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Design and Execution of Hybrid Fuzzy Controller for Speed Regulation of Brushless DC Motor

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Abstract: **An effective algorithm approach to hybrid control systems combining fuzzy logic and conventional control techniques of controlling the speed of BLDC motor assumed to operate in high-performance drives environment is proposed. The introducing of fuzzy logic in the control systems helps to achieve good dynamic response, disturbance rejection and low sensitivity to parameter variations and external influences. The developed control algorithm is robust, efficient and simple. It also assures precise trajectory tracking with the prescribed dynamics. Experimental results have shown excellent tracking performance of the proposed control system, and have convincingly demonstrated the validity and the usefulness of the hybrid fuzzy controller in high-performance drives with parameter and load uncertainties. Satisfactory performance was observed for most reference tracks.**

Keywords: **BLDC Motor, Hybrid Fuzzy Controller, Intelligent Control, Robustness.**

I. INTRODUCTION

Brushless DC motors works similar to the conventional DC motor with the mechanical commutation replaced by an electronically controlled commutation system. It is one of a small-scale motor used in small electric devices such as CD players, hard disk drives, or even small electric cars. Its rotor is mounted with permanent magnet. There is no need for extra field excitation. This motor is well known and popular for position and speed control drive applications. The key advantage of this motor over other types in the same rating is higher ratio of produced torque per weight, faster response, accurate position control, lower moment of inertia, less maintenance, etc. In this paper, mathematical modeling of a small BLDC motor and its electrical drives are the main purpose as described. Presents power loss and efficiency calculation for the BLDC motor, hybrid fuzzy control system, fuzzy logic controller technique, the proposed control scheme, simulation results and conclusions are followed.

II. PRINCIPLES OF THE BLDC MOTOR

A. Mathematical Model of BLDC Motors:

Modeling of a BLDC motor can be developed in the similar manner as a three phase synchronous machine. Since its rotor is mounted with a permanent magnet, some dynamic characteristics are different. Flux linkage from the rotor is dependent upon the magnet. Therefore, saturation of magnetic flux linkage is typical for this kind of motors. As any typical three-phase motors, one structure of the BLDC motor is fed by a three-phase voltage source as shown in Fig. 1. The source is not necessary to be sinusoidal. Square wave or other wave shape can be applied as long as the peak voltage is not exceeded the maximum voltage limit of the motor. Similarly, the model of the armature winding for the BLDC motor is expressed as follows.

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

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

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

or in the compact matrix form as follows.

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R+pL & 0 & 0 \\ 0 & R+pL & 0 \\ 0 & 0 & R+pL \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (4)$$

Where $L_a=L_b=L_c=L=L_s - M$ [H]

L_s is the Armature Self-inductance and M is the Mutual Inductance

$R_a=R_b=R_c=R$: Armature Resistance [Ω]

V_a, V_b, V_c: Teminal Phase Voltage [V]

i_a, i_b, i_c: Motor Input Current [A]

e_a, e_b, e_c: Motor Back emf [V]

p in the matrix represents d/dt

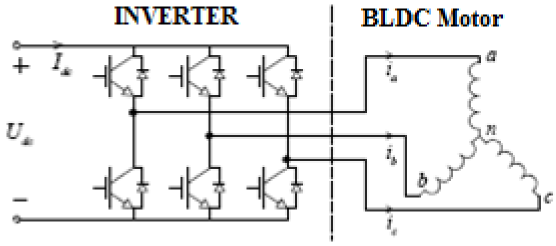

Fig. 1 BLDC Motor Control System

Due to the permanent magnet mounted on the rotor, its back emf is trapezoidal as shown in Fig. 2. The expression of back emf must be modified as expressed in equations (5) – (7).

$$e_a(t) = K_E \cdot \phi(\theta) \cdot \omega(t) \quad (5)$$

$$e_b(t) = K_E \cdot \phi\left(\theta - \frac{2\pi}{3}\right) \cdot \omega(t) \quad (6)$$

$$e_c(t) = K_E \cdot \phi\left(\theta + \frac{2\pi}{3}\right) \cdot \omega(t) \quad (7)$$

Where K_E is the back emf constant and ω is the mechanical speed of the rotor.

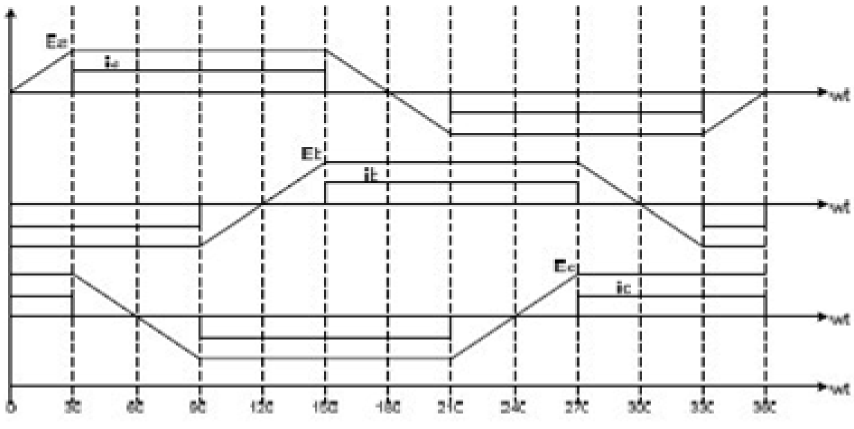

Fig. 2 BLDC Motor Back emf and Motor Phase Currents

The permanent magnet also influences produced torques due to the trapezoidal flux linkage. Given that K_T is the torque constant. The produced torques can be expressed as described in (8).

$$T_E = (e_a i_a + e_b i_b + e_c i_c)/\omega \quad (8)$$

Substitute (5) – (7) into (8), the resultant torque, T_E can be obtained by the following expressions.

$$T_a(t) = K_T \cdot \phi(\theta) \cdot i_a(t) \quad (9)$$

$$T_b(t) = K_T \cdot \phi\left(\theta - \frac{2\pi}{3}\right) \cdot i_b(t) \quad (10)$$

$$T_c(t) = K_T \cdot \phi\left(\theta + \frac{2\pi}{3}\right) \cdot i_c(t) \quad (11)$$

$$T_E(t) = T_a(t) + T_b(t) + T_c(t) \quad (12)$$

With the Newton's second law of motion [5], the angular motion of the rotor cans be written as follows.

$$T_E(t) - T_L(t) = J\frac{d\omega(t)}{dt} + B \cdot \omega(t) \qquad (13)$$

Where T_L: Load Torque [Nm], J: Rotor Inertia [Kgm^2] and B: Damping Constant

B. Supply Source:

Power supply for BLDC motor drives can be in various forms. Sinusoidal supply is typical as the standard power supply of an electric utility, while square waves and PWM are widely used in small power applications. In this paper, only PWM shape is used for study. It is slightly complicated. To generate the PWM shape, it requires operation of high frequency switching devices of electronic inverters, e.g. transistor, MOSFET, etc. The example of natural sampling or sinusoidal PWM wave shape is shown in Fig. 3.

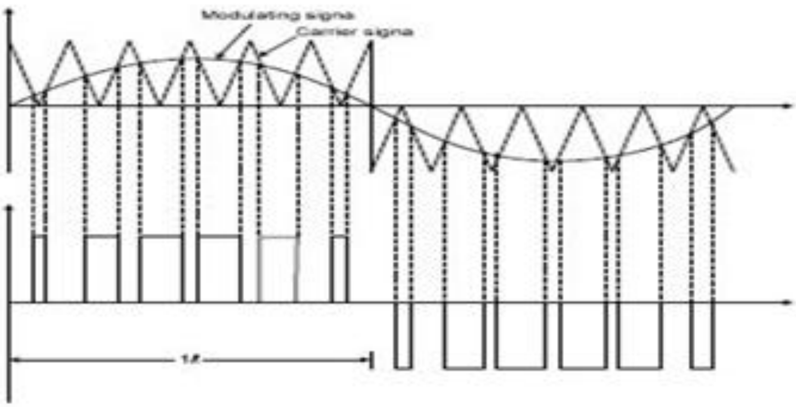

Fig. 3 Natural Sampling PWM Waveform

III. POWER LOSS AND EFFICIENCY CALCULATION

In the BLDC motor, the power losses consist of core losses in the magnetic core, copper losses in the winding and mechanical losses.

A. Copper Losses

The copper losses are 2 *I R* loses. All three-phase windings must be taken into account. Thus, the total armature copper loss (*cu P*) is equated as follows.

$$P_{cu} = \left(i_a^2 + i_b^2 + i_c^2\right)R \qquad (14)$$

B. Core Losses and Mechanical Losses

Mechanical losses are caused by friction (mostly in the bearings) and the dynamic drag to oppose the motion of the rotor or so-called the friction and windage losses (*Pfw*). Corelosses (*Pcore*) are the open circuit losses due to hysteresis property and induced eddy current in the core, which exist as long as the excitation winding energized. To be convenient and very useful for efficiency computation, the core losses, friction losses and windage losses are summed up to give rise to the no-load rotational loses (*Prot*).

$$P_{rot} = P_{core} + P_{fw} \qquad (15)$$

C. Efficiency

The efficiency of a motor is an important performance characteristic. Although its formula is as very simple and is given in equation 16, to compute the efficiency is problem-dependent due to the assumption of power conversion in the machine. In this paper, input and output powers are defined accordingly.

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \qquad (16)$$

$$P_{in} = v_a i_a + v_b i_b + v_c i_c \qquad (17)$$

$$P_{out} = \frac{1}{2}J\omega^2 + T_L\omega \qquad (18)$$

IV. PROPOSED HYBRID FUZZY CONTROL SYSTEM

The conventional controllers, such as the Proportional Integral and Derivative (PID) require a mathematical model representing the system under control. This can be a major limiting factor for systems with unknown varying dynamics such as inertia variations, magnetic saturation, parameter drifts and noisy environments. For most of the basic electric drive applications, these unknown conditions in addition to system nonlinearities can be ignored. High accuracy is not usually imperative. However, for high performance drive applications, disregarding these unknowns may lead to unacceptable tracking performance. Thus, the need for other types of controllers that can account for non linearities requires adaptable conditions in real time. Other methods are now being employed, such as the hybrid fuzzy logic controller, in order to achieve a desired performance level for a high performance motor drive. In order to get control schemes that would be less sensitive to parameter variations than traditional linear PI controllers, we consider the hybrid controller structure shown in Fig. 4.

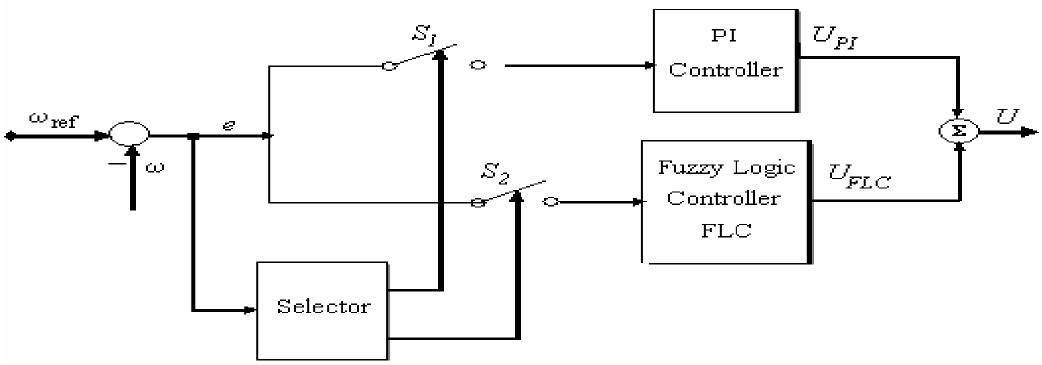

Fig. 4 Structure of Hybrid Controller

The objective of the hybrid controller is to utilize the best attributes of the PI-type and fuzzy controllers to provide a controller which will produce better response than either the Proportional Integral (PI) or the fuzzy logic controller. The switching between the two controllers needs a reliable basis for determining which Controller would be more effective. Both controllers yield good responses to steady-state or slowly changing conditions. To take advantage of the fast response of the PI-type controller, one needs to keep the system responding under the PI controller for a majority of the time, and use the fuzzy controller only the system behavior is oscillatory or tend to overshoot. As can be seen, it is a controller that contains a PD-type fuzzy and a linear PI control algorithm. It has a single input error signal e(k), which internally yields another fuzzy controller input, change error signal Δe(k). This controller is meant as a multimode controller, which has tree modes of operation dictated by the mode of operation selector (Fig. 4).

V. FUZZY LOGIC CONTROLLER

Fuzzy logic control design methodologies are justified because imprecision of the mathematical model used previously. Rule-based controllers try accounting the human’s knowledge about how to control a system without requiring a mathematical model. The main preference of the fuzzy logic is that is easy to implement control that it has the ability of generalization. The approach of the basic structure of the fuzzy logic controller system is illustrated in Fig. 5.

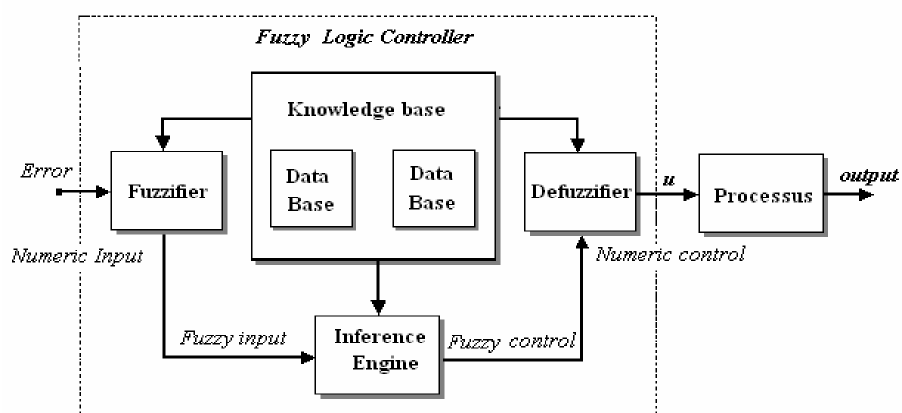

Fig. 5 Structure of Fuzzy Logic Controller

Input and output are non-fuzzy values and the basic configuration of the FLC is featured in Fig. 6.

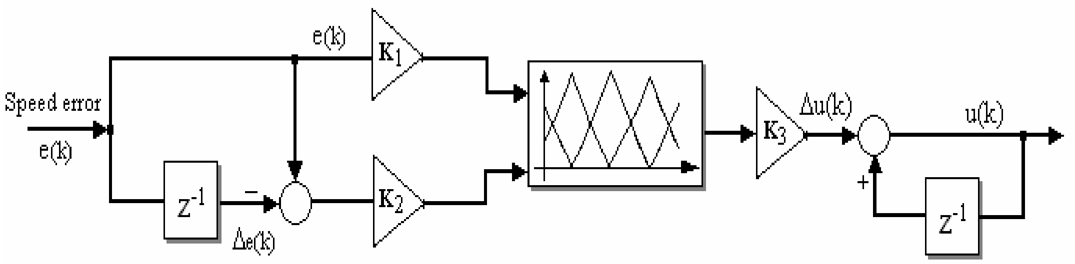

Fig. 6 Block Diagram of Fuzzy Control System

In the system presented in this study, Mamdani type of fuzzy logic is used for speed controller. The command signals to the speed controller are the error 'e(k)' and change rate of error 'Δe(k)'. Speed error e (k) is calculated with comparison between reference speed command ωref **IF** speed error is Zero (**Z**), **AND** rate of change in speed error is another value, **THEN** control is null. For the proposed fuzzy controller, the universe of discourse is first partitioned into the five linguistic variables NB, NS, ZE, PS, PB, triangular membership functions are chosen to represent the linguistic variables and fuzzy singletons for the outputs are used. The fuzzy rules that produce this control action are reported in Table I.

TABLE I: SET OF GENERATED FUZZY RULES FOR PROPOSED SYSTEM

Error / Delta Error	NB	NS	ZE	PS	PB
NB	NB	NB	NS	PB	PS
NS	ZE	NS	ZE	PS	ZE
ZE	PB	PB	ZE	PS	NB
PS	ZE	PS	PB	NS	NB
PB	PB	PS	NS	NS	NB

This implies an inference engine based on 5 implications rules for each of the speed error and its variation, thus a total 25 combinations take place. One can see on Table I, the rules sets of the fuzzy controller. Fig. 3 shows an example of Mamdani's fuzzy inference [10], assuming that applicable fuzzy rules are:

Rule_1: IF e(k) is **PS** AND Δe(k) is **PM** , THEN u(k) is **PS;**
Rule_2: IF e(k) is **PM** AND Δe(k) is **PS** , THEN u(k) is **PM**

where e(k), Δe(k), u are the speed error, the change rate of speed error and the control action, respectively.

The inference law is given as:
μF(u)=Max(i,j,k) IMin(minLei(e),μLΔe(Δe)),
μLuk(u)), μF(u) design the fuzzy control action.

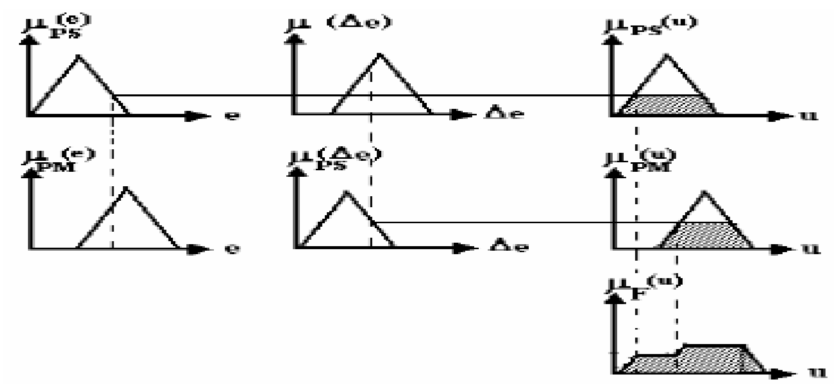

Fig. 7 Mamdani's Fuzzy Inference

The controller treats each measurement as a fuzzy singleton and fuzzy files it using the fuzzy sets shown in Fig.8 where **NB**: **N**egative **B**ig, PB: **P**ositive **B**ig, **NS**: **N**egative **S**mall, **PS**: **P**ositive **S**mall and **ZE**: **Z**ero **E**qual.

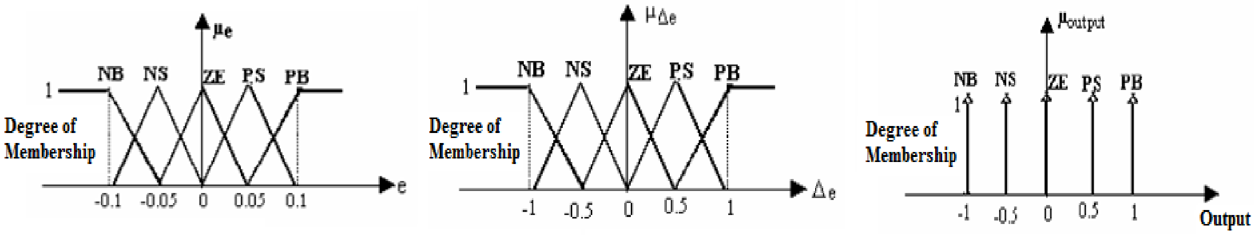

Fig. 8 Fuzzy Sets and its Memberships Functions

Triangular shapes were chosen as the membership functions due to the linear equation in evaluation of membership functions and the output of the fuzzy controller.

VI. CONFIGURATION OF THE PROPOSED CONTROL SYSTEM

Block diagram of implemented drive using PI controller consists of the components illustrated in Fig. 9. The software environment used of these simulation experiments is Matlab with Simulink Toolboxes. The objective of the hybrid controller is to utilize best attributes of the PI-type and fuzzy controllers to provide a controller which will produce better response than either the PI or the fuzzy controller. 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. Careful choice of the method of combining the controllers may result in a highly adequate yet non-oscillatory response. To take advantage of the rapid response of the PI-type 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 overshoots.

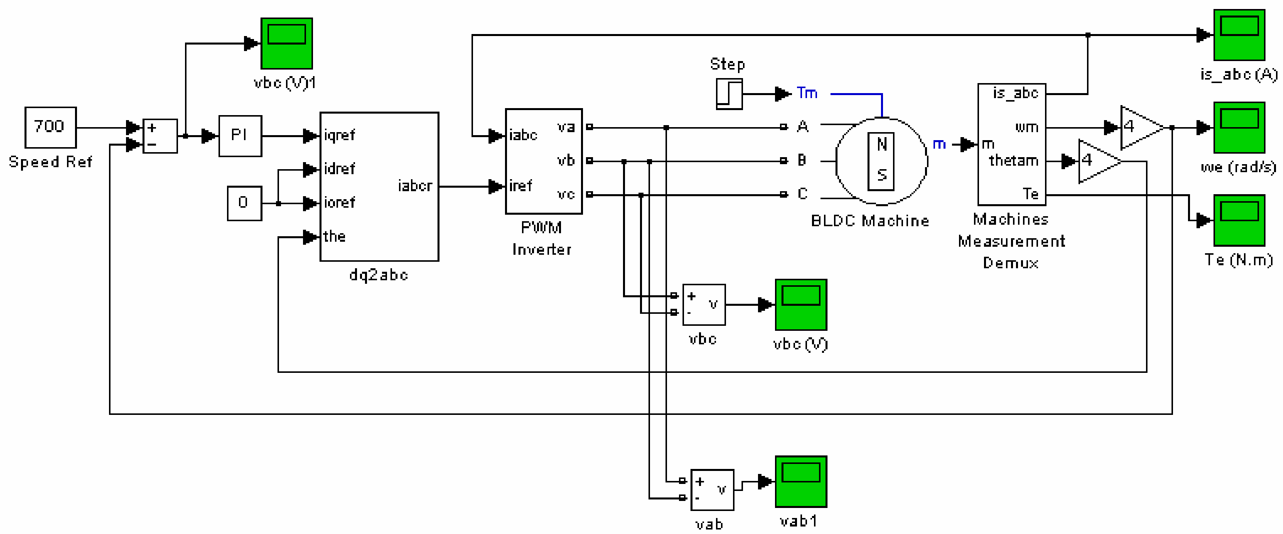

Fig. 9 Block Diagram of Implemented Drive

VII. SIMULATION RESULTS

To demonstrate the proposed PI control scheme success, it has been tested by simulation, in order to evaluate the performances under a variety of operating Conditions. The controller algorithm is housed inside the personal computer with Pentium-4 microprocessor and all numerical values of the simulation model are obtained either by measurements. The software environment used for these simulation experiments is Matlab-software with Simulink Toolboxes.

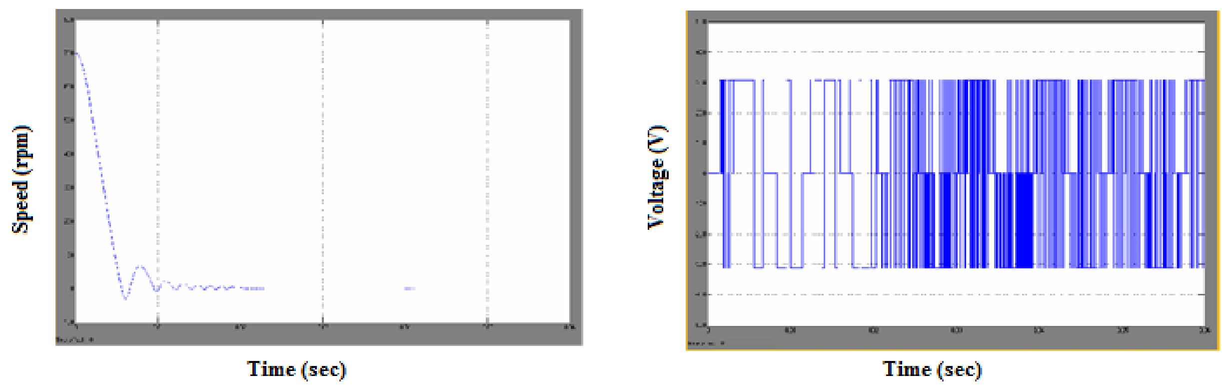

Fig. 10 Simulated Waveform of Control Signal

Fig. 11 Simulated Waveform of Voltage Signal

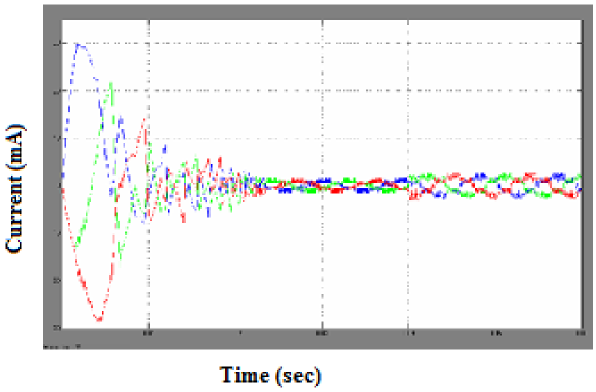

Fig. 12 Simulated Waveform of Current Signal

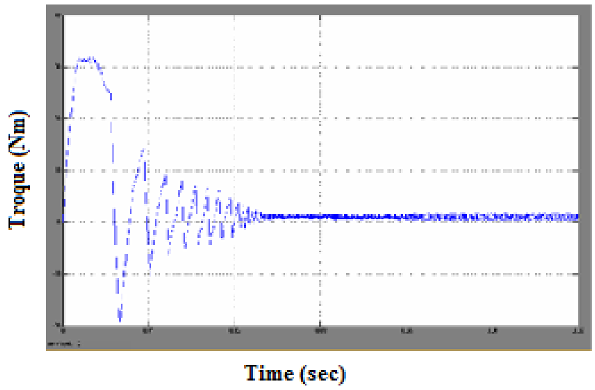

Fig. 13 Simulated Waveform of Torque

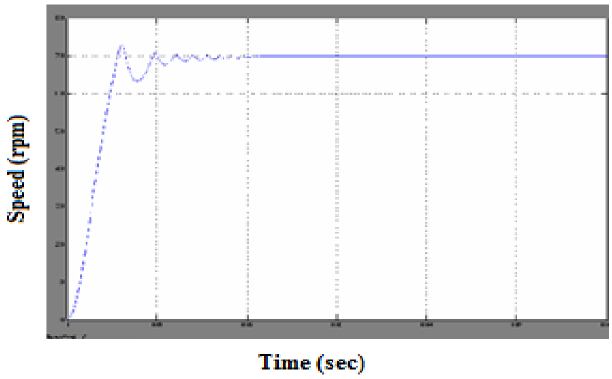

Fig. 14 Simulated Waveform of Speed

All the above test results shows that the proposed PI control strategy is very effective in tracking the selected tracks at all time, while the system transients are effectively reduced. The results presented in Figs. 10, 11, 12, 13, 14 show that the proposed control system works correctly. The proposed scheme of hybrid-fuzzy controller for variety of step changes in the desired set point is under investigation.

VIII. CONCLUSION

Optimizing the motor speed in brushless DC motor using Proportional Integral Controller has been proposed and successfully simulated. The principle of operation, design considerations and simulation results has been presented. The proposed strategy is suitable for both small ratings and large ratings of BLDC drives with low cost. It is an effective strategy to improve the speed in BLDC drives. A Hybrid fuzzy controller is used for the speed regulation in BLDC drives is under investigation for getting better speed regulation.

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