

# Closed-Loop Speed Control of PM-BLDC Motor Fed by Six Step Inverter and Effects of Inertia Changes for Desktop CNC Machine

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**Abstract**—The brushless DC motors with permanent magnets (PM-BLDC) are widely used in a miscellaneous of industrial applications. Usually, these applications are characterized by relatively high torque ripples. In this study, closed-loop speed control of PM-BLDC motor fed by six step inverter for desktop CNC machine investigated. Motor has 3 phases, 0.0089 kg/m<sup>2</sup> /0.00091 kg/m<sup>2</sup> changes inertia moment, 0.005 viscous damping, 3000 rpm reference speed, 4 poles and trapezoidal back EMF wave form. Inverter has 3 bridge arms, snubber resistance 5000 ohms, snubber capacitance 1 uF. Developed speed control PM-BLDC motor use in desktop CNC machine. Also simulated on MATLAB and results are presented in the study.

**Index Terms**—Closed loop systems, permanent magnet machines, position control, variable speed drives.

## I. INTRODUCTION

Nowadays, brushless DC motors with permanent magnets (PM-BLDC) are widely used in a miscellaneous of industrial applications. The permanent magnet brushless dc (BLDC) motor is gaining popularity being used in military, aerospace, computer, automotive, industrial and household products because of its high torque, compactness, and high efficiency [1], [2]. Furthermore, brush maintenance is no longer required, and many problems resulting from mechanical wear of brushes and commutators are improved by changing the position of rotor and stator in DC motor. To alternate the function of brushes and commutator, the BLDC motor requires an inverter and a position sensor that detects rotor position for proper commutation of current [3]–[5]. To improve the performance of BLDC motors, different control methods have been developed by many researchers. Those are such as the field weakening control method, overlapping method, PWM chopping method [6]–[11]. Usually, these applications are characterized by relatively high torque ripples. In this study, closed-loop speed control of PM-BLDC motor fed by six step inverter for desktop CNC machine investigated. Motor has 3 phases, 0.0089 kg/m<sup>2</sup> /0.00091 kg/m<sup>2</sup> changes inertia moment, 0.005 viscous damping, 3000 rpm reference speed, 4 poles and trapezoidal

back EMF wave form. Inverter has 3 bridge arms with IGBTs, snubber resistance 5000 ohms and snubber capacitance 1 microF. Developed speed control PM-BLDC motor use in desktop CNC machine. Developed system simulated using matlab also used in real industrial system. PM-BLDC motor which has closed-loop speed control algorithm used in CNC machine for mechatronic laboratory experiment.

## II. ANALYSIS OF PM-BLDC MOTOR

The stator of a brushless DC motor is equipped with a polyphase winding. The phases are connected to the DC bus through a switching circuit. The switching sequence is controlled so that it is synchronized with the position of the rotor. As a result, the stator produces a rotating magnetic field. The rotor is equipped with permanent magnets, creating a structure with the same number of poles at the stator. The stator switches act like a commutator in a classic DC motor. In brushless permanent-magnet DC (PM-BLDC) motors, the armature currents are commutated exactly according to rotor position. The signal of rotor position may be obtained from a position sensor, or from induced voltages for sensor-less control system [6], [7]. The performance of BLDC motors is analyzed via a time-domain simulation. The voltage equation in the time domain is shown in Equation (1):

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} - \begin{bmatrix} e_d \\ e_q \\ e_0 \end{bmatrix} = \begin{bmatrix} R_1 + L_d \frac{d}{dt} & -L_q \omega_e & 0 \\ L_d \omega_e & R_1 + L_q \frac{d}{dt} & 0 \\ 0 & 0 & R_1 + L_0 \frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}, \quad (1)$$

where  $R_1$ ,  $L_d$ ,  $L_q$ , and  $L_0$  are armature resistance, d-axis synchronous inductance, q-axis synchronous inductance, and 0-axis inductance, respectively.  $\omega_e$  is rotor speed in electrical rad/s. The transformations for terminal voltages, induced voltages, and winding currents are given by the following three equations:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = C^T \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}, \quad (2)$$

$$\begin{bmatrix} e_d \\ e_q \\ e_0 \end{bmatrix} = C^T \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}, \quad (3)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = C \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}, \quad (4)$$

where (2), (3) and (4) are terminal voltages, induced voltages, and winding currents, respectively. The transformation matrices for two phases, three phases, and four phases system, noted as  $C_2$ ,  $C_3$ , and  $C_4$ , are as follows:

$$C_2 = \begin{bmatrix} \cos \theta & \sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}, \quad (5)$$

$$C_3 = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \sin \theta & 1/\sqrt{2} \\ \cos(\theta - \alpha) & \sin(\theta - \alpha) & 1/\sqrt{2} \\ \cos(\theta - 2\alpha) & \sin(\theta - 2\alpha) & 1/\sqrt{2} \end{bmatrix}, \quad (6)$$

$$C_4 = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ \sin \theta & -\cos \theta & 0 \\ -\cos \theta & -\sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \end{bmatrix}, \quad (7)$$

where (5), (6) and (7) are transformation matrices for two phase, three phase, and four phases systems, respectively. Electromagnetic torque is expressed as

$$T_e = T_{load} + J \frac{d\omega_m}{dt} + B\omega_m, \quad (8)$$

where in equation (8),  $T_{load}$  is load torque,  $J$  moment of inertia and  $B$  viscous damping,  $\omega_m$  radial speed of motor. We assumed; all power electronics equipments are ideal, motor is not saturated and motor has no power loss. The effectiveness of proposed system has been validated by comparative studies and simulation results. The proposed system has been simulated by MATLAB software, and a comparative study among the proposed and conventional methods has been done to validate the advantages of proposed method.

PI controller is used as a speed controller for recovering the actual motor speed to the reference. The reference and the measured speed are the input signals to the PI controller. In the Fig. 1,  $K_p$  and  $K_i$  values of the controller are determined by error method for each set speed.

Since the model equations are of non-linear, they are solved by ode4 numerical technique simulated using MATLAB. Table I and Table II are true table of switches

and hall sensor, respectively.

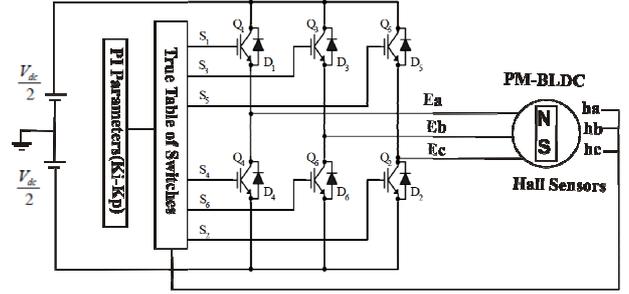


Fig. 1. Block diagram of PM-BLDC with IGBT based inverter.

TABLE I. TRUE TABLE OF SWITCHES.

True table of switches								
Emf-a	Emf-b	Emf-c	Q1	Q2	Q3	Q4	Q5	Q6
0	0	0	0	0	0	0	0	0
0	-1	+1	0	0	0	1	1	0
-1	+1	0	0	1	1	0	0	0
-1	0	+1	0	1	0	0	1	0
+1	0	-1	1	0	0	0	0	1
+1	-1	0	1	0	0	1	0	0
0	+1	-1	0	0	1	0	0	1
0	0	0	0	0	0	0	0	0

TABLE II. TRUE TABLE OF HALL SENSOR.

True table of hall sensor					
ha	hb	hc	Emf-a	Emf-b	Emf-c
0	0	0	0	0	0
0	0	1	0	-1	+1
0	1	0	-1	+1	0
0	1	1	-1	0	+1
1	0	0	+1	0	-1
1	0	1	+1	-1	0
1	1	0	0	+1	-1
1	1	1	0	0	0

These two tables are used for switching the IGBTs.

### III. SIMULATION RESULTS OF PM-BLDC

Closed-loop speed control strategy of PM-BLDC motor consist of IGBT based six step inverter, a speed regulator, and hall sensors, respectively.

Control strategy of PM-BLDC is shown in Fig. 2. this is general view of closed-loop speed control block in Matlab.

Current values changes with the moment of inertia but back-emf closed values. Two different inertia of moment selected the simulated machine and results presented in Fig. 3. The moment of inertia value taken for this case is 0.0089 kg/m<sup>2</sup> and it reaches steady state speed at time 0.25 seconds. When the moment of inertia decreased 0.00091 kg/m<sup>2</sup>, it reaches steady state speed suddenly at time 0.1 seconds. Low moment of inertia means low steady state time for speed and torque, evidence of this is shown in Fig. 3 (a-f).

Closed-Loop Speed Control of PM-BLDC Motor for Desktop CNC

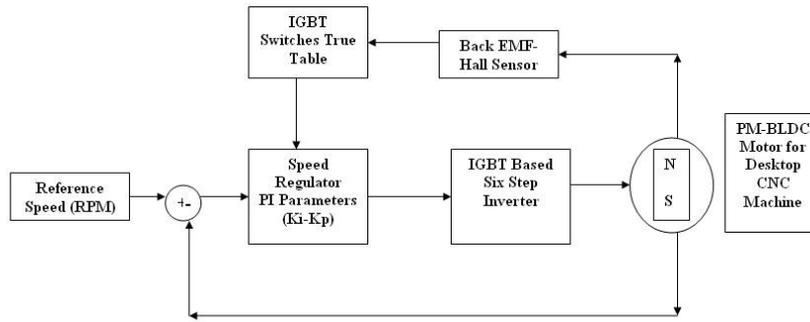


Fig. 2. Closed-loop control of PM-BLDC motor.

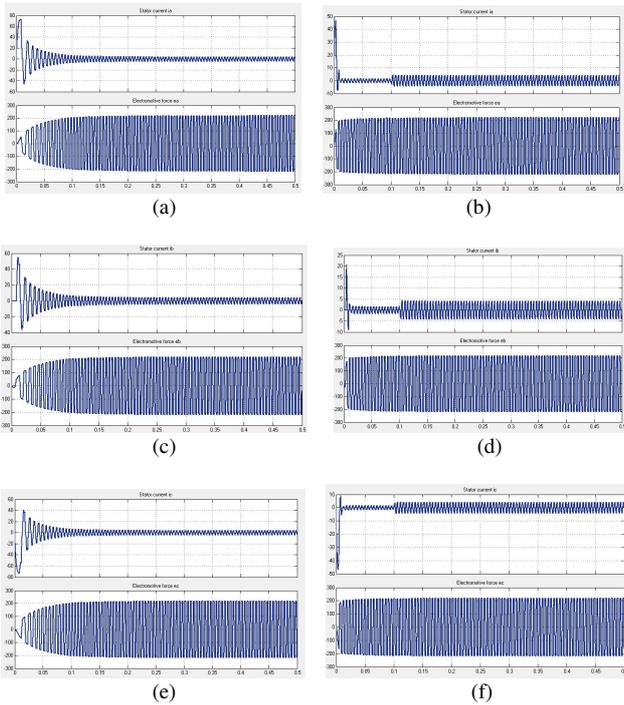


Fig. 3. Currents and Back-EMF changes with inertia of moment (a)  $i_a$  current with  $emf_a$  at  $0.0089 \text{ kg/m}^2$  inertia (b)  $i_a$  current with  $emf_a$  at  $0.00091 \text{ kg/m}^2$  inertia (c)  $i_b$  current with  $emf_b$  at  $0.0089 \text{ kg/m}^2$  inertia (d)  $i_b$  current with  $emf_b$  at  $0.00091 \text{ kg/m}^2$  inertia (e)  $i_c$  current with  $emf_c$  at  $0.0089 \text{ kg/m}^2$  inertia (f)  $i_c$  current with  $emf_c$  at  $0.00091 \text{ kg/m}^2$  inertia.

The moment of inertia value taken for this case is  $0.0089 \text{ kg/m}^2$  and it reaches steady state speed at time  $0.25$  seconds

in Fig. 4 (a).

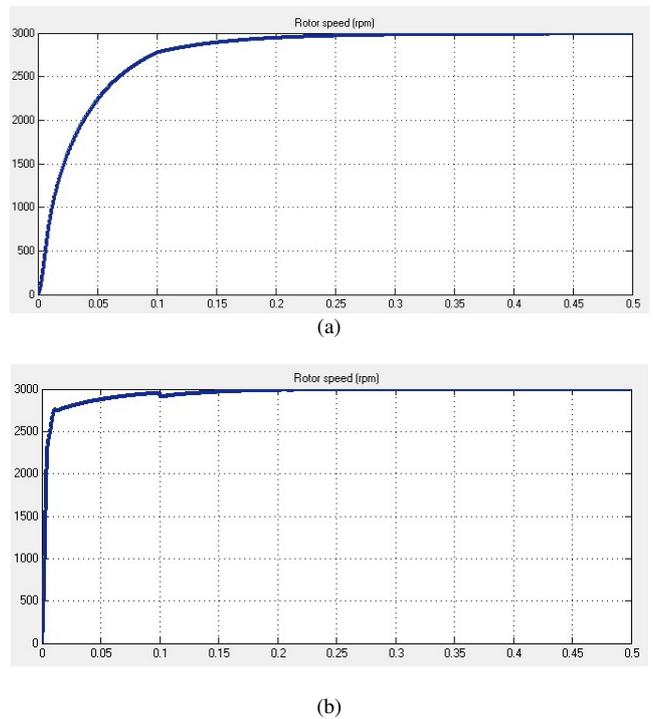
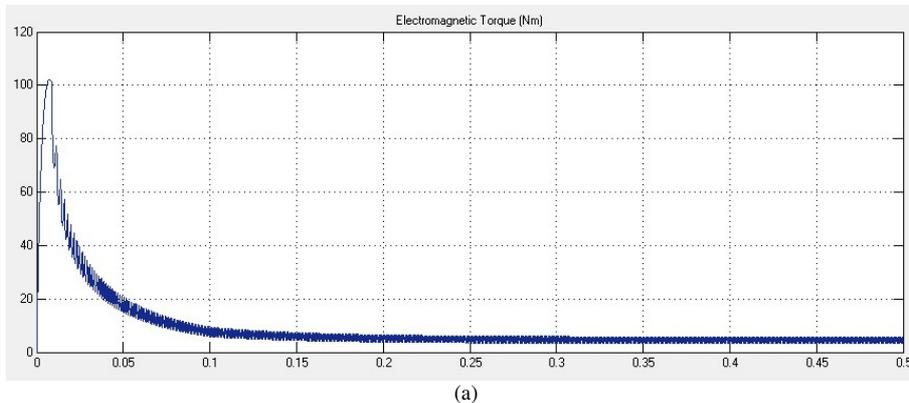


Fig. 4. Speed changes with moment of inertia (a) speed at  $0.0089 \text{ kg/m}^2$  (b) speed at  $0.00091 \text{ kg/m}^2$ .

When the moment of inertia decreased  $0.00091 \text{ kg/m}^2$ , it reaches steady state speed suddenly at time  $0.1$  seconds in Fig. 4 (b).



(a)

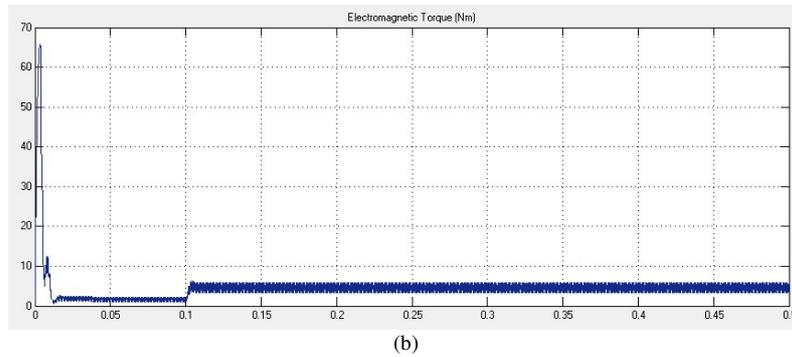


Fig. 5. Torque changes with moment of inertia (a) torque at  $0.0089 \text{ kg/m}^2$  (b) torque at  $0.00091 \text{ kg/m}^2$ .

The moment of inertia value taken for this case is  $0.0089 \text{ kg/m}^2$  and it reaches steady state torque at time 0.25 seconds in Fig. 5 (a). When the moment of inertia decreased  $0.00091 \text{ kg/m}^2$ , it reaches steady state torque suddenly at time 0.1 seconds in Fig. 5 (b). The simulated motor parameters are shown in Table III.

TABLE III. PM-BLDC PARAMETERS.

Name	Value	Unit
Rating	1000	Watt
Pole pairs	4	
Rated speed	3000	rpm
Rated torque	3	Nm
Viscous damping	0.0005	Nms
Inertia of moment	0.0089 / 0.00091	$\text{kg/m}^2$
Resistance Stator	2.8	Ohm
Inductance, $L_H$	0.0085	Henry

#### IV. CONCLUSIONS

Closed-loop speed control of PM-BLDC motor has been investigated for desktop CNC machine. Also effect of inertia of moment investigated influence on reaching steady state time. Two different inertia moments selected for simulation. These are  $0.0089 \text{ kg/m}^2 / 0.00091 \text{ kg/m}^2$ . When the inertia of moment  $0.0089 \text{ kg/m}^2$  selected, it reaches steady state speed at time 0.25 seconds. When the moment of inertia decreased  $0.00091 \text{ kg/m}^2$ , it reaches steady state speed suddenly at time 0.1 seconds. Low moment of inertia means low steady state time for speed and torque. PI controller is used as a speed controller for recovering the actual motor speed to the reference.  $K_P$  and  $K_I$  values of the controller are determined by error method for each set speed.

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