

The Development of Current, Speed and Torque Measurement System for Low Power Electric Vehicle Motion Control Applications

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Abstract. To design motor drives for optimal motion control, and to obtain precise Brushless Direct Current motor model, accurate measurement of motor parameters like phase current, speed and torque is required. They are also desired to provide feedback between the BLDC motor and its controller to develop robust BLDC motor control algorithm. In this paper, phase current, speed and torque measurement technique for Hub BLDC motor is presented to analyze its performance for low power electric vehicle applications. For the phase current measurement, the Hall-Effect current sensor ACS712 is used. The speed of the motor is calculated using internal hall sensor that is connected to dsPIC33F's input capture pin that generates an interrupt whenever a change in the hall sensor signal value occur. Further, an experimental setup is established in the laboratory to measure the torque at varying load and to determine the relationship between motor torque, input current, output power, speed and efficiency.

INTRODUCTION

In recent years, Brushless Direct Current (BLDC) motors also called the permanent magnet synchronous motors are becoming popular in automobiles, medical instruments, appliances, aerospace and robotics. They are also widely used in electric vehicles as they offer higher reliability, silent operation, lower maintenance [1], higher power density, faster dynamic response and high-speed ranges as compared to DC and induction motors. They also offer better speed versus torque efficiency and faster cooling. For the applications where weight and space are the crucial factors, BLDC motors are useful as they offer higher torque v/s size ratio [2]. Despite of all the advantages BLDC motor require complex motor drives and control systems for running them as they are electronically controlled. Hence, a thorough insight of BLDC motor parameters becomes important. The motor parameters that are mentioned in the motor specifications may not be accurate; especially for cheaper BLDC motors thus validating the parameters is beneficial for optimal control. Various attempts have been made in the past to determine motor parameters. Danupon et al. [3] used adaptive Tabu search (ATS) and intensified current search (ICS) to estimate motor parameters like K_e , K_A , τ_m , τ_e and τ_A . Least-squares approximation technique is used to determine Motor parameters like cogging torque, B , Coulomb Friction coefficient and BEMF harmonics using the motor's back-EMF, phase currents, rotor position, and rotor speed [4]. Lei Hao et al. [5] used a hybrid sliding mode observer to estimate the motor speed. Riteshet al. [6] proposed estimated instantaneous torque of BLDC motor for square wave and sinusoidal phase current supply and validated the result using SIMULINK.

The above mentioned methods make use of software to determine motor parameters. A testing setup is still required to validate the characteristics and develop an efficient motor control system. This paper delineates experiment based theoretically investigated parameter identification of BLDC motor. The voltage equation of the BLDC motor is given by:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Where, v_a, v_b, v_c are the phase voltages, R is the phase resistance, i_a, i_b, i_c are the phase currents, L is the inductance, and e_a, e_b, e_c are the induced back electromotive forces.

The dynamic model of the BLDC hub motor consists of mechanical and electrical part both. The load model of the BLDC motor is related to the phase current is expressed by:

$$K_t * i = T_l + B\omega + J \frac{d\omega}{dt} \quad (2)$$

Where, K_t is the torque constant, i is the phase current, T_l is the load torque, B is the friction coefficient, ω is the motor rotation speed, and J is motor inertia.

The motor inertia J is calculated by finding the ratio of torque and acceleration and the friction coefficient B is expressed as:

$$B = K_t * \frac{i_2 - i_1}{\omega_2 - \omega_1} \quad (3)$$

Thus in order to determine motor characteristics, it is desired to precisely measure parameters like speed, phase current and torque to determine K_t, T_l, B and J . We present measurement module for phase current, speed and torque for BLDC Hub motor to determine motor characteristics. Further, an experimental setup is established to derive efficiency and mechanical power of BLDC motor at varying torque. Finally, the relationship between the motor torque, speed, phase current, output mechanical power and efficiency is studied and graphs are plotted.

The remainder of the paper is organized as following: The system design is shown in Section II. Section III and Section IV shows phase current and speed measurement respectively. The torque measurement technique is shown in Section V. Section VI illustrates the experimentation results and Section VI shows the conclusion.

SYSTEM DESIGN

In this paper, a 24V, 20 pole, three-phase BLDC Hub motor is driven by DsPIC33 controller, IR2110 motor driver IC and three phase inverter. Electronic control of three-phase BLDC motor is achieved when the current flows through two phases at a time. For proper commutation of the current the information about the exact rotor position is required. The BLDC Hub motor consists of three Hall Effect based position sensors that are placed 120° apart to detect the initial rotor position. For every possible combination of three hall sensors, 6 switching pulses are generated that are used to determine the next commutation sequence. The block diagram of the system is shown in figure 1. The system comprises of DsPIC controller, signal processing unit, phase current measurement unit using ACS712 current sensor for phase current measurement and a three-phase MOSFET bridge. The hall sensor signal changes its value from low to high or high to low this is read by the input capture pin and an interrupt is generated to send the next commutation sequence to rotate the motor.

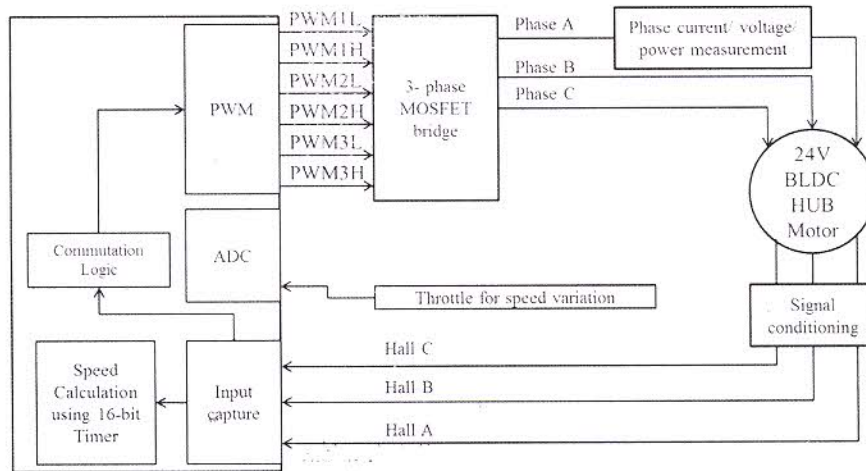


Figure 1: Block Diagram of the system

PHASE CURRENT MEASUREMENT OF BLDC MOTOR

Accurate measurement of the current for all the three phases becomes important to achieve desired dynamic control of the motor using the 3-phase inverter. The three-phase inverter is used to control the three phase BLDC motor and to achieve the desired dynamic torque. Thus, accurate measurement of all the three phase current becomes important to obtain accurate feedback in order to attain desired motor characteristics and for system stability. Most of the systems use low/high side current sensing or inline current sensing using shunt registers. These methods require signal processing and amplification of correct measurement thus increasing the complexity. In the proposed method, the current across the three phases of the motor is measured using ACS712 ELCTR-20A- T current sensors from Allegro Microsystems. It can measure bidirectional current in the range of $\pm 20A$ and the output voltage range is 0V to 4.5V as shown in figure 2. The voltage v_o versus input current i relationship of the sensor is given by:

$$V_{out} = 2.5 - 0.1 * i \quad (4)$$

The output of the ACS12 is connected to the inverting amplifier to increase the sensitivity of the sensor by 2 and voltage level shifting for the microcontroller for the phase current that is in the range of $\pm 4A$ as shown in figure 4. The output voltages V_{o1} and input current i_{in} now follows the following relation:

$$V_{o1} = 2.5 - 0.2i_{in} \quad (5)$$

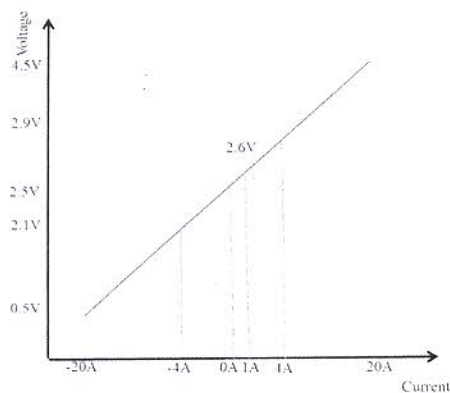


Figure 2: Input current v/s voltage characteristic of ACS712

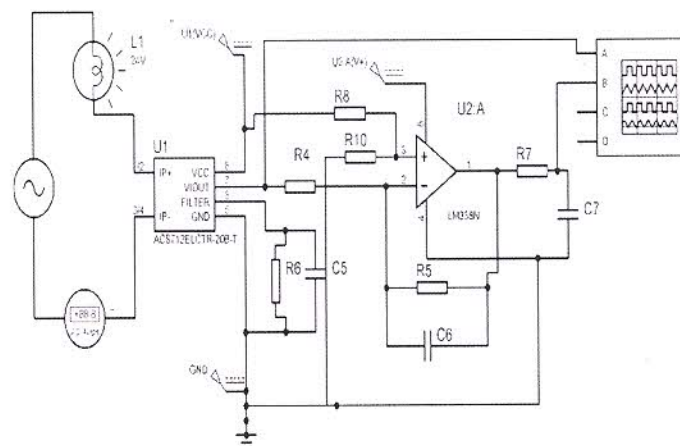


Figure 3: The input current output v/s voltage characteristic of designed circuit

The voltage output of the current sensor is connected to the ADC pin of the microcontroller. The peak-peak and RMS current is then calculated as shown in equation 5 and 6.

$$I(pk - pk) = \frac{V_{sout} * 1000}{S * 2} \text{ Ampere} \quad (6)$$

$$I(RMS) = I(pk - pk) * 1.414 \text{ Ampere} \quad (7)$$

V_{sout} is the ADC voltage of the current sensor ACS712 and S is the sensitivity that is 100 mV/A, $I_{(pk-pk)}$ and $I_{(RMS)}$ are the peak to peak current and RMS current respectively.

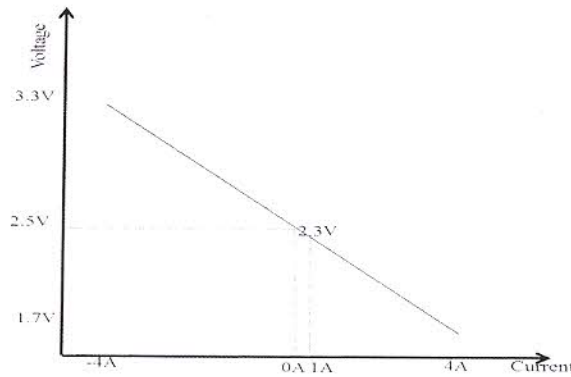


Figure 3: The input current v/s output voltage of designed current sensor circuit

SPEED MEASUREMENT

In E-vehicles, speed control of the BLDC motor is a crucial task as the performance of the system is dependent on factors like load, road conditions and inclination. Thus precise measurement of speed of the motor at various loads is essential to determine the actual speed and the desired speed on the basis of which robust speed control algorithm can be designed. The speed is varied using a throttle. Based on the applied voltage, the dsPIC controller varies the PWM duty cycle to achieve the desired speed by switching the MOSFETs. The speed of the motor is calculated using dsPIC's timer and external interrupt generated by input capture pins whenever a change in hall sensor signal occur. After 6° rotation of motor the outputs of the hall sensor change. Since the motor has 20 poles, so hall sensor table will be traversed 10 times in one mechanical rotation. The proposed method uses only one hall sensor signal output to calculate the speed of the motor without any external encoder. As a result computation speed and complexity both are reduced. To measure the actual speed of the motor, DSPIC's timer is used to count the electrical cycles. The calculation of speed is shown in the following equations. The input clock frequency is given by equation 4. The pulse width modulated signal is used to drive the BLDC Hub motor which includes three Hall sensors placed 120° apart to detect the initial rotor position.

$$f_{in} = \frac{f_c}{256} = \frac{10\text{Mhz}}{256} = 39062.5 \quad (8)$$

Where, f_{in} is the input clock frequency and f_c is the crystal frequency. Now the mechanical RPM w_m is calculated as:

