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Development of a BLDC motor drive with improved output characteristics

Abstract*. A brushless DC (BLDC) motor control based on rotor position sensing scheme is discussed in this paper. A PIC microcontroller is employed to generate pulse width modulation (PWM) signals for driving the power inverter bridge. Parameters required for power PWM generations have been programmed, which provide flexible and online source code modifications in accordance with the motor and circuit requirements. Hardware implementation and simulation results show the effectiveness of the developed motor drive. The flexibility offered by the developed motor control and drive enables the implementation of difference control algorithms for improving the output characteristics of the BLDC motor.*

Streszczenie. *W artykule przedstawiono sterowanie silnikiem bezszczotkowym DC bazujące na czujnikach pozycji wirnika. Mikrokontroler jest wykorzystywany do wytwarzania sygnału PWM zasilającego przekształtnik. Parametry wymagane do generacji sygnału PWM są programowane w zależności od wymagań silnika i napędu. Badania modelu i symulacje pokazują skuteczność zaproponowanej metody. (**Napęd silnika bezszczotkowego z ulepszoną charakterystyką wyjściową**)*

Keywords: BLDC, Motor Drive, Microcontroller, PWM.
Słowa kluczowe: silniki bezszczotkowe DC, .PWM, napęd.

Introduction

In conventional DC motors with brushes, the field winding is on the stator and armature winding is on the rotor. The motor is expensive and needs maintenance because of the brushes, the accumulation of the brush debris and dust, and commutator surface wear. Moreover, in certain hazardous locations, the application of DC brushed motors is limited because of the arcing. This could be solved by replacing the mechanical switching components (commutator and brushes) with electronic semiconductor switches. Brushless DC (BLDC) motor has a permanent magnet rotor and a wound field stator connected to a power electronic switching circuit. BLDC motor drives have high efficiency, low maintenance and long life, low noise, control simplicity, low weight, and compact construction.

BLDC control drive systems are based on the feedback of rotor position obtained at fixed points typically every 60 electrical degrees for six-step commutation of the phase currents [1].

Brushless motors can be classified as either trapezoidal or sinusoidal based on the shape of their back-EMF. In BLDC motors with trapezoidal back-EMFs, the permanent magnets produce a trapezoidal air gap flux density distribution. These motors have higher torque and larger torque ripples compared with motors that have sinusoidal-shaped back-EMF. They are also cheaper and used for general applications [2].

The BLDC drive system consists of BLDC motor, power electronics converter, sensor, and controller as shown in Fig. 1.

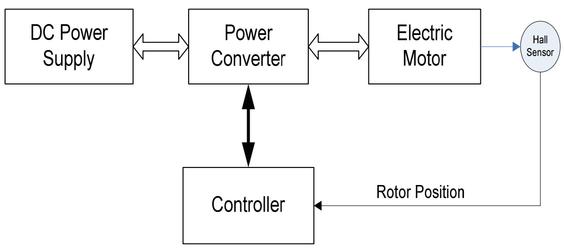


Fig.1: BLDC drive system components

BLDC Motor Control

The pulse width modulation (PWM)-controlled BLDC motor drive system is the most commonly applied technique for driving a motor inverter bridge. An effective comparison of PWM-controlled and pulse-amplitude modulation (PAM)-controlled sensorless BLDC motor drives for refrigerator applications has been presented by Lai et al. [3]. For BLDC motor drives, the inverter can be controlled through either PWM with a fixed DC-link voltage or PAM with controlled DC-link voltage amplitude. A novel microcontroller-based sensorless BLDC motor drive for automotive fuel pumps has been presented in Ref. [4]. The paper describes the speed control of a BLDC motor drive that employs a hard-chopping PWM technique using a digital signal processor. According to the input command, feedback command, and control algorithm, the PWM pulses for each phase generated by the DSP are given to MOSFET/insulated gate bipolar transistor (IGBT) driver [5].

Yen-Shin et al. [6] presented a PWM technique for small-power BLDC motor drives that significantly reduces conduction losses and heat dissipation. Comparative results using conventional PWM techniques have been fully explored to highlight the advantages of the proposed technique [6]. A PWM technique with switching-loss reduction for a five-leg inverter has been presented by Oka et al. [7]. The method advantages in the DC-bus voltage can be fully available. Information on the motor frequency, phase, and amplitude of phase voltage commands is not required in this PWM strategy [7].

To switch the motor stator coils in the correct sequence and at the correct time, the position of the rotor field magnets must be known. The exact location of the rotor field magnets can be detected by Hall Effect sensors or by an encoder. In this paper, the position information fed to the controller will be implemented using Hall Effect sensors.

The function of the controller is to switch the right currents in the right stator coils at the right time in the right sequence using the information supplied by the sensor and processing it with pre-programmed commands to make the motor perform as desired. Embedded microcontrollers are a widely used technology in many devices and systems; nowadays, fewer electrical devices are controlled by means of analogue. Instead, many devices and systems are operated digitally using microcontrollers that can be programmed to perform multiple tasks, which provides easier and flexible control [8].

One of the popular microcontroller products suitable for such motor control applications is the 8-bit PIC18 microcontroller from Microchip. This microcontroller unit (MCU) offers a moderate price/performance ratio with reliable and easy development technology [9].

Implementation of drive control

Digital controller systems are used extensively in the field of motion control. High-performance digital control systems usually require the fast execution of control algorithms. These controllers, which are typically run at a moderate clock frequency and use multiple instruction cycles for each processing step, could provide a flexible and fast motion control system [10].

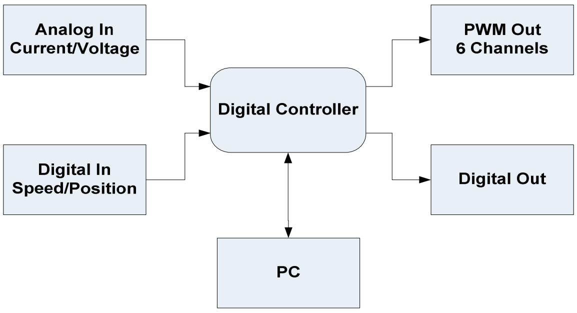


Fig. 2: Block diagram of microcontroller system

The 8-bit microcontroller produced by Microchip Technology Inc. that has special advanced motor control peripherals could deliver better efficiency, quieter operation, wide speed range, and extend the life of motors. This chip provides a complete solution for precise and energy-efficient operation in sophisticated motor control applications through advanced analogue and digital feedback, and three-phase complimentary PWM modules. A block diagram showing the digital signal controller functionality is shown in Fig. 2 [11].

The new IGBTs lead the market today for medium and high power applications. IGBTs feature many desirable properties including high switching speed, low conduction voltage drop, high current-carrying capability, and a high degree of strength. The availability of IGBTs has lowered the cost of systems and made its use economically viable in many practical applications. A recommended switch driver from the IGBT manufacturer is used in this paper. The online design tools provided by the manufacturers and the customer support aids in the selection of a proper switch driver. The gate drive is needed to amplify gate signals generated by an embedded controller and to provide electrical isolation between the control circuit and the power circuit [12], [13].

For a drive system with sensors, the Hall Effect position sensors are used to determine the actual rotor position. The Hall outputs are monitored by the controller, and an appropriate commutation sequence is applied for commutating the motor [14].

A block diagram showing the system connection is illustrated in Fig. 3. A reference speed is given by the user, a popper PWM scheme is applied to the power switch driver, and then the motor is connected to the output of the power bridge. The feedback signals of the BLDC rotor position are fed back using the assembled Hall Effect sensors.

The speed of the motor is varied using PWM outputs on the output voltages. The speed of the motor is directly proportional to the applied voltage. By varying the average voltage across the windings, the motor speed can be changed. This is achieved by altering the duty cycle of the base PWM signal. Maximum speed is achieved when the PWM duty is 100%. In this case, the power switches are ON for 100% of the commutation period. When PWM is less than 100%, the speed is proportional to the duty cycle setting. The speed reference is determined using a potentiometer. Then this reference is converted to a digital signal that is used as a reference for the PWM duty cycle register.

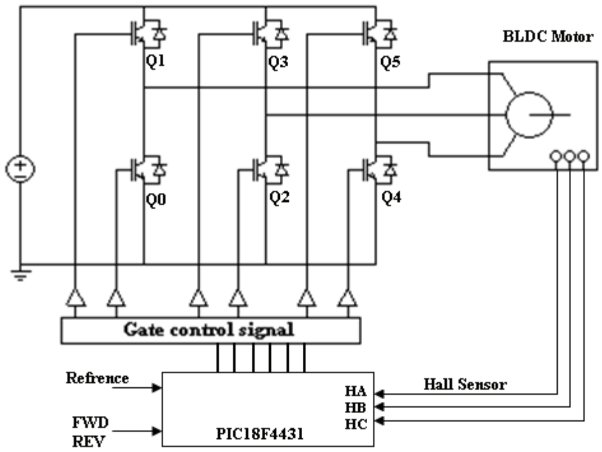


Fig. 3: System connection

The programming task is performed under the MPLAB IDE environment with C18 compiler and ICD2 module. The basic configuration of the PIC 18F4431, the initialization of the PWM module, the ADC module for speed reference and Hall sensors, and duty cycles of the power PWM are presented. At any time, the stop button can be activated to stop the machine and jump back to the beginning of the program. The flow of the program code for BLDC drive based on the Hall Effect sensing of rotor position is shown in Fig. 5.

As an interrupt routine for change notification of rotor position by the Hall sensor, when a Hall sensor changes state, an interrupt pointer is generated in the ISR routine. The program then reads the IC1, IC2, and IC3 inputs, which are then used to load a corresponding value from the state table, and sends the correct PWM output to energize the IGBT switch.

BLDC drive system model

The BLDC motor produces a trapezoidal back-EMF and the applied current waveform is rectangular. The stator resistances of all the windings are assumed equal, and the self-inductance and mutual inductance are constant. The three-phase voltage equations can be expressed as in Equation (1) [15]. The rotor induced currents are neglected and the damper windings are not modelled in this equation.

$$(1)\quad \begin{bmatrix} v_a\\ v_b\\ v_c\end{bmatrix} = \begin{bmatrix}R_S&0&0\\0&R_S&0\\0&0&R_S\end{bmatrix}\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix} + \begin{bmatrix}L_S-M&0&0\\0&L_S-M&0\\0&0&L_S-M\end{bmatrix}\frac{d}{dt}\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix}+\begin{bmatrix}e_a\\e_b\\e_c\end{bmatrix}$$

R_s is the phase resistance, L_s is the self-inductance in L, and M is the mutual inductance. The variables v_a, v_b, and v_c are the phase voltages; i_a, i_b, and i_c are the phase currents; e_a, e_b, and e_c are the phase back-EMF voltages.

The equivalent circuit of the BLDC motor is shown Fig. 4.

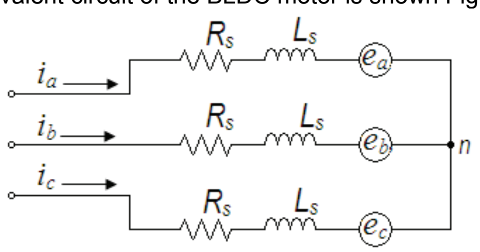


Fig. 4: Brushless DC motor equivalent circuit

Due to the interaction of the current in the stator windings and the magnetic field in rotor magnet, the electromagnetic torque is generated in the BLDC motor.
The electromagnetic torque is given by

(2) $$T_e = (e_a i_a + e_b i_b + e_c i_c)/\omega_m$$

where ω_m is the mechanical speed of the rotor. The equation of motion is

(3) $$\frac{d}{dt}\omega_m = \left(T_e - T_L - B\omega_m\right)/J$$

where T_L is the load torque, *B* is the damping constant, and J is the moment of inertia of the rotor shaft and the load [2].

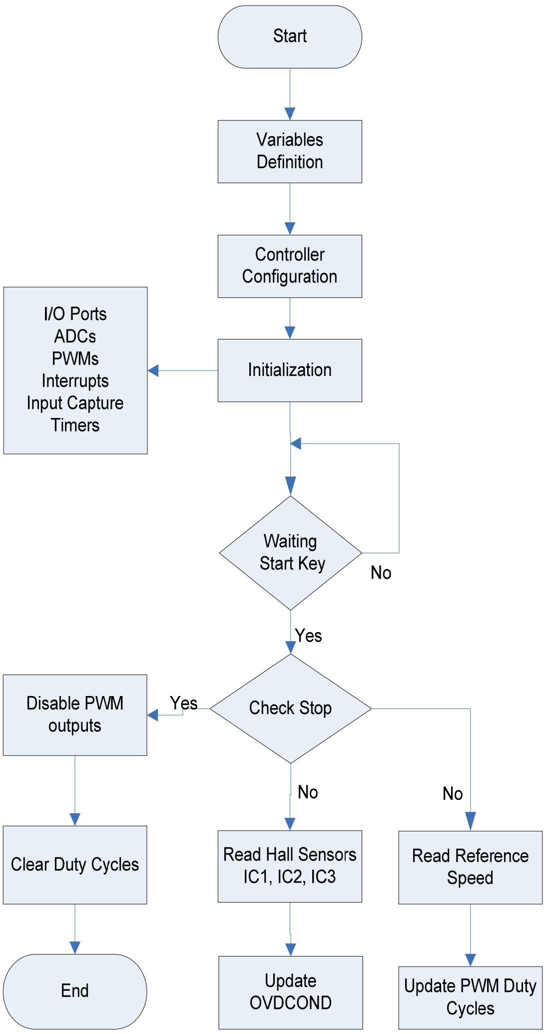


Fig. 5: Flowchart of sensor-controlled BLDC motor

Simulation results

Fig. 6 shows the setup configuration of the BLDC motor simulation using the PSIM. The signals from the Hall sensors are used to generate the proper commutation sequence for the BLDC motor drive. Based on the output of the built-in Hall sensors, the corresponding switch will be energized in accordance to the six-step BLDC commutation principle. There is one transition from high to low or low to high at each 60°; the conduction of each sensor is 120°.
Fig. 7 shows the simulated phase currents of the BLDC motor based on Hall sensor control. There is a transition from high to low or low to high at each 60°; the conduction of each sensor is 120° electrical.

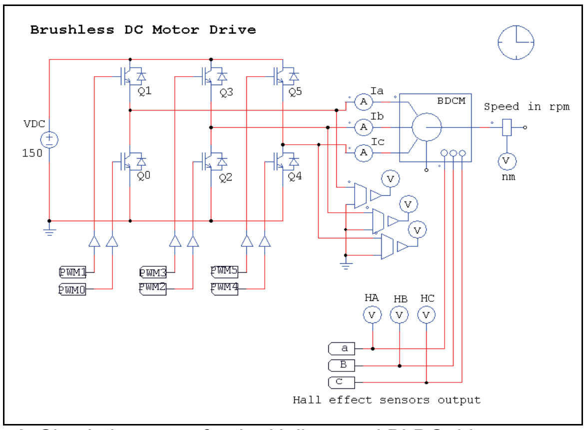


Fig. 6: Simulation setup for the Hall-sensed BLDC drive

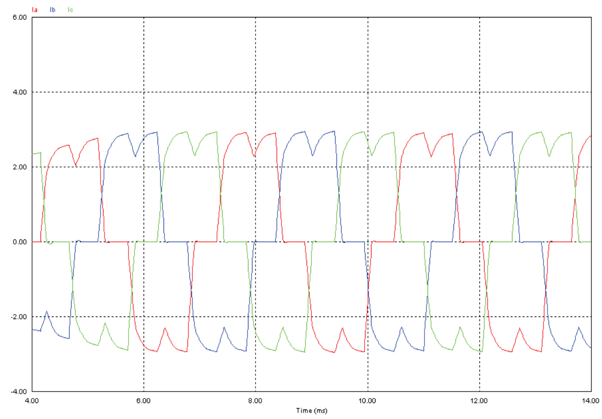


Fig. 7: Phase current waveforms

Experimental results

Fig. 8 shows the hardware implementations consisting of a control board, a three-phase inverter board, and a three-phase permanent magnet brushless motor.

The developed prototype three-phase inverter bridge with the HV driver is connected to the MCU through opto-coupler drivers to provide isolation between the power and the control sides. The developed motor control offers Hall sensor and/or encoder input ports for rotor position feedback. Details regarding the experimental motor are shown in Table 1.

As shown in Fig. 9 (lower waveform), the generated PWM driving signal for the inverter bridge power switches have been chopped to a train of pulses utilized by the PIC microcontroller PWM module.

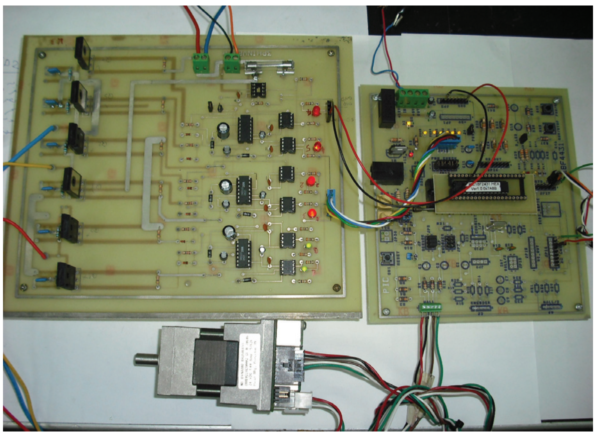
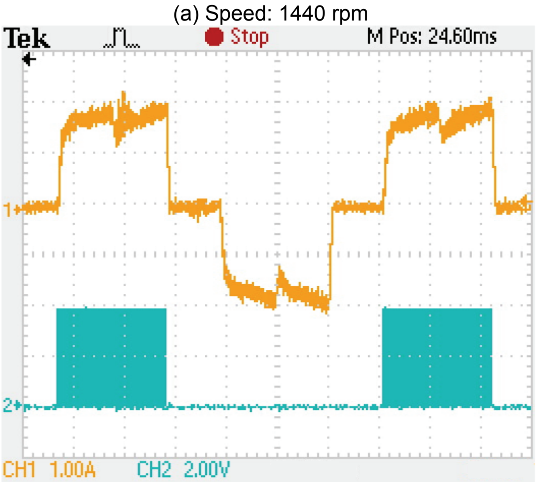


Fig. 8: Hardware implementations

The upper waveform in Fig. 9 shows the measured current of the BLDC motor; the shape of motor current is matched with the current recorded in the simulation. The lower waveform shows the control PWM signal driving the power switch.

(a) Speed: 1440 rpm



(b) Speed: 900 rpm

Fig. 9: Measured motor current and PWM

Conclusion

The generated PWM signals for driving the power inverter bridge for BLDC motor have been successfully implemented using an 8-bit PIC18F4431, as well a PIC18F18F2431 microcontroller. The BLDC motor control based on rotor position sensing scheme has been discussed and successfully implemented. The required references for power PWM generation have been implemented in the PIC code, through which it will provide a flexible and easy-to-change or modify source code in accordance with the motor and circuit requirements. The developed control and power board is functions properly and satisfies the application requirements. Simulation and experimental results verify the effective developed drive operation.

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APPENDIX

Table 1: Brushless DC motor from Hurst (Model: DMB0224C10002)

Rated power	26.46 W
Rated speed	2054 rpm
Rated voltage	24 V
Rated current	1.16 A
Number of poles	10 Poles
Phase resistance (R)	4.03 Ω
Phase inductance (L)	4.6 mH at 1 kHz
Torque constant (Kt)	0.069 Nm/A
Back EMF constant (Ke)	7.24 Vp/rpm

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