Brushless DC Motor Control Using a Digital Signal Controller

J. Rizk, A. Watson, , A. Hellany, M. Nagrial

Abstract— This paper presents the design and implementation of a DSP-based low cost Brushless DC (BLDC) motor controller that is comparable to other more cost effective motors. This objective is met by simple design and careful component selection. To provide further cost effectiveness and ease of design a high performance 16-bit digital signal controller (DSC) is used. Sensorless control using the back EMF zero crossing technique is utilized, eliminating the need for hall sensors thus further reducing cost and increasing reliability. The speed is varied using the pulse width modulation (PWM) technique. To verify the proposed method a prototype motor controller is constructed and tested.

Keywords— Brushless DC Motor, PWM, Sensorless Control

I. Introduction

The Brushless DC (BLDC) motor is used for consumer and industrial applications owing to its compact size, controllability and high efficiency. The main limitation to the wider deployment of BLDC motors is the cost of the electronic controller including position sensors. Despite the technical capabilities of power electronics matching the requirements of electronic commutation, induction motors are often preferred due to lower cost. The BLDC motor has many advantages over the induction motor, including better efficiency and power factor. The BLDC motor is also easier to control especially in its trapezoidal configuration [1]. BLDC motors can be divided into two types, sinusoidal back EMF and trapezoidal back EMF. This study utilizes a three phase BLDC motor with trapezoidal back EMF as shown in Figure 1.

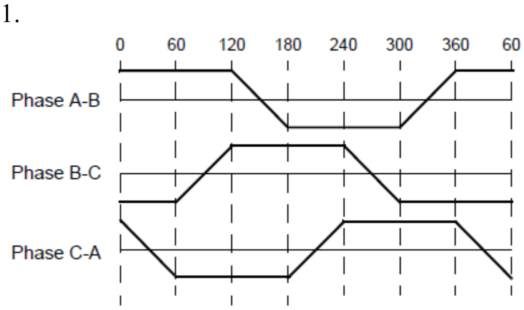

Figure. 1 Trapezoidal back EMF

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In recent decades, research and development on sensorless control strategies and their subsequent implementation have been reported [2]. A review of prior work indicates that cost minimization has emerged as the main focus of speed control applications. In light of this information a simple low cost BLDC motor controller is proposed. A review of the different subsystems that make up the motor controller is undertaken. A digital signal controller with pulse width modulation and back EMF sensorless control is used to reduce the cost and complexity of the motor control hardware.

II. Sensorless Control Technique

BLDC motors can be commutated by monitoring the back EMF signals instead of the Hall sensors. Every commutation sequence consists of one motor winding driven high, one driven low and the third winding left floating. By measuring the voltage in the floating winding, the zero crossing point (ZCP) can be found. The ZCPs occur when the back EMF is zero, during which time the phase voltage equals half of Vdc. When the ZCP is detected the commutation signal is generated by the digital signal controller. Figure 2 describes the corresponding positions of zero crossing points [3].

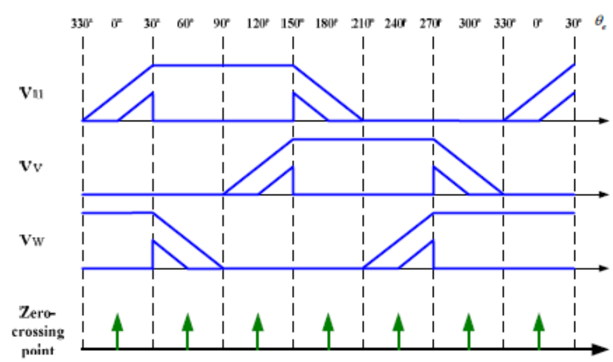

Figure 2: Phase terminal voltage and ZCP

The back EMF technique is very handy when it comes to cost and complexity. Since back EMF is proportional to speed it is impossible to identify the rotor at standstill. However, for applications where operation near zero speed is not required the motor can be started in open loop until there is sufficient back EMF to detect the zero cross point [4]. The importance of sensorless control for electronic commutation cannot be over emphasized and should be utilized if possible. Obvious reasons in favor of sensorless control are cost, reliability and ability to withstand harsh environments. It also makes the

BLDC motor more competitive with other drive technologies such as AC induction motors which do not require rotor position feedback [5].

III. PWM CONTROL TECHNIQUE

Pulse Width Modulation (PWM) serves to control the average output voltage given a fixed input voltage. This is achieved by using power switches to vary the time for which the dc input is applied to the load [6]. In the proposed PWM technique the duty cycle generated by the digital signal controller (DSC) is varied to control the average applied voltage across the windings and hence the speed of the motor. A speed control loop is used to control the PWM duty cycle delivered to the motor. The speed of the motor is specified by a potentiometer which is connected to one of the analog-to-digital channels of the DSC. The range of voltage reference varies from 0 to 5V. Turning the potentiometer clockwise increases this reference and hence the motor speed. PWM makes control of the motor speed very easy to implement. The main advantage of PWM control over resistive power control is that variable power can be supplied to the motor by varying the duty cycle with minimal power loss [7]. The following expressions are used to calculate duty cycle and average voltage applied across the winding.

$$\%Dutycycle = \frac{t_{on}}{T} \times 100 \quad ,$$

$$V(avg) = Dutycycle \times Vdc$$

Where t_{on} is turn on time, T is the period of PWM signal, Vdc is the dc input voltage applied to the inverter bridge and V (avg) is the average dc voltage applied across the winding.

IV. CONTROLLER DESIGN

Figure 3 shows the block diagram of the proposed BLDC motor control system. The following sections give a brief description of each subsystem.

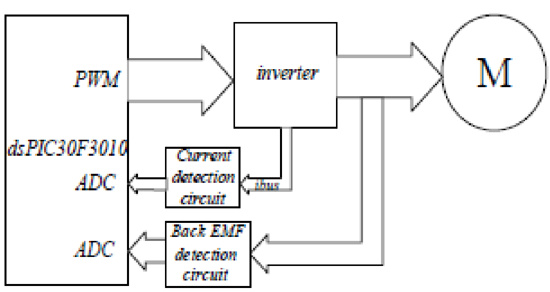

Figure 3: Block diagram of motor control system

A. *16-bit Digital Signal Controller*

The central processing unit is implemented by a digital signal processor. A digital signal processor (DSP) provides high speed, high resolution and sensorless control algorithms at lower system costs [8]. The proposed controller utilizes the 28 pin 16-bit dsPIC30F3010 digital signal controller (DSC). The dsPIC DSC is a single chip solution with microcontroller peripherals such as power control pulse width modulation and high speed analog to digital converters (ADC). The specialised hardware peripherals provide efficient motor control with limited support circuitry, reducing the complexity of the motor control hardware. Moreover, breakthroughs in semiconductor cost have allowed the DSC to become comparable in cost with the low cost 8 bit microcontroller whilst still providing higher speed and precision.

B. *Three-Phase Inverter and Gate Driver*

The driving circuit is implemented to drive six power MOSFETs controlling the BLDC motor. A standard three phase inverter is used and shown in figure 4.

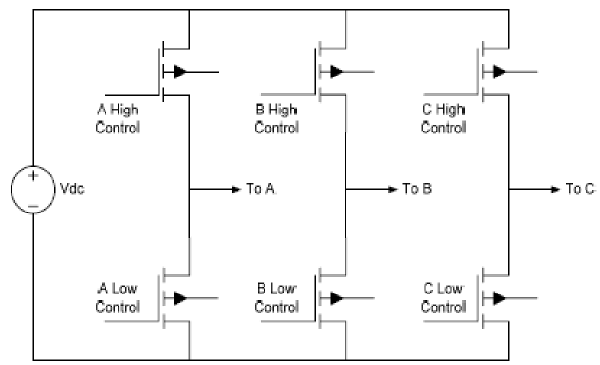

Figure 4: Standard three phase inverter

The switches chosen were power MOSFETs rated for 60 volts and 16 amps. N-channel power MOSFETs were used to reduce the number of different parts in the design. To drive the MOSFETs, a high speed MOSFET driver IC is used. The MOSFET driver chosen for the design is the IR2101 package from International Rectifier. The single 8-pin package has both a high and low side gate driver. As such, one IR2101 is capable of driving one MOSFET pair. Since the motor controller is intended for a three phase motor there are three identical gate driver circuits. The recommended connections given by the IC's data sheet are used to interface the inverter to the driver. Each gate driver circuit contains a bootstrap circuit that consists of a diode, capacitor and gate resistors. The bootstrap circuit is used to generate a voltage between Vb and Vs (refer to figure 5). This circuit has the advantage of being simple and cost effective.

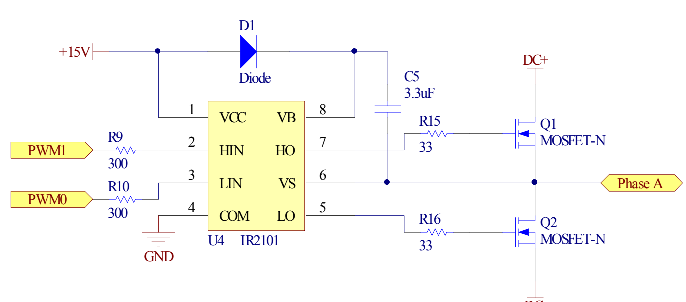

Figure 5: Gate driver circuit

As mentioned above, only two phases are actively driven at one time with the active phases always connected to opposite rails of the DC supply. Through symmetry this means the star point is always ½ Vdc, regardless of the polarity of the voltage across the two active phase windings. The zero crossing point is therefore detected when the phase back EMFs cross ½ Vdc [9]. The back EMF is only detected in the floating phase. Since the speed estimation algorithm is estimated in the DSC, an analog to digital converter is needed to convert the analog non-excited phase back EMF signals to digital signals. Each phase detection circuit is connected to the ADC unit allowing the DSC to obtain the terminal voltage of the phase. The three phase terminal voltages and Vdc are fed into the ADC via voltage dividers with only one of the phase terminal voltages detected each commutation. The voltage divider circuit is used to reduce the phase voltages to a level that the ADC can measure efficiently. The scaling for each winding and Vdc is done by resistor pairs and is shown in Figure 6 and Figure 7 respectively.

In this application based on a motor voltage of 24V the resistor pairs used give a full scale value of approximately 2.4V and so, the zero crossing voltage is approximately 1.2V. The zero crossing point can therefore be easily obtained through the comparison of Vdc and ½Vdc. Since the true commutation point is 30 electrical degrees behind the zero crossing point, timer 2 and 3 of the DSC are employed to implement the 30 degree offset required for correct commutation [10].

C. *Back EMF Detection Circuit*

Apart from the voltage divider circuits the implementation is single chip eliminating the need for comparators and reducing the cost to that of the required resistors.

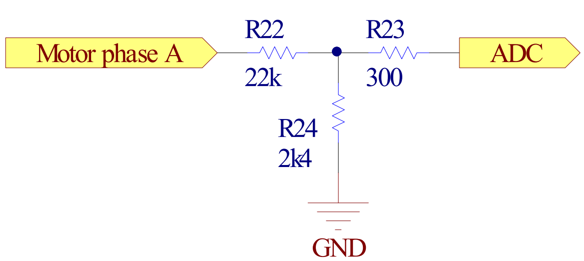

Figure 6: Voltage divider circuit for single phase

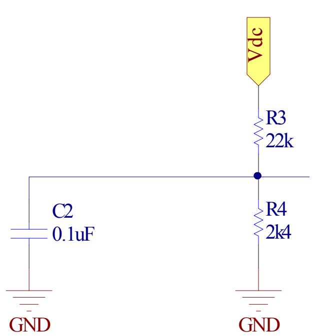

Figure 7: Voltage divider circuit for Vdc

D. Current Detection Circuit

As well as back EMF detection the drive system is dependant on current detection for control. Usually at least two-phase currents are required for control of a three-phase machine. However, in this study the phase currents are sensed from the dc link current and hence one sensor is sufficient for current control of the machine. The implemented technique allows the currents to be sensed inexpensively with a precision resistor by measuring the voltage drop across it [2]. This solution is used widely in low-cost motor drives and is described below.
A low cost shunt resistor is used to sense the current. The shunt is inserted between the negative DC bus of the inverter bridge and the ground of the board. The 0.1 ohm shunt resistor gives a voltage corresponding to the current flowing into the motor winding. The voltage is amplified using an op amp circuit with a gain of eleven, and fed into an ADC channel on the DSC. The amplified voltage is also compared to a voltage reference using a comparator. The voltage reference is set using a potentiometer. The range of voltage reference varies from 0V to 3.3V. Turning the potentiometer clockwise increases the reference and counter clockwise reduces the reference. Its value is set so that the current protection activates when the maximum current permitted by the board is reached [11]. If the maximum current set by the potentiometer is exceeded, the Fault A pin goes low indicating an over current fault. Figure 8 shows the implemented current detection circuit.

A MCP6002 operational amplifier and MCP6544 comparator were chosen for the current detection circuit. Both were supplied from the +5V rail, ensuring the digital signal controller's ADC doesn't see more than 5V on its inputs. The gain of the op amp circuit is determined by the following formula:

$$Gain = 1 + \frac{R_1}{R_2} = 1 + \frac{10k}{1k} = 11,$$

E. Power Supply

A power supply circuit is needed to provide logic level components as well as other components that were unable to operate from the 24V main power supply. A 15V power supply is generated for the gate drivers using a +15V linear regulator. This 15V regulator is passed through a +5V regulator to drive a 5V supply to the DSC and surrounding control circuit.

V. CONTROL SCHEME IMPLEMENTATION

r used for experimental testing is a 24V three phase wye connected motor with trapezoidal back EMF. The designed controller circuit works as follows. The PWM signals drive three gate drivers, which in turn, drive the three phase bridge inverter circuit connected to the three motor windings. Two motor windings are energized at any one time in exact synchronism with the rotor motion whilst the third winding is left open. In this study the BLDC motor is run without sensors so the back EMF on the unexcited winding is monitored to sense the rotor magnet position. Each phase detection circuit is connected to an ADC channel. Using the

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ADC of the digital signal controller, the back EMF zero crossing point is determined. Based on zero crossing of back EMF signals, motor commutation is decided in the firmware. The driven phases are then commutated at periodic intervals to run the motor. Figures 9-11 show the implementation of the controller parts.

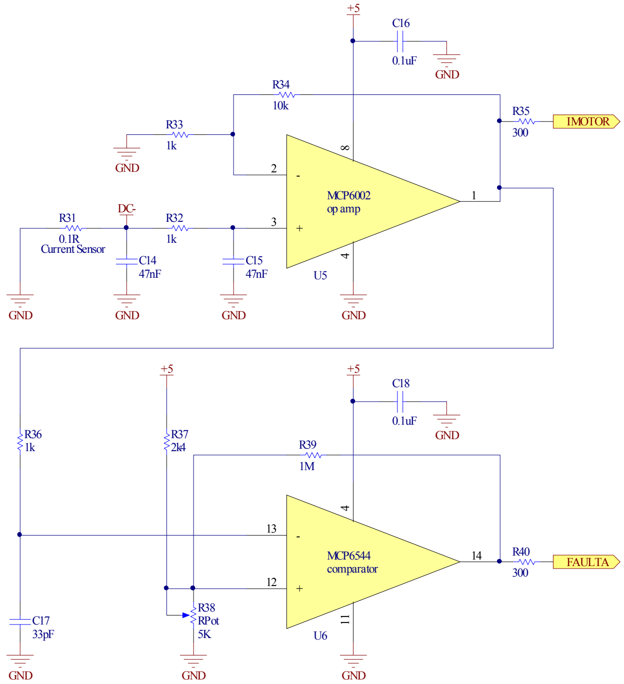

Figure 8: Current Detection Circuit

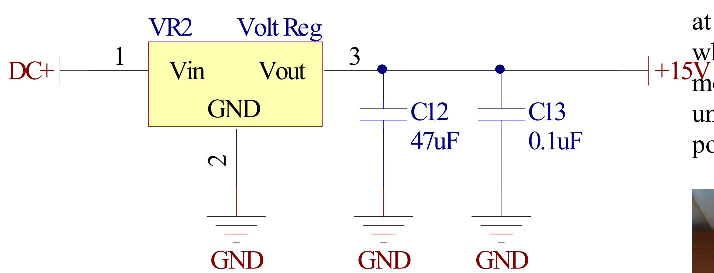

Figure 9: +15 linear regulator circuit

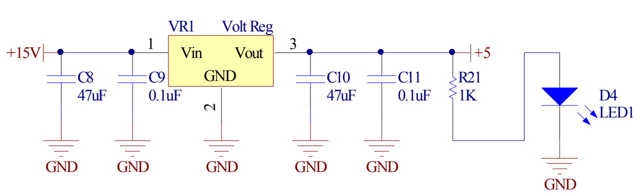

Figure 10: +5V linear regulator circuit

Reliable firmware was critical to reliable motor operation. The DSC was programmed so that only two output MOSFETs are switched on based on sensorless feedback. MPLAB IDE version 8.36 was used for the development environment; the Microchip C30 optimizing compiler used for compilation and the PIC kit 3 used for programming. The program was written in the C programming language.

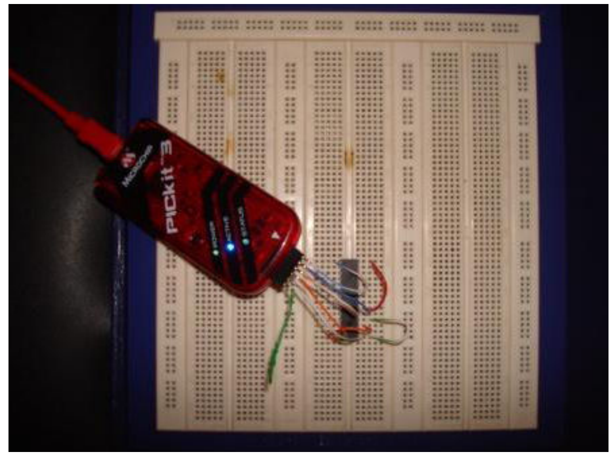

Figure 11: Programming of DSC using PIC kit 3

VI. EXPERIMENTAL RESULTS

A prototype was constructed in order to implement the proposed technique.

6.1 The hardware

Figure 12 shows the motor controller circuit setup on two breadboards. The controller circuit was tested and works as follows. The PWM signals drive three gate drivers, which in turn, drive the three-phase bridge inverter circuit connected to the three motor windings. Two motor windings are energized at any one time in exact synchronism with the rotor motion whilst the third winding is left open. In this study the BLDC motor is run without sensors so the back EMF on the unexcited winding is monitored to sense the rotor magnet position.

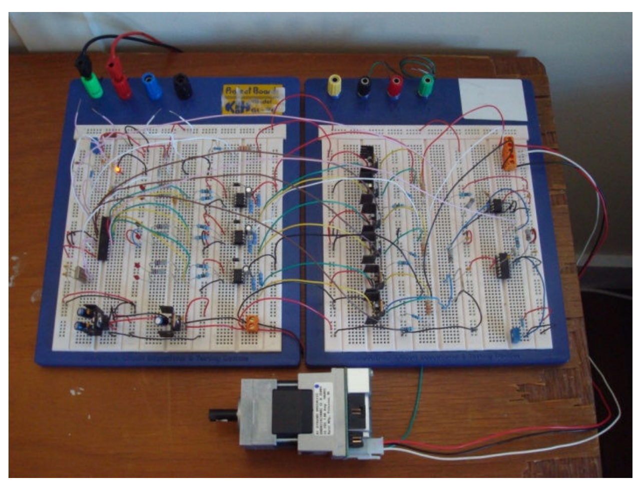

Figure 12: Experimental setup

Each phase detection circuit is connected to an ADC channel. Using the ADC of the digital signal controller, the back EMF zero crossing point is determined. Based on zero crossing of back EMF signals, motor commutation is decided in the

firmware. The driven phases are then commutated at periodic intervals to run the motor.
Initially MOSFET failure occurred due to the high temperature of the devices. Heat sink was then attached to the power MOSFETs and linear voltage regulators to resolve the problem

6.2 Discussion

A sensorless BLDC motor is used in the laboratory experiment. The PWM carrier frequency is set at 20 kHz. The experimental results confirm the validity of the system. First the performance of the three-phase inverter module is shown. In figure 13, the phase voltages have been measured at the three motor winding terminals between the half bridge and ground of the inverter. It can be seen that the Phase A waveform is synchronized with the PWM signal half of the time. This satisfies six step commutation as there are six PWM signals, and there are six combinations of stator excitation each lasting 60 electrical degrees. This means each winding is energized twice per electrical revolution by two different PWM signals. The implemented full bridge inverter satisfies the design specifications as only two windings are energized at any one time.

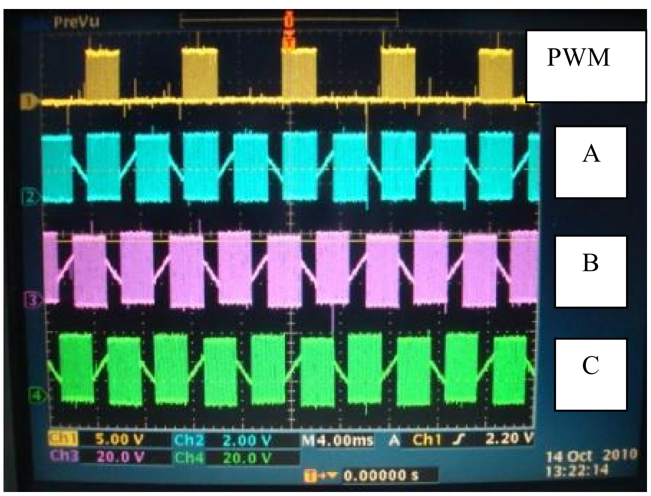

Figure 13: Phase waveforms at motor winding terminals

Next the performance of the back EMF detection circuit is shown. In figure 14, the three back EMF waveforms are measured at the ADC unit of the digital signal controller. Using resistor pairs as voltage dividers, the phase voltages have been successfully scaled down to a level that the digital signal controller can measure.

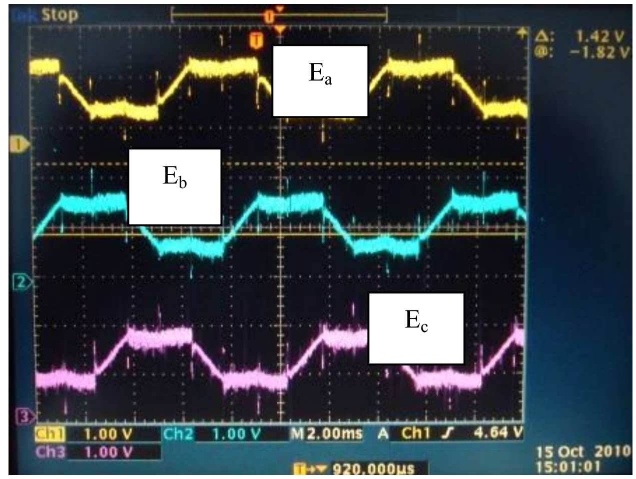

Figure 14: Scaled back EMF waveforms at digital signal controller

Figure 15 contrasts the motor winding waveform and scaled back EMF waveform of Phase A. The measurements show that at 50% duty cycle, the average voltage across the motor winding (channel 1) is 12.5-volts and the average voltage of the scaled back EMF (channel 2) is approximately 1.2-volts. This is also the zero crossing point as specified in section 4.5. Obtaining the zero crossing point is the main objective of the implemented sensorless control method.

Figure 16 magnifies Phase A to highlight the zero crossing point. The waveforms verify that good performance can be achieved by the implemented back EMF detection method.

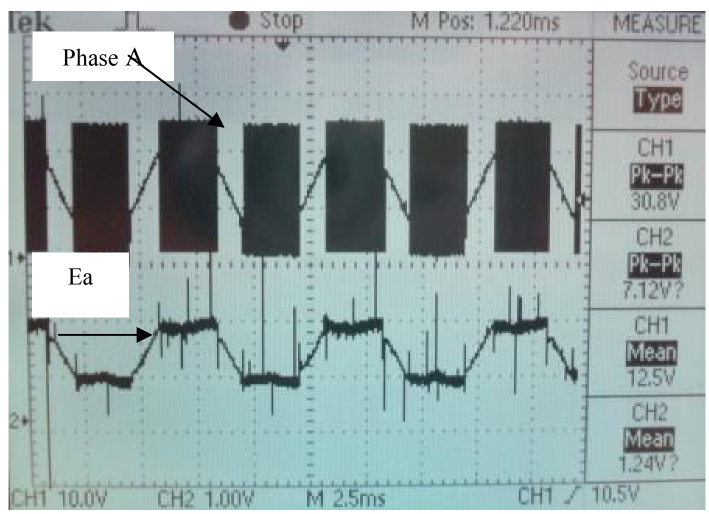

Figure 15: Motor winding and scaled back EMF waveforms for Phase A

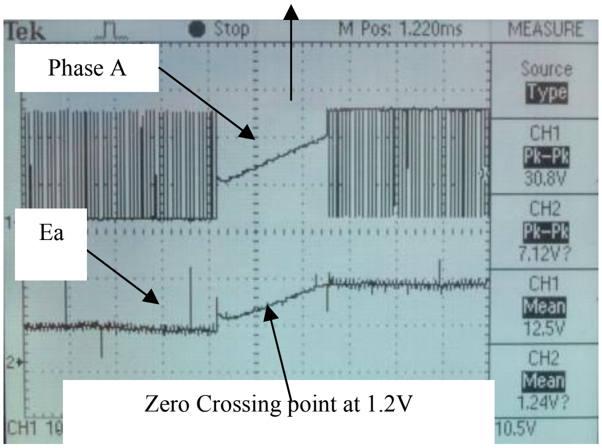

Figure 16: Magnifying of a zero crossing point for Phase A

6.3 Performance

Experimental results show good motor performance over a wide speed range. Variable speeds were achieved through varying the duty cycle of the PWM signal at no load. Figure 17 compares the speed to the duty cycle, which varies from 30% to 100%. Below 30%, the speed could not be measured as the motor stalled. This is due to insufficient back EMF for detection at low speeds. It was determined from experimentation that the motor develops sufficient amplitude at about 900rpm. Since the amplitude of back EMF is proportional to speed, it is also impossible to detect the back EMF zero crossing point when the motor is at standstill. Therefore, a suitable starting procedure must be employed in the firmware.

The startup procedure is implemented as follows. Two motor phases are energized to lock the rotor in a predefined position, before a commutation signal is applied advancing the rotor. The frequency of the commutation signals is gradually increased speeding up the rotor by the increasing currents. Once the rotor speed reaches 900 rpm the voltages of the three phases are detectable and the system starts to detect the zero crossing point. After detecting the zero crossing point, the operation of the motor is changed to self-controlled mode (Zezhong et al. 2008). The BLDC motor has a linear speed curve between 900 rpm and 3100 rpm making it suitable for motion control applications where operation near zero speed is not required. These results support the literature review which states that sensorless control is difficult at low speeds.

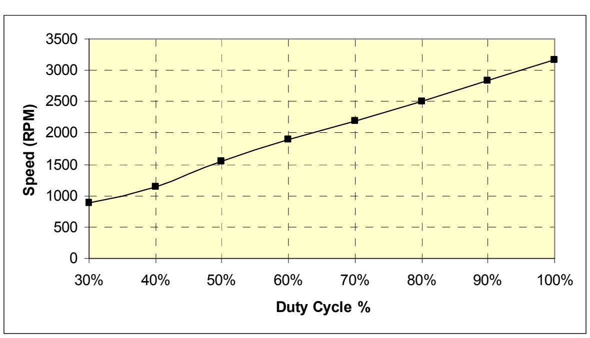

Figure 17: The speed verses duty cycle

VII. Conclusion

The 28-pin dsPIC30F3010 is an ideal low-cost solution to control a sensorless BLDC motor. Its specialised hardware peripherals provide efficient motor control with limited support circuitry, reducing the cost and complexity of the motor control hardware. The implemented sensorless control technique is ideal for use in appliance, automotive and industrial applications where operation near zero speed is not required. Currently more than 65% of electrical energy in developed countries is consumed by electric motors. Most of this energy is consumed by three phase induction motors rated at below 10kW. Considering below 10kW BLDC motors out perform induction motors in areas of efficiency and power factor, breakthroughs in semiconductor cost will push this exciting technology to the forefront. The growing global trend toward energy conservation makes it quite possible that the era of PM brushless motor drive is just around the corner.

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