Design and Implementation of a Low Cost Speed Control System for a BLCD Motor

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Abstract: This paper describes the development of a speed control system of low cost to the DC brushless motor. It also explains the operation of these motors, the Trapezoidal method of control and the modeling of dynamic system using Matlab®, Control programming is implemented in a general purpose PIC microcontroller.

Key-Words: Microprocessors, circuits, drivers, servo, speed control, PI control.

1. Introduction

Nowadays it is common to find cases where the requirements in the areas of engineering, including robotics, model airplanes, military and medicine, demand stable, efficient, accurate and low cost control systems. This motivation speeds up the investigation of different ways to solve this problem, starting from the question: how to implement permanent magnet motor, these motors use permanent magnets on the rotor to reduce overall consumption. Additionally, you can design an optimal control system to manipulate the motors and make the most of the best features we provide. Implementing the control sensors effect Hall permit to obtain information about the location of the rotor, thereby ensuring an accurate control of speed and position.

2. Brushless Motor CD

Motor Brushless Direct Current (BLCD) or brushless, is a synchronous motor phase, which is fed through a power converter (inverter) with direct current, which consists of three phases: each with a physical separation of 120°.

In conventional DC motors (Brushed CD) current switching is mechanically achieved, through the device called commutator or switch. In BLCD motors, currents and voltages are applied in each motor winding and are independently monitored by electronic switching (inverter). This way, the problem of the conventional switch can be eliminated. This method eliminates disadvantages including: friction, inertia and greater axial length, also lost due to heating and electromagnetic noise. Finally, it eliminates constant maintenance by periodic replacement of brushes [1, 2].

The stator of this motor is composed of three coils and the permanent magnet rotor. Its operating principle is based on a sequential feeding, developed by an electronic source in the stator, whose input is connected to a circuit CD, and the rotor is synchronized.

Several techniques have been listed to control these motors [1, 2, 3], among which include:

1. Scalar Control (V/Hz).
2. Trapezoidal commutation. (BLCD).
4. Vector Control.
5. Field Oriented (FOC).
6. Direct Torque Control (DTC).

The use of this method, is the first scaled approach to the BLCD motor, it is based on controlling the currents of the motor energizing two terminals simultaneously while the third is kept off. The balanced sequential succession depends on the position of the rotor which is obtained by the Hall sensors, producing changes of 60 degrees (electrical) by sectors as shown in Figure 1. Similarly Figure 2 shows the emf and currents [2, 3, 4, 5].
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![Figure 1. Location of the phases, sensors, sectors and sequences.](image1)

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The common way of feeding an BLCD motor is to connect it to a star (Y) with a phase inverter as shown in Figure 3, where the power devices, usually MOSFET or IGBT, are used for switching circuit according to the control, depending on the signal from the three Hall effect sensors [4, 5, 6, 7, 8].

In Table 1, exposes the switching sequence (Step Six Mode), where the maximum motor torque field is achieved when the stator winding and the permanent magnets of the rotor are offset by 90°. For this, the strategy adopted consists of dividing a full rotation in 6 parts, 60° each.

![Figure 2. Hall position sensors, emf's ideals and current per phase.](image2)

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3. Mathematical Modeling Of Motor BLCD

BLDC motor modeling involves the solution of various electrical and mechanical differential equations, each depending on the motor input and its parameters. The electrical simulation parameters: are resistance, inductance and mutual inductances per phase, and mechanical: the moment of inertia and the friction coefficient. These parameters can be treated like constants in the simulation [6, 7 and 8].

As shown in Figure 2, this represents a simplified model BLCD motor, where it is assumed that the motor input is connected to the output of the inverter and the inverter input to a fixed source of CD [6, 7 and 8].

Applying Kirchhoff's law to the voltage of the three phases of the stator windings, we have [6, 8]:

\[
\begin{align*}
    v_a &= R_a i_a + L_{a} \frac{di_a}{dt} + L_{wb} \frac{di_b}{dt} + L_{wc} \frac{di_c}{dt} + e_a, \\
    v_b &= R_b i_b + L_{a} \frac{di_a}{dt} + L_{wb} \frac{di_b}{dt} + L_{wc} \frac{di_c}{dt} + e_b, \\
    v_c &= R_c i_c + L_{a} \frac{di_a}{dt} + L_{wb} \frac{di_b}{dt} + L_{wc} \frac{di_c}{dt} + e_c. 
\end{align*}
\]

Where the stator resistances per phase are indicated as Ra, Rb and Rc, the inductances own per
Recent Researches in Automatic Control, Systems Science and Communications

Recent researches have been made in the field of automatic control, systems science, and communications, which have led to a better understanding of the fundamental principles underlying these disciplines. These advancements have been driven by the need for more efficient and reliable systems, especially in the context of modern communication technologies.

The control of a system is often achieved through a combination of feedback and feedforward control strategies. Feedback control is used to maintain the system's output within a desired range, while feedforward control is used to anticipate disturbances and adjust the system's behavior accordingly.

Mathematical models of systems are crucial for the design and analysis of control systems. These models allow engineers to predict the system's behavior under different conditions and to design controllers that can stabilize or optimize the system's performance.

In the context of communications, the focus has been on developing new communication protocols and technologies that can support higher data rates and lower latency. This includes advancements in wireless communication, optical communication, and satellite communication.

Overall, the research in these areas is critical for the development of new technologies that can improve the efficiency and reliability of systems in various industries, from transportation and manufacturing to healthcare and finance.

4. Speed Control Simulation

The simulation environment of Matlab Simulink® has a great flexibility and expandability that allows the possibility of developing a set of functions for a detailed analysis of this system. The graphical interface allows the selection of functional blocks interactively, and in the description of signal flow. The simulation was constructed in several steps as calculations of the phase currents, the phase voltages, torque, speed and position of the rotor, and finally the emf, which will be described below based on the previous modelling [6, 7, 8].

Equation (1) gives the currents in the different phases:

\[ i_a = \frac{R_a}{L_a} e_a + \frac{1}{L_a} \int_{t_0}^{t} e_a dt + i_b + i_c \]

Equation (2) gives the currents in the different phases:

\[ i_b = \frac{R_b}{L_b} e_b + \frac{1}{L_b} \int_{t_0}^{t} e_b dt + i_a + i_c \]

Equation (3) gives the currents in the different phases:

\[ i_c = \frac{R_c}{L_c} e_c + \frac{1}{L_c} \int_{t_0}^{t} e_c dt + i_a + i_b \]

\[ T_{em} = P_{em} = 1 \omega \sum_{i=1}^{3} e_i i_i \]

Equation (4) gives the currents in the different phases:

\[ T_{em} = 1 \omega (e_{i_a} + e_{i_b} + e_{i_c}) \]

The mechanical equation is Newton's 2nd law for rotational motion:

\[ T_{em} = J \frac{d\omega}{dt} + B\omega - T_c \]

Where:
- \( T_c \) is the load torque.
- \( \omega \) is the electrical angular speed of the rotor.
- \( \omega_m \) is the mechanical angular velocity of the rotor.
- \( J \) is the moment of inertia.
- \( B \) is the coefficient of friction or viscosity.

The induced emf is trapezoidal so the peak value is given by Faraday's Law [6], where:

\[ E_p = N(Blv) = N(Blr \omega) = N\Phi \omega = \lambda \omega \]

Where:
- \( N \) is the number of turns per phase.
- \( B \) is the field flux density.
- \( l \) is the rotor length.
- \( v \) is the linear speed of the rotor.
- \( r \) is the radius of the rotor.
- \( \omega \) is the rotor electrical angular velocity.
- \( \Phi \) is the flow field.
- \( \lambda \) is the concatenation of flow.

The induced emf can be written as [6]:

\[ e_a = f_a(\theta)\lambda \omega, e_b = f_b(\theta)\lambda \omega, e_c = f_c(\theta)\lambda \omega \]

The functions \( f_a(\theta) \), \( f_b(\theta) \), \( f_c(\theta) \) and \( k(\theta) \) are out of date functions including 120°, which can be trapezoidal or sinusoidal, depending on the type of control. It should be kept in mind that the emfs \( e_a, e_b, e_c \) must have a maximum magnitude of normalized absolute value (unitary).

Fig. 4. Phase currents

Where \( v_a, v_b, v_c \) are the voltages from the three-phase inverter bridge, motor input. An important parameter, \( v \) can also be seen which is the node or neutral star connection and is given by [6]:

\[ v_n = \frac{1}{3} (v_a + v_b + v_c) - (e_a + e_b + e_c) \]

Then, by having the values of the currents per phase, we proceed to find the electromagnetic torque reference from equation (5):

Fig. 5. Electromagnetic torque.

The speed of the system is obtained from equations (6) and (7), and its simulation with Simulink®, shown in Figure 6.
The emf is obtained from equation (9) as shown in Figure 7.

To achieve the trapezoidal waveforms sine waves 120° degrees out of phase are generated, which eliminates the use of a saturation phase block, and to finally obtain the trapezoidal emf per phase, as illustrated in Figure 1.

The open loop system is obtained by bringing together all the previous blocks in together with the block BLCD, which is also integrated by the Universal Bridge1 block, obtained from SimPower System Blockset (Phase Inverter) and the inverter control represented by block drives the whole system is shown in Figure 8.

This model was obtained by simulating the open-loop speed response as can be seen in Figure 9. Looking for higher accuracy to implement the closed loop system, we chose to implement the first tuning method of Ziegler - Nichols, also known as a method of adjustment in open loop. To find parameters like the delay time $T_d$ and the time constant $T$, a straight red aid was added to Figure 9 [8, 9].

From the previous figure we obtained values $T_d = 0.0085$ sec and $T = 0.068$ sec. To calculate the PI controller these values are shown in equations (11), (12), (13) and (14).

$$K_p = 0.9 \left( \frac{T}{T_d} \right) = 7.2 \quad (11)$$

$$T_i = T_d / 0.3 = 0.028 \text{ seg} \quad (12)$$

$$K_i = K_p / T_i = 0.27T / T_d^2 = 254.11 \quad (13)$$

$$PI(s) = K_p \left( 1 + 1/T_i s \right) = K_p + K_i / s \quad (14)$$

Using this controller a performance suitable for speed control of electric motors, including the BLCD may be achieved [9]. From Figure 10, it can be seen the speed control design in closed loop, where the speed reference has a value of 10,000 rpm, it was used for feedback a voltage source voltage controlled by SIMpower System Blockset, where a speed control is developed by a DC bus.

In Figure 11 the response for a closed loop system input 5,000 rpm and a load torque $T_c = 20$ Nm is observed.

5. DESIGN AND IMPLEMENTATION OF SPEED CONTROL SYSTEM

For the implementation of speed control system a Maxon BLDC motor (EC-MAX 318 068) from the Maxon Precision Motor Inc. company was used [10].

In the literature related to the speed control systems for BLDC motors are several applications using DSPs [11, 12, 13], FPGAs [14, 15, 16] or
microcontrollers, including PIC [16, 17, 18]. The use of the last one was motivated mainly by its low cost and accessibility to these devices. Microchip [20] recommends for motor control BLCD the use of high-end family PIC18F1X30 and PIC18FXX31. It was decided to use a mid-range PIC16F877A PIC, which does not provide all the functionality that a high-range provides, but does not restrict the development at a lower cost. W. Brown [17] presents a development with the PIC16F877A, but the control is only sinusoidal. For a better visualization of the implemented speed control system, a block diagram of the entire system is shown in Figure 12.

The mid-range PIC16F877A microcontroller developed by Microchip Inc. Company uses Flash technology. This has powerful (instruction execution than 200 nsec) with easy programming (only 35 instructions) [21]. This satisfies the needs to perform motor control. Taking into consideration the characteristics of this device, it is possible highlight the most important ones, consisting of 2 independent PWM modules, especially dedicated to the motor, in addition features 8 channels of A / D, one of which was used for regulating the motor speed.

In Figure 13 shows the electrical circuit connection to the microcontroller.

In Figure 14 (a) 6 shows the activation signals provided by the microcontroller. 16 (b) this figure shows the measurement of emf between phases A and B.

In Figure 15 shows the high-side drivers for S1, S2 and S3, and low side drivers for the S2, S4 and S6, which are responsible for correct ignition devices power MOSFETs, adapting the control signal of 0 Microcontroller - 5V to 0 - 12V.

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In Figure 16 shows the dynamic response of the speed. The response speed of the motor is without load for a speed of 5000 rpm, to establish the length 94,975 msec (≈ 0.1 seconds).

6. CONCLUSIONS

We modeled and simulated the motor BLCD with the help of Matlab®, mainly in developing the Six Step Mode and its interaction with the motor, which reached to control the motor speed as desired.

The simulation of the closed loop system was performed using a PI controller setting the first method of Ziegler - Nichols, once simulated the open loop system. In the simulation the PI controller proved to be a sufficiently robust and tolerant to noise. It does not possess a derivative term, as in the case of the PID controller. Similarly smooth speed changes were obtained by getting proper control and good torque characteristics.
Implementation was performed using a microcontroller PIC 16F877A, which was sufficient to achieve the control objectives, where the schedule was adjusted to the processing power and memory of the device. A control board low cost was designed and built, which demonstrated its robustness and noise immunity during the trial period. This proves the accessibility of this control technology for this application.

Finally, if one wants to obtain major presentations to use another microcontroller of frequency bigger than 20 MHz, since the speed in these motors depends directly on the frequency of the pulses. We also recommend implementing the power amplifier with the TC4469 to obtain faster switching using MOSFETs for its high switching speed.

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