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DEVELOPMENT OF MATHEMATICAL MODEL AND SPEED CONTROL OF BLDC MOTOR

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ABSTRACT

An electronically commutated Brushless DC motors are enormously used in many industrial applications which increases the need for design of efficient control strategy for these noiseless motors. This paper deals with a closed loop speed control of BLDC motor and performance of the BLDC motor is simulated. The duty ratio is regulated by PI controller, which governs the duty cycle of the PWM pulses applied to the switches of the inverter to run the motor at steady state speed. The simulation of the proposed scheme was done using MATLAB software package in SIMULINK environment. In order to highlight the effectiveness of the speed control of BLDC motor, the studies are conducted at different load torques and the corresponding speed is recorded using MATLAB/SIMULINK.

Keywords: BLDC Motor, Closed Loop Speed Control, Duty Ratio, Hall Effect Sensors, PI Controller

1. INTRODUCTION

The Brushless DC (BLDC) motor is rapidly gaining popularity by its utilization in various industries, such as appliances, automotive, aerospace, consumer, medical, industrial automation equipment and instrumentation [1]. As the name implies, the BLDC motors do not use brushes for commutation instead of they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors a few of these are better speed versus torque characteristics, high dynamic response, high efficiency long operating life, noiseless operation [2]. The major disadvantage of BLDC motor is their higher cost and relatively greater degree of complexity introduced by the power electronics converter [3]. The speed of the motor is directly proportional to the applied voltage across the winding the speed can be altered, by varying the duty cycle of PWM signal [4].

A Brushless DC motor has a rotor with permanent magnets and a stator with windings. The brushes and commutator have been eliminated and the windings are connected to the control electronics energize the winding with particular sequence of switching pulses [5]. The energized stator winding leads the rotor magnet, and switches just as the rotor aligns with the stator [6].

A permanent Magnet AC motor, which has a trapezoidal back EMF, is referred to as brushless DC motor (BLDC) [7]. The BLDC drive system is based on the feedback of rotor system at fixed points for commutation of the phase currents [8]. The BLDC motor requires quasi-rectangle shaped currents fed into the machine. Alternatively, the voltage may be applied to the motor every 120°, with current limit to hold the current within motor capabilities [9]. Because the phase currents are excited in synchronism with the constant part of the back EMF, constant torque is generated. The electromagnetic torque of the BLDC motor is related to the product of phase, back EMF and current. The back EMF in each phase is trapezoidal in shape and is displaced by 120 electrical degrees with respect to each other in 3 phase machine [10]. A rectangle current pulse is injected into each phase so that current coincides with the back EMF waveform. Hence the motor develops an almost constant toque.

In this paper proposed a simulation model of a BLDC motor with using a PI controller, which responsible to govern the duty cycle of PWM pulses to inverter switches. The studies were conducted at different load torques and the corresponding speed is recorded using MATLAB/SIMULINK. In this model the trapezoidal back EMF waveforms are mathematically modeled a function of rotor position.

II DYNAMIC MODELING OF BLDC MOTOR

Modeling of a BLDC motor can be developed in the similar manner as a three-phase synchronous machine. Since there is a permanent magnet mounted on the rotor, some dynamic characteristics are different. Consider a cylindrical rotor and the stator have 3 phase winding a, b, and c. The rotor is the permanent magnet rotor, and hence the air gap is uniform. Stator has 3 phases with distributed winding structure with star connected. The dynamic equation of phase a, phase b, phase c, are follows as

$$V_{an} = R_s + L\frac{di_a}{dt} + M\frac{di_b}{dt} + M\frac{di_c}{dt} + e_a \tag{1}$$

Similarly for phase b and phase c

$$V_{bn} = R_s + L\frac{di_b}{dt} + M\frac{di_c}{dt} + M\frac{di_a}{dt} + e_b \tag{2}$$

$$V_{cn} = R_s + L\frac{di_c}{dt} + M\frac{di_c}{dt} + M\frac{di_b}{dt} + e_c \tag{3}$$

Where

L is armature self-inductance [H],
M is armature mutual inductance [H],
R is armature resistance [Ω],
V_{an} ,V_{bn} and V_{cn} are terminal phase voltage [V],
i_a , i_b and i_c are motor input current [A],
e_a , e_b and e_c are motor back -EMF [V].

These are stator three equations, the rotor is a permanent magnet, and the rotor does not have any winding. So, rotor structure not having any equation. These three equations can be represented in the form of a matrix.

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R_S & 0 & 0 \\ 0 & R_S & 0 \\ 0 & 0 & R_S \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} P \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{4}$$

In the BLDC motor, the back –EMF is related to a function of rotor position and the back –EMF each phase has 120 degrees phase angle difference so equation of each phase should be as follows as:

$$e_a = K_a f_a(\theta)\omega_r, e_b = K_b f_b\left(\theta - \frac{2\pi}{3}\right)\omega_r, e_c = K_c f_c\left(\theta - \frac{2\pi}{3}\right)\omega_r \tag{5}$$

$$V_{an} = R_s + L\frac{di_a}{dt} + M\frac{d(i_b + i_c)}{dt} + e_a \tag{6}$$

$$V_{an} = R_s + L\frac{di_a}{dt} - M\frac{di_a}{dt} + e_a \tag{7}$$

$$V_{an} = R_s + (L - M)\frac{di_a}{dt} + e_a \tag{8}$$

$$V_{an} = R_s + L_S\frac{di_a}{dt} + e_a \tag{9}$$

$$V_{bn} = R_s + L_S\frac{di_b}{dt} + e_b \tag{10}$$

$$V_{cn} = R_s + L_S\frac{di_c}{dt} + e_c \tag{11}$$

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R_S & 0 & 0 \\ 0 & R_S & 0 \\ 0 & 0 & R_S \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L_S \begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} = \left\{ \begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} - \begin{bmatrix} R_S & 0 & 0 \\ 0 & R_S & 0 \\ 0 & 0 & R_S \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \right\} \frac{1}{L_s} \tag{13}$$

So, these three simultaneous differential equations which can be solve by any numerical technique. For example, we can solve this equation using Runga Kutta fourth order method to solve the 3 equations and get the values of i_a , i_b and i_c . The value of the total torque as follows.

$$e_a = K_a\omega_r \tag{14}$$

$$P_m = (e_a i_a + e_b i_b + e_c i_c) \tag{15}$$

$$T_e = \frac{P_m}{\omega_{rm}} = \frac{(e_a i_a + e_b i_b + e_c i_c)}{\omega_r} \frac{P}{2} \tag{16}$$

$$T_e = \frac{(K_a i_a + K_b i_b + K_c i_c)\omega_r}{\omega_r} \frac{P}{2} \tag{17}$$

$$T_e = \frac{P(K_a i_a + K_b i_b + K_c i_c)}{2} \tag{18}$$

The equation of mechanical part is represented as follows

$$T_e - T_L = \frac{J d\omega_{rm}}{dt} + B\omega_{rm} \tag{19}$$

$$\frac{J d\omega_r}{\frac{P}{2} dt} + \frac{B\omega_r}{\frac{P}{2}} + T_L = T_e \tag{20}$$

$$\frac{d\omega_r}{dt} = \frac{P}{2J}\left(T_e - T_L - \frac{2B}{P}\omega_r\right) \tag{21}$$

III PROPOSED CONTROL SCHEME

Block diagram of closed loop speed control of BLDC motor using with PI controller as shown in fig.1.

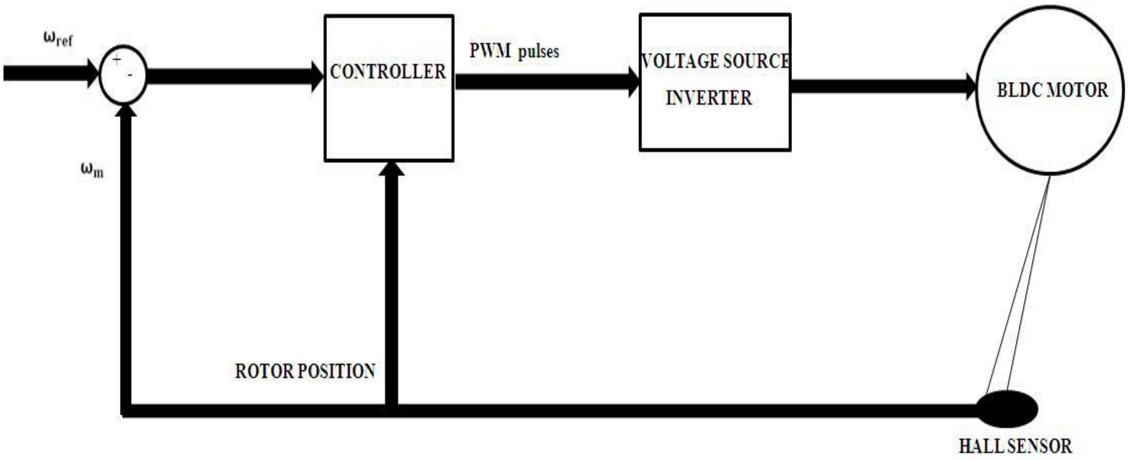

Fig1: Block diagram of closed loop speed control of BLDC motor

The BLDC motor is used in electromechanical actuator in the real time applications. The electromechanical actuator should be controlled in closed loop where only speed loop is to be closed in this application. The hall sensor is used as feedback element for closing the speed loop. Summer compare the reference speed and measured speed. The value of error generated according to measured speed. Using a proper proportional and integral gain the error is amplified and duty cycle is modified to drive the motor to desired speed until the error becomes zero. The relation between error and duty ratio is

$$\text{Duty ratio} = \text{error}^{*} K_p$$

Where

K_p = proportional and integral gain

The error magnitude determines the duty ratio and according to that output voltage of inverter varies and speed of motor controlled.

IV RESULTS AND DISCUSSIONS

The developed MATLAB/SIMULINK model in fig.2 provides the speed control of BLDC motor using PI controller and the simulation results provide necessary waveforms for the analysis of closed loop speed control of BLDC drives.

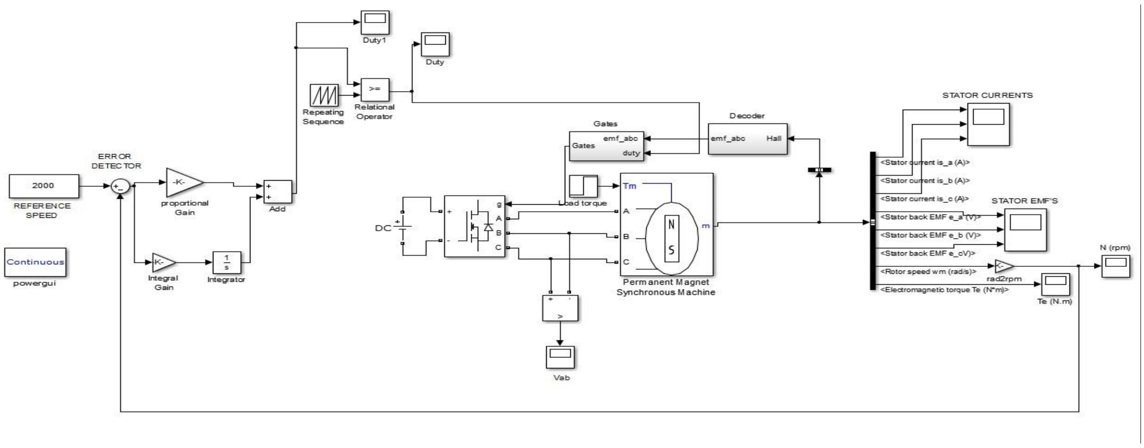

Fig 2: Simulation model of closed loop speed control of BLDC motor

4.1. Back EMF detection from hall sensor

The back EMF detection from hall sensor based on logic sequence which is given in Table1.The model implemented in simulation as show in fig.3 to generate trapezoial nature of back EMF from hall sensor.

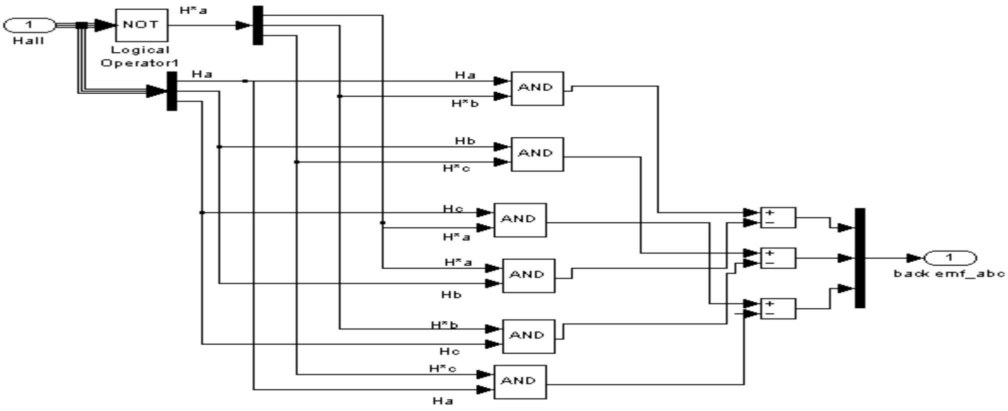

Fig3: Back EMF detection from hall sensor

Table1: Truth table for Back EMF detection from hall sensor

H_a	H_b	H_c	E_a	E_b	E_c
0	0	0	0	0	0
0	0	1	0	-1	+1
0	1	0	-1	+1	0
0	1	1	-1	0	+1
1	0	0	+1	0	-1
1	0	1	+1	-1	0
1	1	0	0	+1	-1
1	1	1	0	0	0

4.2. Commutation signal generation

Based on truth Table2, the model developed to generate appropriate commutation signal which is controlled by duty ratio signal as shown in fig.4.

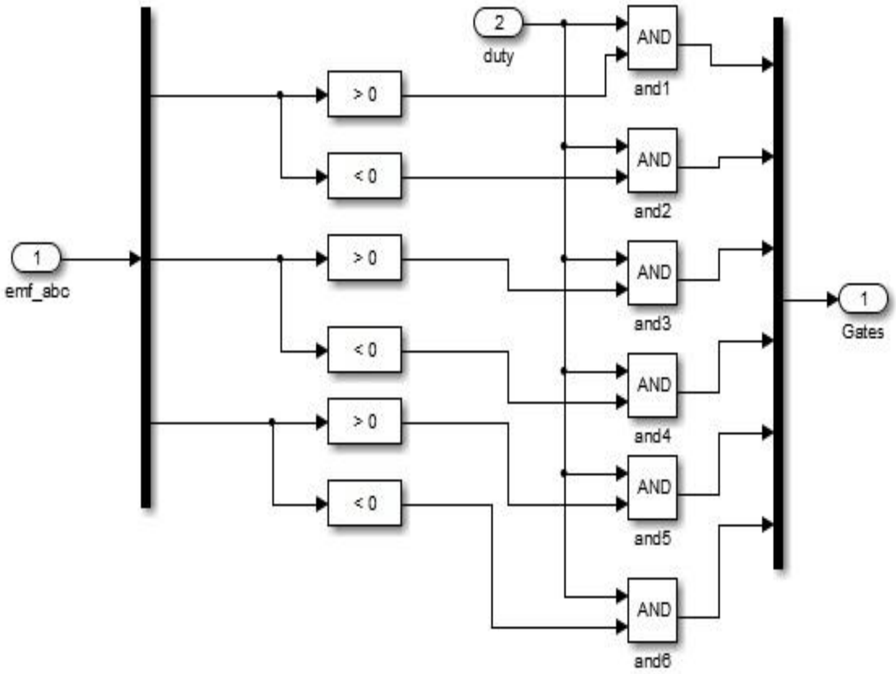

Fig4: commutation signal from back EMF and duty ratio

Table2: Truth table for to generate commutation signal from back EMF and duty ratio

E_a	E_b	E_c	Q1	Q2	Q3	Q4	Q5	Q6
0	0	0	0	0	0	0	0	0
0	-1	+1	0	0	0	1	1	0
-1	+1	0	0	1	1	0	0	0
-1	0	+1	0	1	0	0	1	0
+1	0	-1	1	0	0	0	0	1
+1	-1	0	1	0	0	1	0	0
0	+1	-1	0	0	1	0	0	1
0	0	0	0	0	0	0	0	0

4.3. Duty Ratio And Switching Pulses

Fig.5 & fig.6 shows duty ratio generated according to PI controller and the switching pulses generated for inverter switches from Q1toQ6.

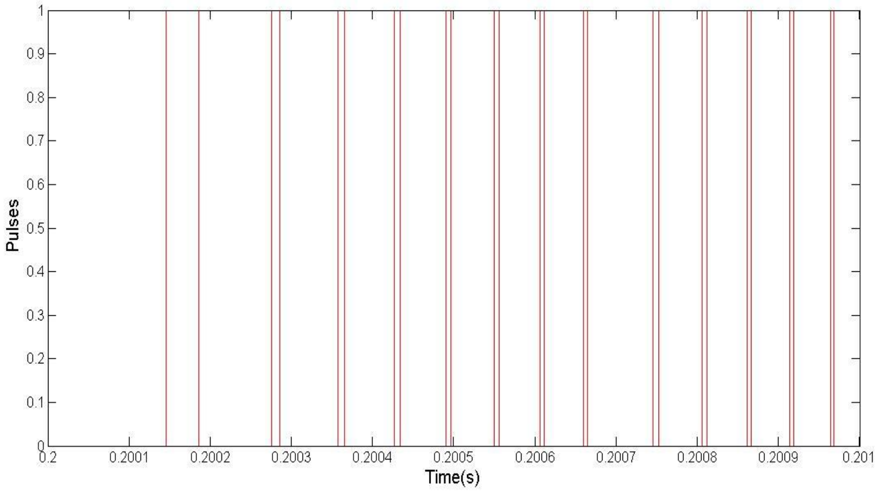

Fig5: Duty ratio generated according to PI controller

The phases of stator winding in BLDC motor at a time two winding should be energized for this inverter switches every time two switches turn ON , one switches from upper group and another from lower group of inverter. Phase displacement between pair to pair of switches 60 degree mode operation. The switching pulses from Q1 to Q6 as shown in figure 6.

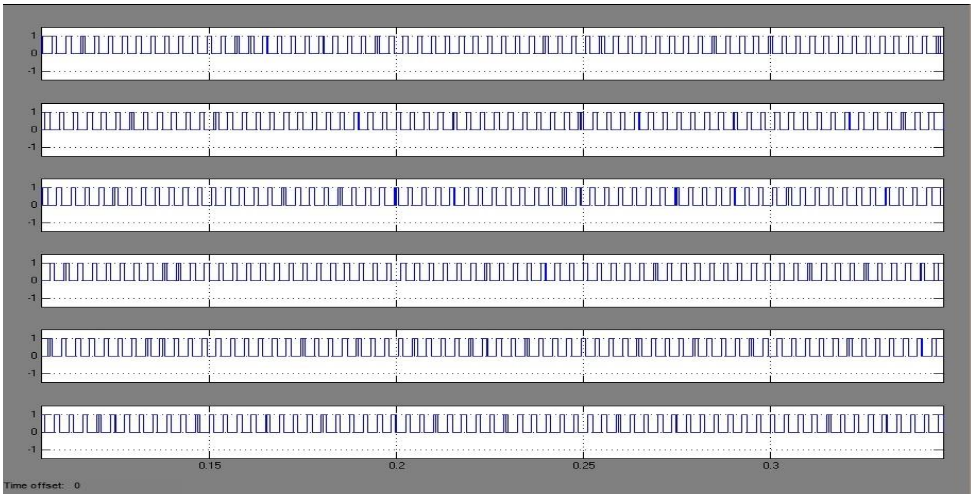

Fig6: switching pulse for Q1 to Q6

4.4. Rotor speed without load

Rotor speed at no load condition as shown in fig.7

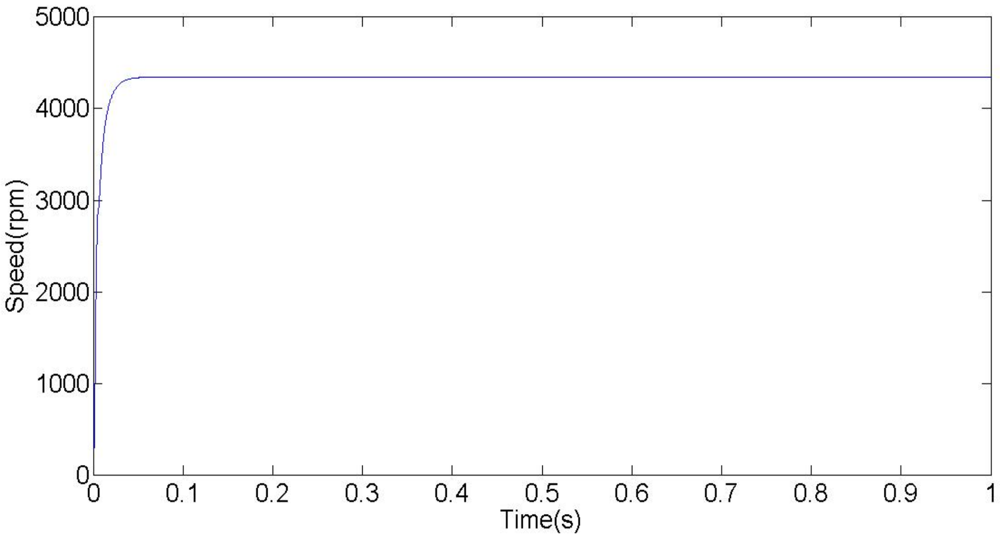

Fig7: Rotor speed at no load condition

4.5. Rotor different speed with constant torque load

The different speed of motor with constant load is shown in fig.8. Rotor different speed are 4000rpm , 3500rpm, 3000rpm given as load torque disturbance at t = 0.1sec the generated error from measured speed with respective reference speed then error compensated by PI controller, speed response settled to steady state.

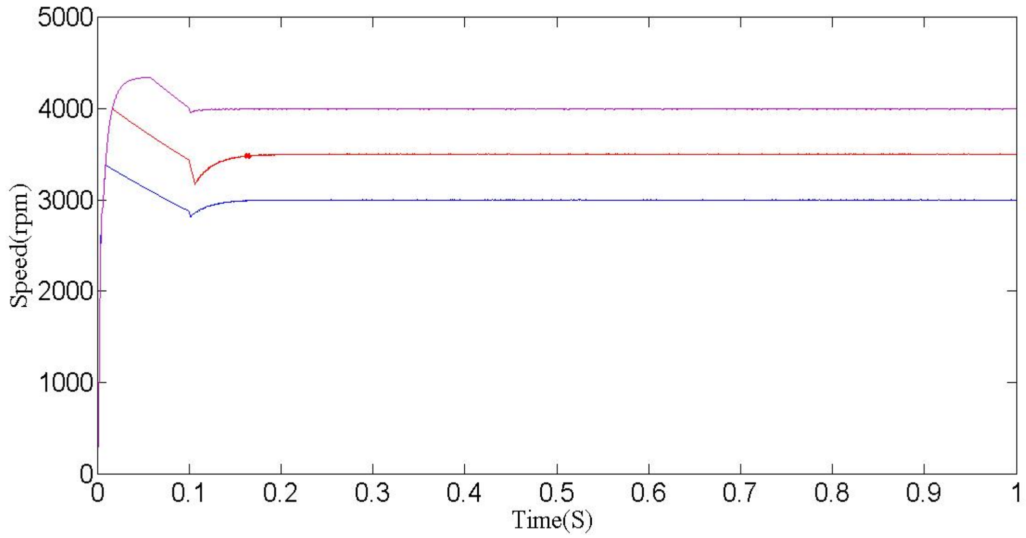

Fig8: Rotor different speed with constant load torque

4.6. Rotor speed with different load torque

Fig.9 shows 2000rpm as normal speed with different load torque disturbance at t = 0.1sec, t = 0.2 sec and t = 0.3 sec. the every instant load torque is not constant at t = 0.1sec load torque 0.5N-m similarly at t = 0.2sec load torque 1 N-m and t = 0.3sec load torque 1.5N-m. The closed loop system brings the speed to the normal value by adjusting the output voltage of the inverter.

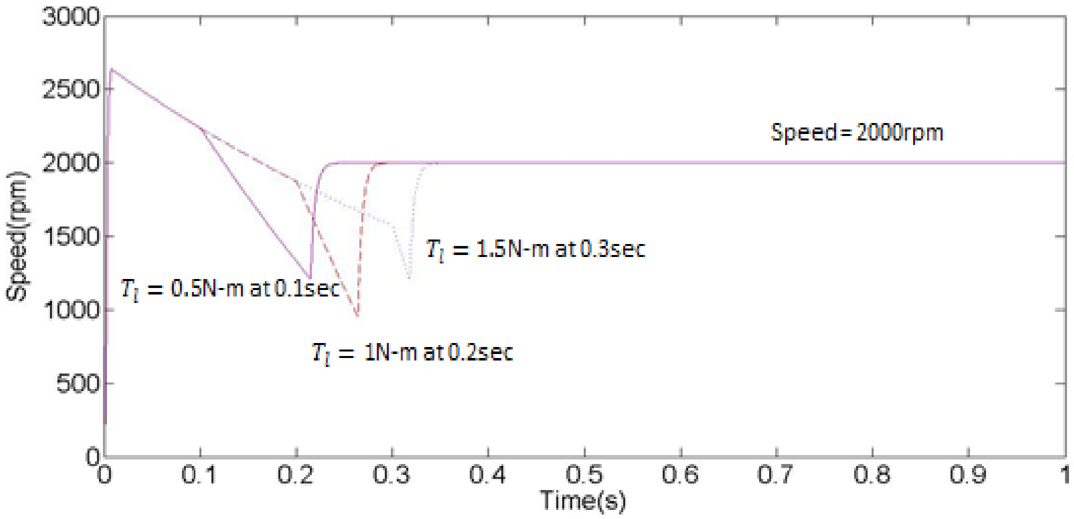

Fig 9: Rotor speed with different load torque at different instant.

V CONCLUSION

In this paper the control scheme for speed control of BLDC motor using PI controller is proposed. The performance of the BLDC motor shows satisfactory performance under no- load and variable load condition. The simulation of PI controller, using MATLAB/SIMULINK to control the speed of flexible BLDC motor, proves that the desired speed is attained with shorter response time. The dynamic characteristic of motor is obtained and the analysis reveals that PI controller is capable of controlling the motor drive over wide speed range.

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