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 Haoet 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:

$$K_t * i = T_l + Bw + J\frac{dw}{dt} \quad (2)$$

Where, K_t is the torque constant, i is the phase current, τ_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:

$$B = Kt * \frac{i2 - i1}{w1 - w2} \quad (3)$$

Thus in order to determine motor characteristics, it is desired to precisely measure parameters like speed, phase current and torque to determine Kt, Tl, 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.

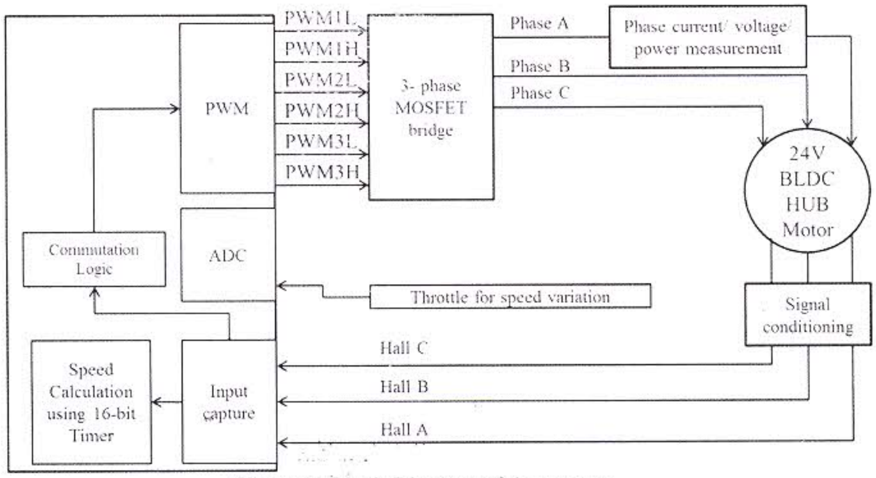

Figure 1: Block Diagram of the system

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 ±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:

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

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 ±4A as shown in figure 4. The output voltages V_{o1} and input current i_{in} now follows the following relation:

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

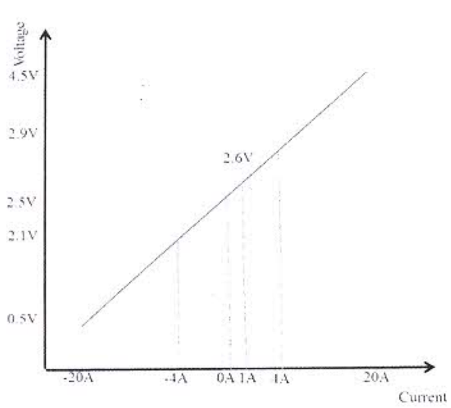

Figure 2: Input current v/s voltage characteristic of ACS712

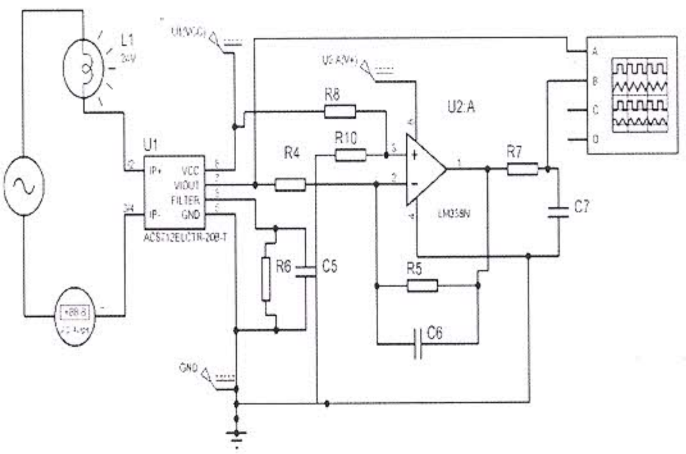

Figure 3: The input current output v/s voltage characteristic of designed circuit

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.

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

$$\boldsymbol{I(RMS) = I(pk-pk) * 1.414 \; Ampere} \tag{7}$$

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.

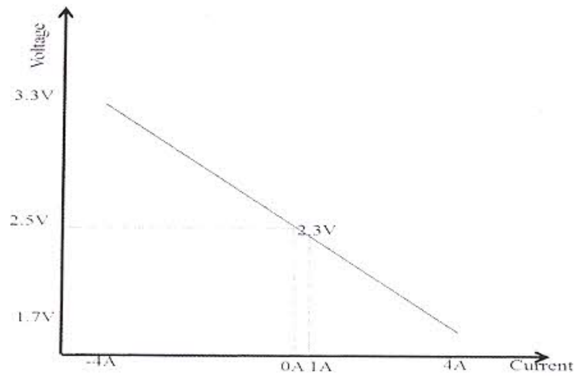

Figure 3: The input current v/s output voltage of designed current sensor circuit

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 120^0 apart to detect the initial rotor position.

$$fin = \frac{fc}{256} = \frac{10Mhz}{256} = 39062.5 \tag{8}$$

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

$$wm = \frac{60}{T} * fin \quad (9)$$

Where, T is the timer value and C is the input clock to the timer.

. TORQUE MEASUREMENT

To determine the characteristics of the 3-phase BLDC hub motor load test is performed in the lab using a Drum Brake torque testing setup. While being simple it is accurate enough to provide the torque value. The frame of the setup is made from mild steel c channel beams as shown in the figure 1. The motor can be clamped at the two bottom raised beams. The frame is heavy to have higher inertia and avoid vibrations. The frame has two holes on the upper bridge which are separated by a distance approximately equal to the diameter of the motor drum. Two lead screws are locked in position by the holes and the two internally threaded handles. The screws are attached with weight/force measurement device which can further be attached to a friction belt that is going around the surface of the motor drum. During this experiment, the motor is operated at rated voltage and maximum speed. The mechanical load is applied by Rotating the handle will lead to tightening of the belt around the motor drum which increases the friction and in turn the torque load is applied on the motor. The difference in weighing scales readings provides us with the net force applied by the motor on the belt. Multiplying the same with the radius of the motor body provides us with the torque being applied by the motor. This can be represented by the below equation:

$$T = \Delta F * r * g \ Nm \quad (10)$$

Here, ΔF is the difference between the weight scale readings and r is the radius of motor drum and g is the acceleration due to gravity.

The efficiency of the motor is calculated using the electrical input power and the mechanical output power. The input power of the 3-phase BLDC motor is the sum of power of all the three phases. The input power is usually measured directly by finding the product of input voltage and current for sinusoidal waveform. For non-sinusoidal current and voltage, the instantaneous power is calculated using the Digital oscilloscope. DSO multiplies and integrates phase current and phase voltage to get the total power as shown in Figure 5. The mechanical output power of the motor is based on the BLDC motor's speed and load and is expressed as:

$$Po = \frac{2\pi NT}{60} \ W \quad (11)$$

The efficiency η of the motor is defined as:

$$\eta = \frac{Pi}{Po} \quad (12)$$

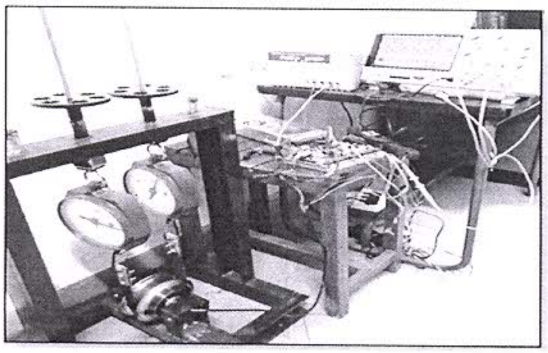

Figure 4: Experimental Setup – drum brake setup

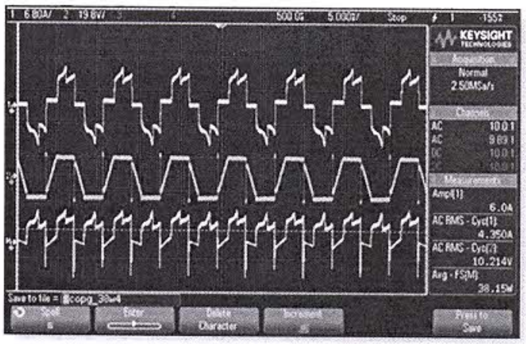

Figure 5: Phase current and Phase voltage waveform and input power calculation

RESULTS AND DISCUSSIONS

The paper present measurement module for phase current, speed and torque for BLDC Hub motor to determine motor characteristics. The relationship between phase current, power, efficiency, speed with respect to torque is shown in figure 6. Experimental investigations showed that for minimum torque 0.55 Nm, the observed efficiency is 67% at 213 RPM. For 7 Nm torque, the derived efficiency is 76% at 126 RPM as shown in figure 6. For a WYE connected BLDC hub motor, line-to-line resistance is measured using ohmmeter. Dividing it by 2 gives the phase resistanceR_a. The phase inductance L_a.The calculations in this paper are done by neglecting the power losses. The BEMF constant is calculated by measuring the line to line voltage $K_{e(l-l)}$ as per equation:

$$K_{e(Phase)} = \frac{\left(K_{e(l-l)}\right)}{1.73} \tag{13}$$

The electrical time constant τ_e is expressed as:

$$\tau_e = \frac{L_a}{\sum R_a} \tag{14}$$

The measured parameters are listed in table 1.

Table 1: Measured BLDC motor parameters

Parameter	Symbol	Value	Unit
Phase winding resistance	R_a	0.155	ohm
Phase winding inductance	L_a	0.000161	H
Maximum Torque	τ	7.6	Nm
Electric Time Constant	τ_e	0.00035	sec
Motor voltage constant	(Ke)	10.36	V-sec/rad
Maximum Motor Efficiency	η	87	%

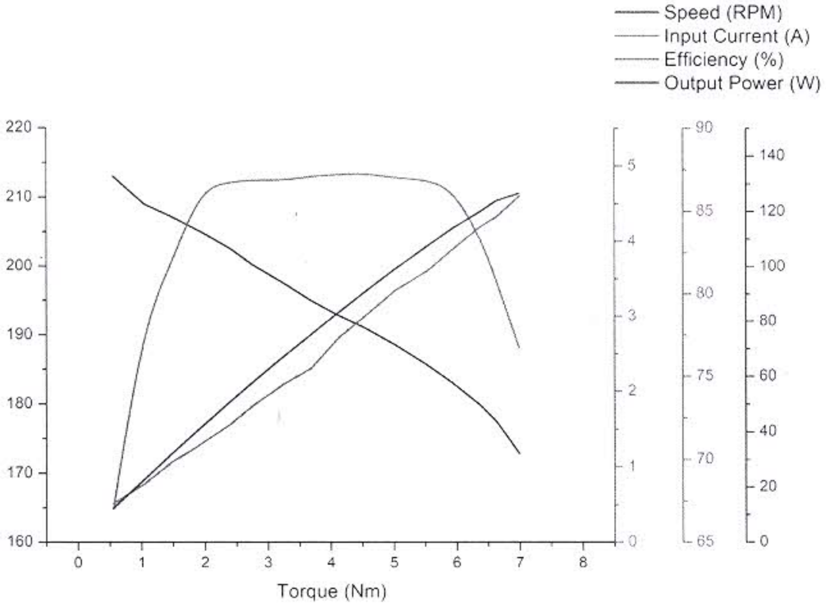

Figure 6: Characteristic graph of BLDC motor

CONCLUSION

The current, speed and torque measurement system is detailed in the present paper. The electronic circuit for current measurement is developed and tested successfully. The experimental investigations are performed using drum brake arrangement for BLDC motor to determine its characteristics such as speed vs torque, speed vs power, speed vs efficiency. The characteristic analysis of the BLDC motor with varying loads is performed taking into consideration for its application in small electric vehicles.

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