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Modeling and Analysis of PI Controller Based Speed Control of Brushless DC Motor Drive

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Abstract

The Brushless DC motors (BLDC) find widespread applications in domestic and industries due to their low and high power density and ease of speed control. To accomplish desired level of performance the motor requires suitable speed controllers. In case of permanent magnet Brushless DC motors, usually control of speed is reached by using proportional integral (PI) controller. Although the conventional PI controllers are widely used in the industry due to their simple control structure and ease of implementation, these controllers pose difficulties where there are some control complexity such as nonlinearity, load disturbances and parametric variations. Moreover PI controllers require precise linear mathematical models. In this paper, the analysis and mathematical modeling of BLDC motor is implemented. Also, speed control of three phase BLDC motor drive using power electronic device is projected by using matlab/Simulink. The simulation result shows the improved performance of developed Brushless DC motor drive.

Keywords: Brushless DC motor (BLDC), converter, dynamic model, feedback control, simulink, speed control.

Introduction

The adjustable-speed drive is preferred over a fixed speed motor due to energy saving, velocity or position control and betterment of transients. The purpose of a motor speed controller is to take a signal representing the demanded speed and to drive the motor at that speed [1]. Brushless DC motors are mostly preferred because they offer several advantages, including long lifetime, reduced noise and good weight/size to power ratio. Brushless DC motors are used in a growing number of applications such as computer hard drives, CD/DVD players and PC cooling fans [2]. The detailed construction of a conventional BLDC motor is shown in Fig.1. High power BLDC motors are found in electric vehicles, hybrid vehicles and some industrial machinery. The selection of a right BLDC motor for various applications is most important as described by many researchers [3-5]. The permanent-magnet brushless DC motors with trapezoidal back emf finds a variety of applications in aerospace, automotive, industries, military, computers, household products etc. due to higher efficiency, higher torque, higher power factor, increased power density, ease of construction ,ease of control and ease of maintenance [6].

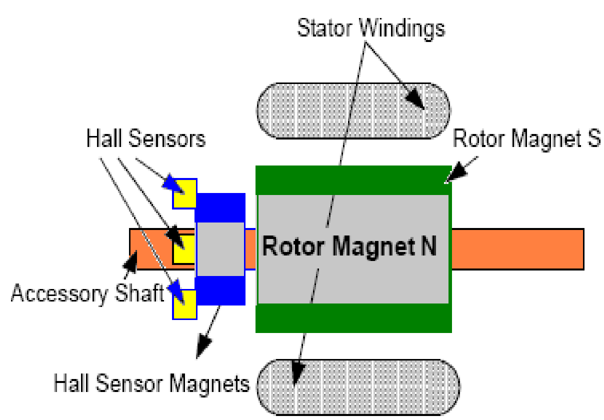

Fig1. Detailed construction of a conventional BLDC motor

The simplified model of a BLDC motor is shown in Fig.2. A four-switch three-phase BLDC motor drive is proposed to simplify the topological structure of the conventional inverter. To exploit the four-switch BLDC motor drive's advantage of lower cost, a single-current-sensor control strategy with PI controller is proposed [7]. A brush less dc motor is defined as a permanent synchronous machine with rotor position feedback. The brushless motors are generally controlled using a three phase power semiconductor bridge.

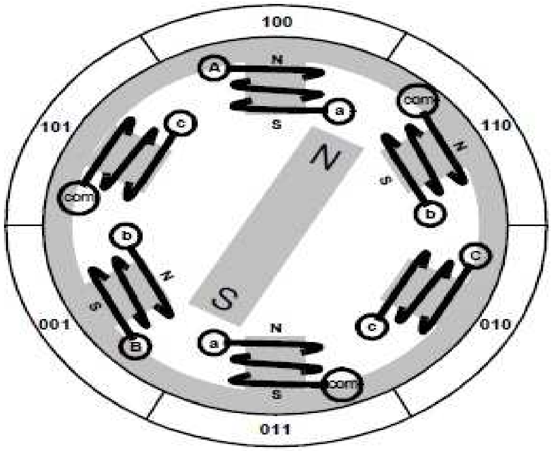

Fig.2. A simplified BLDC motor construction

The motor requires a rotor position sensor for starting and for providing proper commutation sequence to turn on the power devices in the inverter bridge. Based on the rotor position, the power devices are commutated sequentially every 60 degrees. Instead of commutating the armature current using brushes, electronic commutation is used for this reason it is an electronic motor. This eliminates the problems associated with the brush and the commutator arrangement such as sparking and wearing out of the commutator brush arrangement, thereby, making a BLDC more rugged as compared to a dc motor. The BLDC motors have many advantages over DC motors. A few of these are:

• High dynamic response
• High efficiency
• Long operating life
• Noiseless operation
• Higher speed ranges

The designed four-switch BLDC motor drive shows satisfying performance despite the reduction of current sensor. In the fractional-to-40-hp power range, the available ac servos include the induction, permanent-magnet synchronous, and brushless dc motors (BDCM) [8]. The BDCM has a trapezoidal back EMF, and rectangular stator currents are needed to produce a constant electric torque.. Typically, Hysteresis or pulse width-modulated (PWM) current controllers are used to maintain the actual currents flowing into the motor as close as possible to the rectangular reference values. Although some steady-state analysis has been done [9], the modeling, detailed simulation, and experimental verification of this servo drive have been represented by the researchers [10]. Proportional-integral (PI) control with hysteresis or pulse width modulation (PWM) switching is the most widely used speed control technique for BLDC motors with trapezoidal back EMF. The PI controller causes the steady state error to reduce to zero [11]. A PI-controlled system is less responsive to real and relatively fast alterations in state and so the system will be slower to reach set point [12]. The PID controllers, when used alone, can give poor performance when the PID loop gains must be reduced so that the control system does not overshoot, oscillate or hunt about the control set point value [13]. It can be easily implemented on analog or digital components because it is well understood, simple, and in practice for a fairly long period of time. To enhance the performance or to reduce the cost has been focus of development work for a long time. The aim of this paper is that it shows the improved dynamics response of speed with the PI controller to control a speed of BLDC motor for tracking the motor speed as per the load variations by using MATLAB/Simulink package.

Mathematical Modeling of BLDC Motor

Typically, the mathematical model of a Brushless DC motor is similar to the conventional DC motor. The BLDC Motor has three windings on the stator and a permanent magnet rotor on the rotor. The currents induced in the rotor can be neglected due to the high resistivity of both magnets and stainless steel.
The phase voltage equations in matrix form is represented as,

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Where,

V_{as}, V_{bs} and V_{cs} are the stator phase voltages,
R_s is the stator resistance per phase,
I_a, i_b and i_c are the stator phase currents,
L_{aa}, L_{bb} and L_{cc} are the self-inductance of phases a, b and c,
L_{ab}, L_{bc} and L_{ac} are the mutual inductances between phases a, b and c,
e_a,e_b,e_c are the phase back electromotive forces .

The following assumptions are made for modeling of the BLDC motor.

1. The resistance of all the winding is equal.
2. No change in the rotor reluctance with angle because of a no salient rotor

Then,

$$L_{aa}=L_{bb=}L_{cc=}L \quad (2)$$
$$L_{ab=}\ L_{ba=}L_{bc=}\ L_{cb=}L_{ac=}\ L_{ca=M} \quad (3)$$

Substituting equations (2) and (3) in equation (1) gives the stator phase voltages as,

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (4)$$

Where the stator phase voltages are defined by,
$V_{as}=V_{ao}-V_{no}$, $V_{bs}=V_{bo}-V_{no}$ and $V_{cs}=V_{co}-V_{no}$
Where,
V_{ao}, V_{bo}, V_{co} and V_{no} are the pole voltages.
The stator phase currents are forced to be balanced
i.e $i_a+i_b+i_c=0$

Therefore, the stator phase voltages in state space from is given as,

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (5)$$

It has been assumed that back EMF e_a,e_b and e_c have trapezoidal wave from.

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \omega_m \lambda_m \begin{bmatrix} f_{as}(\theta_r) \\ f_{bs}(\theta_r) \\ f_{cs}(\theta_r) \end{bmatrix} \quad (6)$$

Where

ω_m-the angular rotor speed in radians per sec,
λ_m - the flux linkage,
θ_m - the rotor position in radian

The electromagnetic toque is defined as,

$$T_e = [e_a i_a + e_b i_b + e_c i_c] / \omega_m \text{ (N-m)} \quad (7)$$

The moment of inertia is described as

$$T = J_m + J_l$$

The equation of the simple motion system with inertia J, friction coefficient B, and load
Torque T_l is,

$$J \frac{d\omega_m}{dt} + B\omega_m = (T_e - T_l) \quad (8)$$

The electrical rotor speed and position are related by

$$\frac{d\theta_r}{dt} = \frac{p}{2} \omega_m \quad (9)$$

Combining the all relevant equations, the system in state-space form is represented as,

$$x = Ax + Bu + Ce \quad (10)$$

Where,

$$x = [i_a \quad i_b \quad i_c \quad \omega_m \quad \theta_r]^t$$

$$A = \begin{bmatrix} -\frac{R_s}{L-M} & 0 & 0 & -\frac{\lambda_m}{J} f_{as}(\theta_r) & 0 \\ 0 & -\frac{R_s}{L-M} & 0 & -\frac{\lambda_m}{J} f_{bs}(\theta_r) & 0 \\ 0 & 0 & -\frac{R_s}{L-M} & -\frac{\lambda_m}{J} f_{cs}(\theta_r) & 0 \\ \frac{\lambda_m}{J} f_{as}(\theta_r) & \frac{\lambda_m}{J} f_{bs}(\theta_r) & \frac{\lambda_m}{J} f_{cs}(\theta_r) & -\frac{B}{J} & 0 \\ 0 & 0 & 0 & \frac{P}{2} & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{L-M} & 0 & 0 & 0 \\ 0 & \frac{1}{L-M} & 0 & 0 \\ 0 & 0 & \frac{1}{L-M} & 0 \\ 0 & 0 & 0 & \frac{1}{L-M} \end{bmatrix}$$

$$C = \begin{bmatrix} -\frac{1}{L-M} & 0 & 0 \\ 0 & -\frac{1}{L-M} & 0 \\ 0 & 0 & -\frac{1}{L-M} \end{bmatrix}$$

$$u = [v_{as} \quad v_{bs} \quad v_{cs} \quad T_l]^t$$

$$e = [e_a \quad e_b \quad e_c]^t$$

Design of PI Controller

The main reason why feedback is very important in systems is to be able to attain a set-point irrespective of disturbances or any variation in characteristics of any form. A proportional integral-derivative is control loop feedback mechanism used in any applications to control the system. In industrial process, a PI controller attempts to correct that error between a tracked variable and reference set point and then the output is corrected which can adjust the process accordingly. The PI controller calculation involves two separate modes namely proportional mode, integral mode. The proportional mode determine the reaction to the current error, integral mode determines the reaction based recent error. The weighted sum of the two modes output as corrective action to the control element. The PI controller is widely used in industry due to its ease in design and simple structure. The PI controller algorithm can be implemented as

$$outpu(t) = K_p e(t) + K_I \int_0^t e(t)dt$$

(11)

Where e(t)= Reference value-calculated value.

Proposed Method of Speed Control of BLDC Motor

The basic block diagram of Brushless DC motor (BLDC) drive based on PI controllers is shown in fig.3. The proposed drive consists of speed controller, reference current generator, PWM current controller, position sensor, the motor and power electronic controlled based current controlled voltage source inverter. The speed of the motor is compared with its reference value and the speed error is processed in proportional- integral (PI) speed controller.

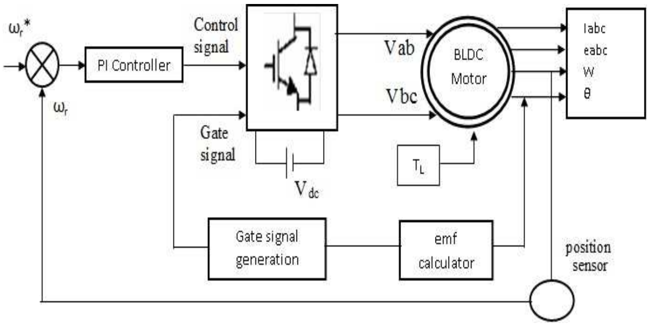

Fig.3. block diagram of PI controller based speed control of BLDC motor drive

The outer speed loop is designed to improve the static and dynamic characteristics of the system. As the system performance is decided by the outer loop, the disturbance caused by the inner loop can be limited by the outer loop. The emf is calculated by taking the angle θ in to consideration which is used to generate gate signal that will be applied to the power electronic converter. On the other hand the position sensor tracks the speed signal and will be compared with the reference signal to determine the error signal which is then allowed to pass through PI controller for compensation and to generate the corresponding control signals for the inverter. The Hall Effect sensors provide the portion of information need to synchronize the motor excitation with rotor position in order to produce constant torque. It detects the change in magnetic field. The inverter is then used to control the speed of the BLDC motor drive at the desired torque demand.

Simulation Results

Simulink model with the PI controller for the speed control of BLDC motor is developed in Matlab. The simulation is run for a specific amount of time (say 1 to 2 sec) in Matlab. From the simulation results it is clear that the PID controller is non-overshoot and initiate speed curve stable. When the sudden increase in load or a sudden change in rotational speed is desired this PI control system provides better robustness and faster tracking capabilities for speed control. The rotor is standstill at time zero with onset of the speed reference, the speed error, torque reference, and attains maximum value. The current is made to follow the reference by the current controller. Therefore, the electromagnetic follows the reference value. The PI speed controller comes into action and tracks the reference speed. From these figures it is clear that the speed response has no overshoots and oscillations and confirms the proper design of PI controller. The simulation results showing the performance of the PI controlled drive system is shown from Fig.4 to Fig.6. The gating signal and control signal for the inverter are shown in Fig.7 to Fig.8. The phase voltage of BLDC motor drive is shown in Fig.9 to Fig.10. The speed error and the electromagnetic torque of the drive system are shown in Fig.11 to Fig.12. It is observed that the drive takes 0.5 sec to reach the set speed.

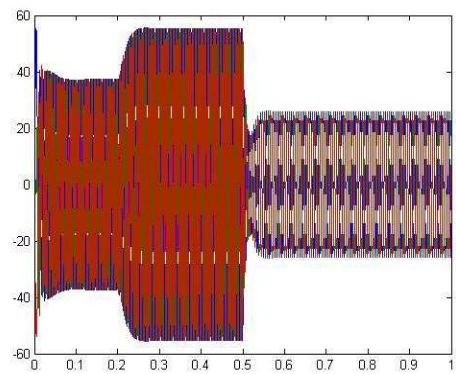

Fig.4. Phase currents of BLDC motor

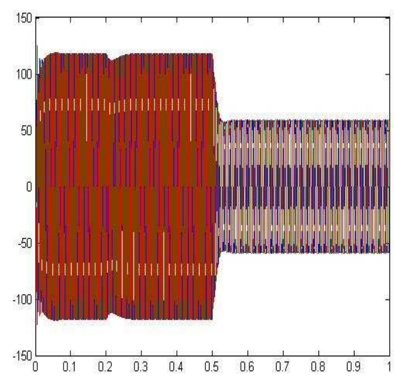

Fig.5. phase voltages of BLDC motor

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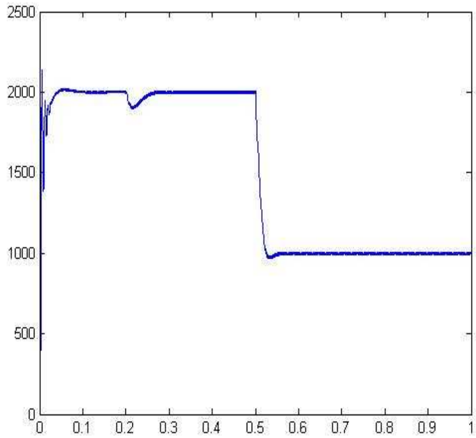

Fig.6. Speed of BLDC motor drive

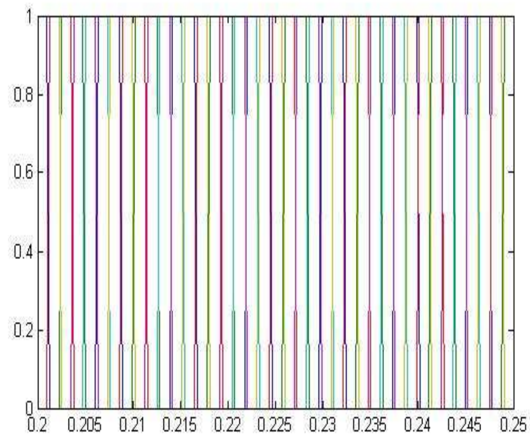

Fig.7. Gate signals to the inverter circuit

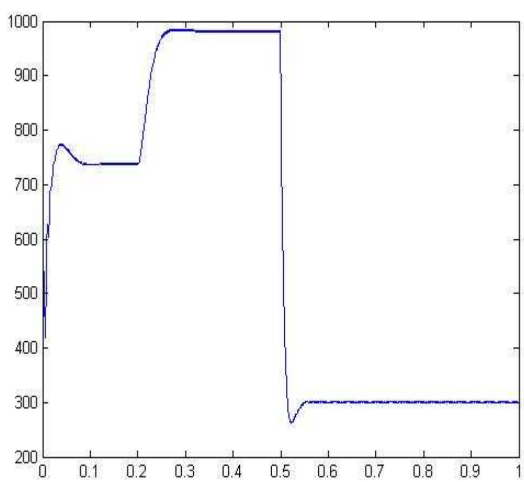

Fig.8. Control signals from the PI controller

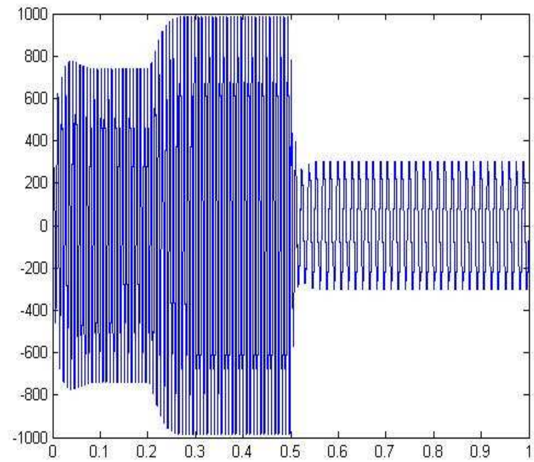

Fig.9. input phase voltage, V_{ab} to the BLDC motor drive

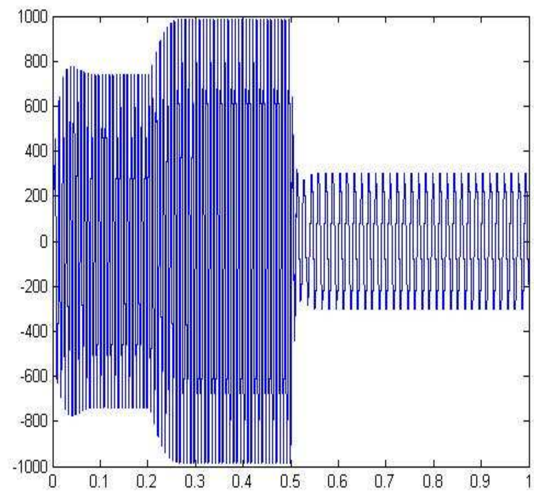

Fig.10. input phase voltage, V_{bc} to the BLDC motor drive

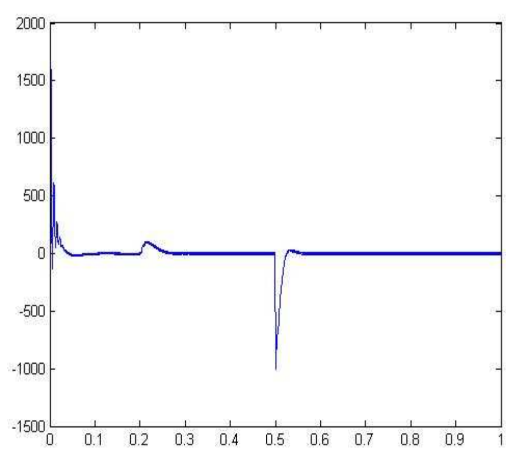

Fig.11. speed error of the BLDC motor drive

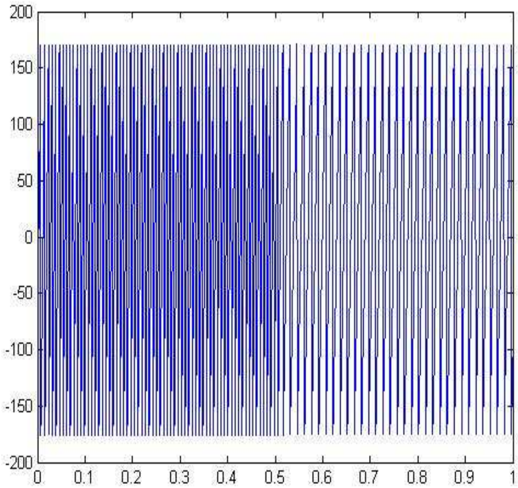

Fig.12.electromagnetic torque of BLDC motor drive

Conclusion

In this paper it is shown that BLDC motor is a good choice for various applications due to higher efficiency, higher power density and higher speed ranges compare to other motor types. The detailed modeling and the simulation of PI controller based speed control of BLDC motor and its torque response results are observer by using MATLAB. The Output characteristics and simplicity of model make it effectively useful in design of BLDC motor drives with different control algorithms in different applications. The simulation results demonstrate that the simulated Waveforms fit theoretical analysis well. However, the simulation involves solving many simultaneous differential equations and the results obtained are highly dependent upon the choice of the system solver.

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