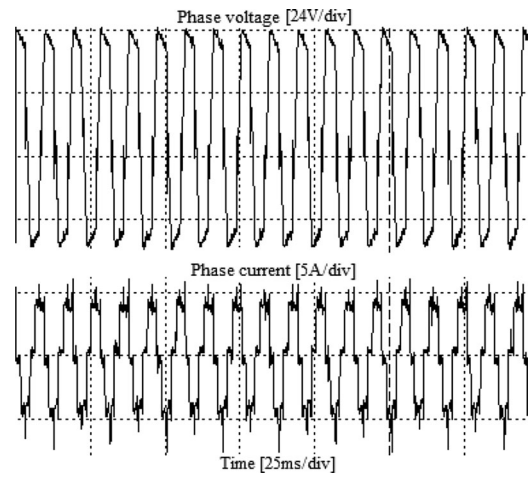

Fig. 13. Phase voltage and current response for 100% Dutycycle.

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, Timer2 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 ANDing 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

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

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

where t_{on} is turn-on time, T is total time period of PWM signal, V_{dc} is the dc input voltage applied to the inverter, and V_o (avg) is the average dc voltage applied across the phase windings.

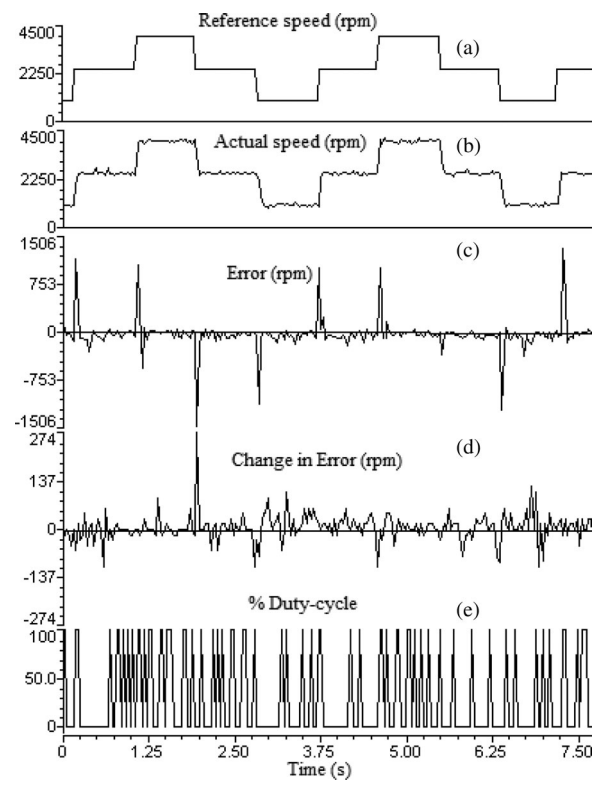

Fig. 14. Speed response of the Fuzzy controller-based BLDC servomotor drive for step change in reference speed with system parameters J_1, R_1 and 100% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) Change in Error; (e) %Duty cycle.

B. Results and Discussion

The experimental results obtained for fuzzy controller-based BLDC servomotor drive under different operating conditions such as step change in reference speed, different inertia of the system, different phase resistance of the BLDC servomotor, and with load disturbance are shown in Figs. 12–18 and Fig. 20.

Fig. 12 shows the speed responses of the system for a particular change in load pattern from 100–20–60–100% with load disturbance, reference speed = 4000 r/min, different system inertia J_1 and J_2, and different phase resistance of the motor R_1 and R_2.

The speed responses obtained for three different combinations of system parameters: 1) J_1 and R_1; 2) J_2 and R_1; and 3) J_2 and R_2 with 100% load applied to the BLDC servomotor and reference speed of 4000 r/min are shown in Fig. 12(a)–(c).

It is inferred from the speed responses that this system is able to track the speed error and follow the reference speed for different combinations of inertia of the system and phase resistance of BLDC servomotor and with load disturbance. The steady-state error is found to be within ±60 r/min. The speed response of the system with parameters J_1 and R_1 is found to

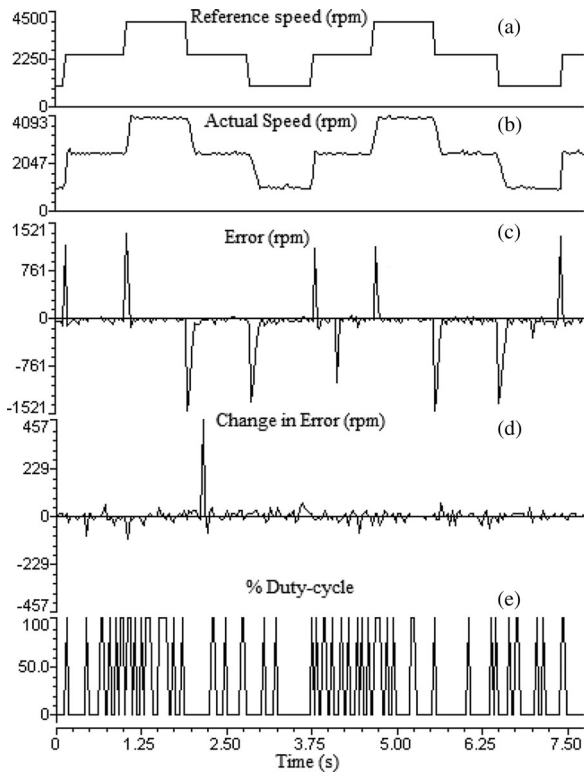

Fig. 15. Speed response of the Fuzzy controller-based BLDC servomotor drive for step change in reference speed with system parameters J_1, R_1 and 20% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) Change in Error; (e) %Duty cycle.

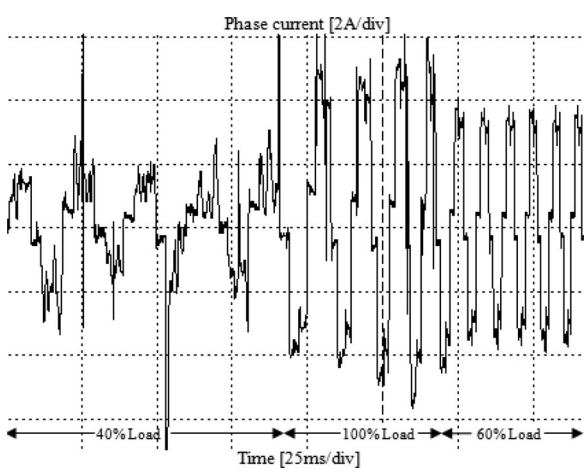

Fig. 16. Phase current response for step change in load applied to the BLDC servomotor.

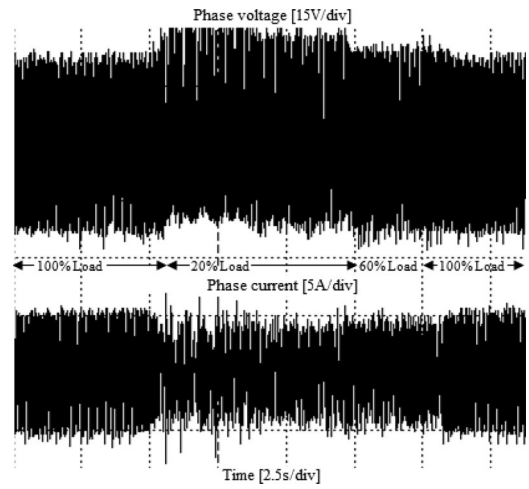

Fig. 17. Phase voltage and current response for step change in load applied to the BLDC servomotor.

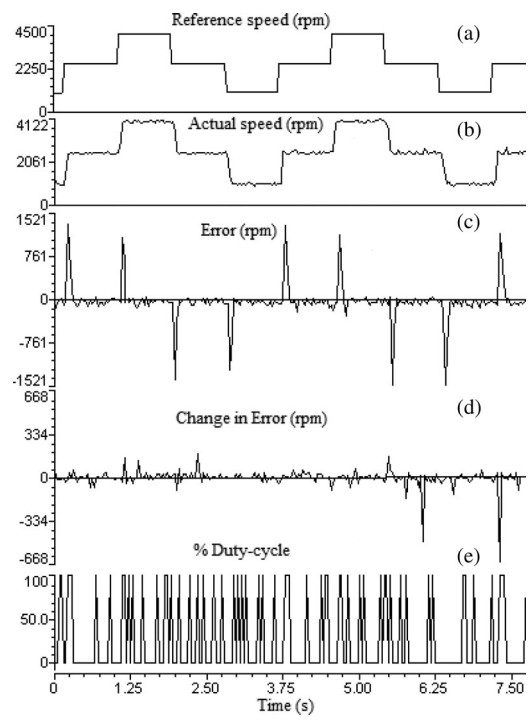

Fig. 18. Speed response of the Fuzzy controller-based BLDC servomotor drive for step change in reference speed with system parameters J_2, R_1 and 100% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) Change in Error; (e) %Duty cycle.

quickly reach the steady state after load disturbance as compared with speed response obtained with system parameters J_2 and R_1, and J_2 and R_2. The settling time of the speed response obtained with system parameters J_2 and R_1 is found to be much higher than other two combinations. However, the speed response of fuzzy controller-based BLDC servomotor drive is found to be much faster than PID controller-based BLDC servomotor drive under load conditions.

The phase current and phase voltage response obtained when the duty cycle of the IGBT switches is 100% is shown in Fig. 13. The phase voltage is almost trapezoidal in shape and phase current is a 120° square wave.

The speed response, its corresponding error, and percent change in duty cycle of the IGBT switches due to step change in reference speed from 1000–2500–4000–2500–1000 r/min with system parameters J_1 and R_1 and 100% load applied to the BLDC servomotor are shown in Fig. 14. The settling time, rise time, steady-state error, and deceleration time of the speed response are found to be 300, 250 ms, ±60 r/min, and 200 ms, respectively. The speed response is found to exhibit overshoot when there is a sudden large change in reference speed. This

system is able to track the speed error and maintains the actual speed close to the reference speed whenever there is a change in reference speed. The BLDC servomotor is found to decelerate within 200 ms when 100% load is applied to the BLDC servomotor. The duty cycle of the IGBT switches is found to vary proportional to error and provide the required control voltage to the BLDC servomotor.

The speed response obtained with system parameters J_1 and R_1 and 20% load applied to the BLDC servomotor is shown in Fig. 15. The settling time, rise time, steady-state error, and deceleration time of the speed response are found to be 300, 250 ms, ±60 r/min, and 300 ms, respectively. The deceleration time is found to have increased with decrease in load applied to the BLDC servomotor. It is found that speed response of fuzzy controller-based BLDC motor drive is almost similar to the speed response of the PID controller-based BLDC motor drive with system parameters J_1 and R_1.

The peak amplitude of phase current is found to increase when there is a sudden increase in load and decrease when there is a sudden decrease in load applied to the BLDC servomotor. The peak amplitude of phase current is found to be 1 A at 20% load, 2 A at 40% load, 3 A at 60% load, 4 A at 80% load, and 5 A at 100%. The variation of phase current due to change in load applied to the BLDC servomotor is shown in Fig. 16. The torque developed by the BLDC servomotor at 4000 r/min is 0.084 N·m at 20% load, 0.168 N·m at 40% load, 0.252 N·m at 60% load, 0.336 N·m at 80% load, and 0.42 N·m at %100 load applied to BLDC servomotor.

The phase current and phase voltage response obtained due to percentage change in load from 100–20–60–100% is shown in Fig. 17. It is found that the peak amplitude of phase back EMF increases when there is a sudden decrease in load. This is because the speed increases due to sudden decrease in load. Similarly, the peak amplitude of phase back EMF decreases when the speed decreases because of a sudden increase in load.

The speed response, its corresponding error, and percent change in duty cycle of the IGBT switches due to step change in reference speed from 1000–2500–4000–2500–1000 r/min with system parameters J_2 and R_1 and 100% load applied to the BLDC servomotor are shown in Fig. 18. The settling time, rise time, steady-state error, and deceleration time of the speed response are found to be 200, 150 ms, ±60 r/min, and 200 ms, respectively. This system is found to track the speed error and maintain actual speed close to the reference speed. Moreover, this system accelerates and decelerates faster as compared to the PID controller-based BLDC servomotor drive system with parameters J_2 and R_1 and 100% load applied to the BLDC motor. The duty cycle of the IGBT switches is found to vary proportional to error and provide the required control voltage to the BLDC servomotor. The photograph of the experimental setup is shown in Fig. 19.

The speed response, its corresponding error, and percent change in duty cycle of the IGBT switches due to step change in reference speed from 1000–2500–4000–2500–1000 r/min with system parameters J_2 and R_2 and 100% load applied to the BLDC servomotor are shown in Fig. 20. The settling time, rise time, steady-state error, and deceleration time of the speed response are found to be 250 ms, 200 ms, ±60 r/min, and 200 ms, respectively. It is found that speed response always follows the change in reference speed and settles close to the reference speed. The speed response is found to be much faster than PID controller-based BLDC servomotor drive with system parameters J_2 and R_2 and 100% load applied to the BLDC motor. The decelerating time is found to be less due to increase in the load applied to the BLDC servomotor. When the load applied to the BLDC servomotor is reduced to 20%, the decelerating time increases to 300 ms. The duty cycle is found to vary proportional to error and provide required control voltage to the BLDC

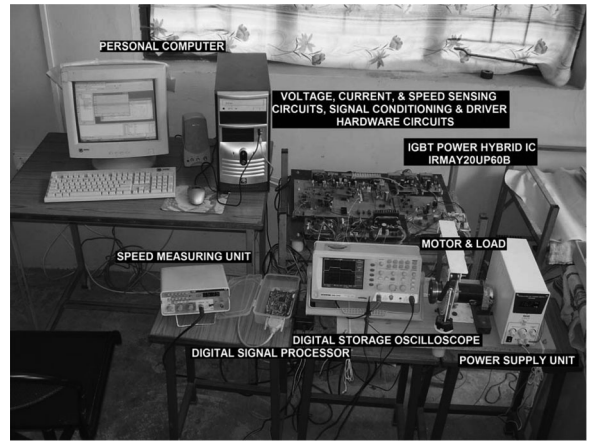

Fig. 19. Photograph of the experimental setup.

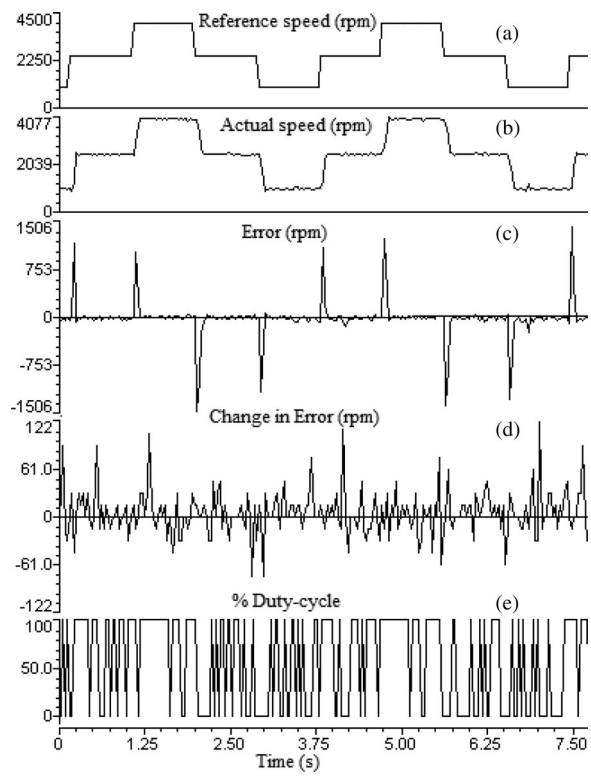

Fig. 20. Speed response of the Fuzzy controller-based BLDC servomotor drive for step change in reference speed with system parameters J_2, R_2 and 100% Load. (a) Reference speed; (b) Actual speed; (c) Error; (d) Change in Error; (e) %Duty cycle.

TABLE II
EXPERIMENTAL RESULTS OF PID CONTROLLER-BASED BLDC SERVOMOTOR DRIVE

PARAMETERS OF THE TESTED SYSTEM	SETTLING TIME, t_s (ms)	RISE TIME, t_r (ms)	DECELERATION TIME, t_d (ms)	STEADY-STATE ERROR
J_1, R_1, LOAD:100%	300	250	200	±60rpm
J_1, R_1, LOAD:20%	300	250	350	±60rpm
J_2, R_1, LOAD:100%	900	700	400	±60rpm
J_2, R_1, LOAD:20%	900	700	500	±60rpm
J_2, R_2, LOAD:100%	400	300	250	±60rpm
J_2, R_2, LOAD:20%	400	300	400	±60rpm

TABLE III
EXPERIMENTAL RESULTS OF FUZZY CONTROLLER-BASED BLDC SERVOMOTOR DRIVE

PARAMETERS OF THE TESTED SYSTEM	SETTLING TIME, t_s (ms)	RISE TIME, t_r (ms)	DECELERATION TIME, t_d (ms)	STEADY-STATE ERROR
J_1, R_1, LOAD:100%	300	250	200	±60rpm
J_1, R_1, LOAD:20%	300	250	300	±60rpm
J_2, R_1, LOAD:100%	200	150	200	±60rpm
J_2, R_1, LOAD:20%	200	150	280	±60rpm
J_2, R_2, LOAD:100%	250	200	200	±60rpm
J_2, R_2, LOAD:20%	250	200	300	±60rpm

motor. The experimental results of fuzzy controller-based BLDC servomotor drive are given in Table III.

V. CONCLUSION

The PID and fuzzy control techniques are successfully implemented for the BLDC servomotor drive system. The effect of parameter variations on the performance of the BLDC servomotor drive system is investigated with experimental results. The experimental results given in Tables II and III show that speed response of fuzzy controller-based BLDC servomotor drive is similar to the speed response of PID controller-based BLDC servomotor drive when the system parameters are J_1 and R_1. However, the speed response of fuzzy controller-based BLDC servomotor drive is found to be better than the speed response of PID controller-based BLDC servomotor drive when the system parameters are J_2 and R_1 and J_2 and R_2. Therefore, PID controller-based BLDC servomotor drive failed to provide improved performance under parameter variations of the system. But, the experimental results clearly show that fuzzy controller-based BLDC servomotor drive can provide an improved speed response with consistently same rise time, and settling time when the system is subjected to load disturbance, parameter variations, and step change in reference speed. Since the fuzzy control system is easy to design and implement, effective in dealing with the uncertainties and parameter variations, and has better overall performance, fuzzy controller-based BLDC servomotor drive system may be preferred over PID controller-based BLDC servomotor drive for automation, robotics, position and velocity control systems, and industrial control applications.

APPENDIX

SPECIFICATIONS OF BLDC MOTOR

Rated Voltage	36V
Rated Current	5A
No. of Poles	4
No. of Phases	3
Rated Speed	4000 RPM
Rated Torque	0.42 N.m
Torque Constant	0.082 N.m/A
Mass	1.25 kg
Inertia	23e-06 kg-m^2
Resistance per phase	0.57 Ω
Inductance per phase	1.5 mH

ACKNOWLEDGMENT

The authors thank the Management and Principal of Sri Ramakrishna Engineering College, Coimbatore, JNTUH, Hyderabad, and AICTE, New Delhi, for providing valuable support and facilities to carry out this study.

REFERENCES

[1] R. Krishnan, *Permanent Magnet Synchronous and Brushless DC Motor Drives: Theory, Operation, Performance, Modeling, Simulation, Analysis, and Design—Part 3, Permanent Magnet Brushless DC Machines and their Control*. Boca Raton, FL: CRC Press, 2009, pp. 451–563.

[2] P. Pillay and R. Krishnan, "Modeling, simulation, and analysis of permanent-magnet motor drives, part ii: The brushless dc motor drive," *IEEE Trans. Ind. Appl.*, vol. 25, no. 2, pp. 274–279, Mar./Apr. 1989.

[3] R. Shanmugasundram, K. M. Zakariah, and N. Yadaiah, "Low-cost high performance brushless dc motor drive for speed control applications," in *Proc. IEEE Int. Conf. Adv. Recent Technol. Commun. Comput.*, Kottayam, India, Oct. 27–28, 2009, pp. 456–460.

[4] R. Shanmugasundram, K. M. Zakariah, and N. Yadaiah, "Digital implementation of fuzzy logic controller for wide range speed control of brushless dc motor," in *Proc. IEEE Int. Conf. Veh. Electron. Safety*, Pune, India, Nov. 10–12, 2009, pp. 119–124.

[5] A. K. Wallace and R. Spee, "The effects of motor parameters on the performance of brushless dc drives," *IEEE Trans. Power Electron.*, vol. 5, no. 1, pp. 2–8, Jan. 1990.

[6] V. M. Varatharaju, B. L. Mathur, and K. Udhyakumar, "Speed control of PMBLDC motor using MATLAB/Simulink and effects of load and inertia changes," in *Proc. 2nd Int. Conf. Mech. Electr. Technol.*, Sep. 10–12, 2010, pp. 543–548.

[7] J. G. Ziegler and N. B. Nichols, "Optimum settings for automatic controllers," *Trans. Amer. Soc. Mech. Eng.*, vol. 64, pp. 759–768, 1942.

[8] J. C. Basilio and S. R. Matos, "Design of PI and PID controllers with transient performance specification," *IEEE Trans. Edu.*, vol. 45, no. 4, pp. 364–370, Nov. 2002.

[9] Q. Wang, T. Lee, H. Fung, Q. Bi, and Y. Zhang, "PID tuning for improved performance," *IEEE Trans. Contr. Syst. Technol.*, vol. 7, no. 4, pp. 457–465, Jul. 1999.

[10] A. Rubaai, D. Ricketts, and M. D. Kankam, "Laboratory implementation of a microprocessor-based fuzzy logic tracking controller for motion controls and drives," *IEEE Trans. Ind. Appl.*, vol. 38, no. 2, pp. 448–456, Mar./Apr. 2002.

[11] Pierre Guillemin, "Fuzzy logic applied to motor control," *IEEE Trans. Ind. Appl.*, vol. 32, no. 1, pp. 51–56, Jan./Feb. 1996.

[12] M. A. Akcayol, A. Cetin, and C. Elmas, "An educational tool for fuzzy logic-controlled BDCM," *IEEE Trans. Edu.*, vol. 45, no. 1, pp. 33–42, Feb. 2002.

[13] R. A. Krohling, H. Jaschek, and J. P. Rey, "Designing PI/PID controller for a motion control system based on genetic algorithm," in *Proc. IEEE 12th Int. Symp. Intell. Contr.*, Istanbul, Turkey, Jul. 1997, pp. 125–130.

[14] A. Rubaai, D. Ricketts, and M. D. Kankam, "Development and implementation of an adaptive fuzzy-neural-network controller for brushless drives," *IEEE Trans. Ind. Appl.*, vol. 38, no. 2, pp. 441–447, Mar./Apr. 2002.

[15] H.-x. Wu, S.-k. Cheng, and S.-m. Cui, "A controller of brushless DC motor for electric vehicle," *IEEE Trans. Magn.*, vol. 41, no. 1, pp. 509–513, Jan. 2005.

[16] F. Rodriguez and A. Emadi, "A novel digital control technique for brushless DC motor drives," *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2365–2373, Oct. 2007.

[17] Y.-S. Lai, F.-s. Shyu, and Y.-H. Chang, "Novel loss reduction pulse width modulation technique for brushless dc motor drives fed by MOSFET inverter," *IEEE Trans. Power Electron.*, vol. 19, no. 6, pp. 1646–1652, Nov. 2004.

[18] A. Sathyan, N. Milivojevic, Y.-J. Lee, M. Krishnamurthy, and A. Emadi, "An FPGA-based novel digital PWM control scheme for BLDC motor drives," *IEEE Trans. Ind. Electron.*, vol. 56, no. 8, pp. 3040–3049, Aug. 2009.

[19] J. Murphree, B. Brzezinski, and J. Parker, "Using a fixed-point digital signal processor as a PID controller," in *Proc. Amer. Soc. Eng. Edu. Annu. Conf. Expo.*, Montreal, QC, Canada, 2002, pp. 1–8.

[20] M. A. Rahman and M. A. Hoque, "On-line self-tuning Ann-based speed control of a PM DC motor," *IEEE/ASME Trans. Mechatronics*, vol. 2, no. 3, pp. 169–177, Sep. 1997.

[21] S. Weerasooriya and M. A. El-Sharkavi, "Identification and control of a dc motor using back-propagation neural networks," *IEEE Trans. Energy Convers.*, vol. 6, no. 4, pp. 663–669, Dec. 1991.

[22] H. Melkote and F. Khorrami, "Nonlinear adaptive control of direct-drive brushless dc motors and applications to robotic manipulators," *IEEE/ASME Trans. Mechatronics*, vol. 4, no. 1, pp. 71–81, Mar. 1999.

[23] R. Shanmugasundram, K. M. Zakariah, and N. Yadaiah. (2012, May). Modelling, simulation and analysis of controllers for brushless direct current motor drives. *J. Vib. Control* [Online]. pp. 1–15. Available: http://jvc.sagepub.com/content/early/2012/05/11/1077546312445200

[24] R. Shanmugasundram, K. M. Zakariah, and N. Yadaiah. (2012, Jun.). Effect of parameter variations on the performance of direct current (dc) servomotor drives. *J. Vib. Control* [Online]. pp. 1–12. Available: http://jvc.sagepub.com/content/early/2012/06/14/1077546312448080

[25] H. Grabner, W. Amrhein, S. Silber, and W. Gruber, "Nonlinear feedback control of a bearingless brushless dc motor," *IEEE/ASME Trans. Mechatronics*, vol. 15, no. 1, pp. 40–47, Feb. 2010.

[26] S. B. Ozturk and H. A. Toliyat, "Direct torque and indirect flux control of brushless dc motor," *IEEE/ASME Trans. Mechatronics*, vol. 16, no. 2, pp. 351–360, Apr. 2011.

[27] J.-W. Kim and S. W. Kim, "Design of incremental fuzzy PI controllers for a gas-turbine plant," *IEEE/ASME Trans. Mechatronics*, vol. 8, no. 3, pp. 410–414, Sep. 2003.

[28] R.-E. Precup, S. Preitl, I. J. Rudas, and M. L. Tomescu, "Design and experiments for a class of fuzzy controlled servo systems," *IEEE/ASME Trans. Mechatronics*, vol. 13, no. 1, pp. 22–35, Feb. 2008.

[29] Y.-W. Tu and M.-T. Ho, "Robust second-order controller synthesis for model matching of interval plants and its application to servo motor control," *IEEE Trans. Control Syst. Technol.*, vol. 20, no. 2, pp. 530–537, Mar. 2012.

[30] C. Ganesh and S. K. Patnaik. (2012, Jan.). Artificial neural network based proportional plus integral plus derivative controller for a brushless dc position control system. *J. Vib. Control* [Online]. pp. 1–12. Available: http://jvc.sagepub.com/content/early/2012/01/10/1077546311429840

R. Shanmugasundram (M'12) received the B.E. degree in electrical and electronics engineering from STJ Institute of Technology, Karnatak University, Dharwad, India, in 1995, and the M.E. degree from Anna University, Chennai, India, in 2004.

He is currently an Associate Professor in the Department of Electrical and Electronics Engineering, Sri Ramakrishna Engineering College, Coimbatore, India. His research interests include intelligent systems design and development of advanced controls using tools of computational intelligence for motion control systems.

Mr. Shanmugasundram is an active member of the Indian Society for Technical Education and Jawaharlal Nehru Technological University Forum of Science and Technology.

K. Muhammad Zakariah received the B.E. degree in electrical engineering, the M.Sc. degree in engineering, and the Ph.D. degree in 1965, 1973, and, 1984, respectively, from the University of Madras, Coimbatore, India.

He was the former Dean and the Head of the Department of Electronics and Communication, SNS College of Technology, Coimbatore, India. He is currently working as a Consultant for technical activities at various leading engineering colleges located in Coimbatore, Tamilnadu, India. He has 25 international journal and conference publications to his credit. His research interests include linear and nonlinear control systems and adaptive and process control.

Dr. Zakariah is a Fellow of the Institution Engineers, India, Institution of Valuers, India, and Indian Society of Lighting Engineers, India, and a Life Member of the Indian Society for Technical Education.

N. Yadaiah (SM'07) received the B.E. degree in electrical engineering from the College of Engineering, Osmania University, Hyderabad, India, in 1988, the M.Tech. degree in control systems from the Indian Institute of Technology, Kharagpur, India in 1991, and the Ph.D. degree in electrical engineering from Jawaharlal Nehru Technological (J.N.T.) University, Hyderabad, India, in 2000.

Currently, he is a Professor in the Department of Electrical and Electronics Engineering at JNTUH College of Engineering (Autonomous), Hyderabad, India. He is currently involved in one ongoing research project from the All India Council for Technical Education, New Delhi, India, and has completed one research project of the Indian Space Research Organisation, India. He has 85 international journal and conference publications to his credit. He visited the University of Alberta, Edmonton, AB, Canada, from May to July 2007 as a Visiting Professor. He has also visited the U.S. in 2003 to attend an academic program. He is an Editorial Board Member of the *Journal of Computer Science*, India. His research interests include adaptive control, artificial neural networks, fuzzy logic, nonlinear systems, and process control.

Dr. Yadaiah received the Young Scientist Fellowship of the Andhra Pradesh State Council for Science and Technology in 1999. He is a Fellow of the Institution of Engineers, India, and of the Institute of Electronics and Telecommunication Engineers, India, and a Life Member of the Systems Society of India and Indian Society for Technical Education.