A Novel Direct Back EMF Detection for Sensorless Brushless DC (BLDC) Motor Drives

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Abstract-A novel back EMF detection method for Sensorless BLDC motor drives without the motor neutral point voltage information is presented in this paper. The true phase back EMF signal can be directly obtained from the motor terminal voltage by properly choosing the PWM and sensing strategy. As a result, the method proposed is not sensitive to switching noise, no filtering is required, and good motor performance is achieved over a wide speed range. The detailed circuit model is analyzed and experimental results verify the analysis and demonstrate advantages of the new technique.

I. INTRODUCTION

Brushless DC (BLDC) motors are becoming widely used as small horsepower control motors due to their high efficiency, silent operation, compact form, reliability, and low maintenance. When using three-phase six-step commutation, current flows in only two phases at any time, leaving the third motor terminal floating. The zero crossing of back EMF of the floating phase can be detected to determine the commutation sequence without Hall sensors. The conventional and most-commonly used method is to build a virtual neutral point that will, in theory, be at the same potential as the center of a Y wound motor and then to sense the difference between the virtual neutral and the voltage at the floating terminal [1][2]. However, when using a chopping drive, the PWM signal is superimposed on the neutral voltage, inducing a large amount of electrical noise. This method tends to have a narrow speed range and a poor signal to noise ratio since in many applications the voltage must be attenuated to reduce the sensed voltage into the allowable common mode range of the sensing circuit. This paper presents a novel back EMF sensing method which does not require neutral voltage information. The true back EMF can be detected directly from terminal voltage by properly choosing the PWM and sensing strategy. The PWM signals are only applied to high side switches and the back EMF is detected during PWM off time. Since no scaling or filtering of the signals is required, good signal/noise ratio and response are achieved. This sensorless BLDC driver can provide a much wider speed range than the conventional approach.

II. BRUSHLESS DC (BLDC) MOTORS AND CONTROL

Generally, brushless DC (BLDC) motors are driven by a three-phase inverter with what is called six-step commutation. The commutation phase sequence is like AB-AC-BC-BA-CA-CB. Each conducting phase is called one step. The conducting interval for each phase is 120 electrical degrees. Therefore, only two phases conduct current at any time, leaving the third phase floating. In order to produce maximum torque, the inverter should be commutated every 60^o so that current is in phase with the back EMF. The commutation timing is determined by the rotor position, which can be determined every 60^o by detecting zero crossing of back EMF on the floating coil of the motor. Figure 1 shows the typical inverter configuration and current commutation sequence.

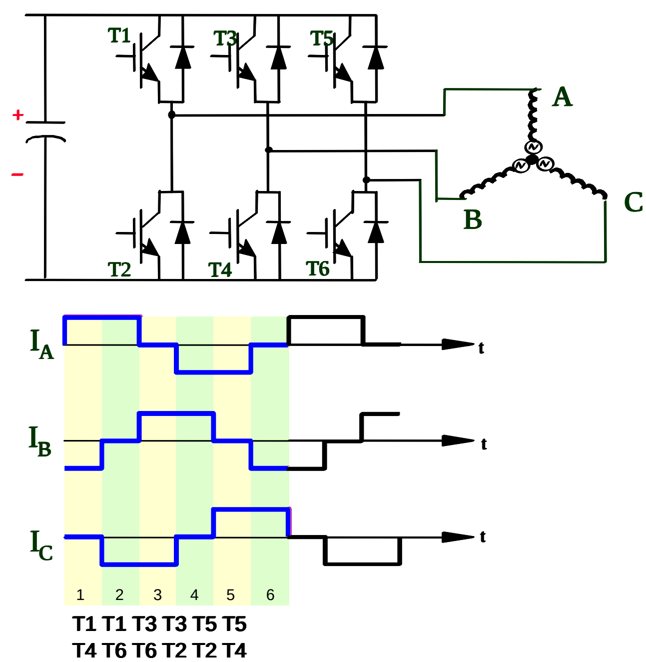

Fig.1. Inverter configuration and current commutation sequence for BLDC motor

0-7803-7404-5/02/$17.00 (c) 2002 IEEE

III. Proposed Direct Back EMF Sensing

The phase back EMF voltage is referred to neutral point of the motor. Since the center point of the motor is typically not available, the commonly used method reconstructs the neutral voltage information. Figure 2 shows the detection circuit based on motor virtual neutral voltage. Voltage dividers and low pass filters are necessary to process the signals. The low pass filter will introduce a phase delay for the zero crossing of the phase back EMF. The first problem with this scheme is low signal/noise ratio at low speed, since the back EMF amplitude is directly proportional to the motor speed. The second problem is that the low pass filter at high speed introduces too much phase delay. Consequently, the conventional back EMF sensing method is only good for narrow speed range.

If the proper PWM strategy is selected, the back EMF voltage referred to ground can be extracted directly from the motor terminal voltage.

For BLDC drive, only two out of three phases are excited at any instant of time, leaving the third phase floating. The PWM drive signal can be arranged in three ways:

- On the high side: the PWM is applied only on the high side switch, the low side is on during the complete step.
- On the low side: the PWM is applied on the low side switch, the high side is on during the complete step.
- On both sides: the high side and low side are switched on/off together.

In this paper, PWM on the high side is selected. Figure 3 shows a circuit model to conduct the analysis.

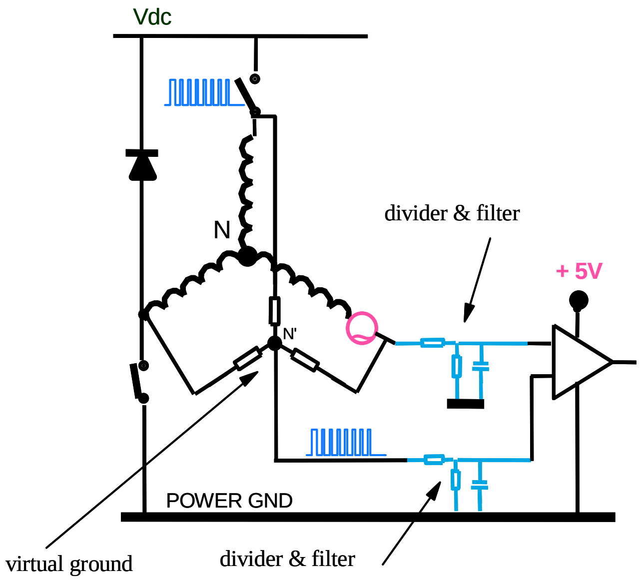

Fig.2. Back EMF sensing based on virtual neutral point

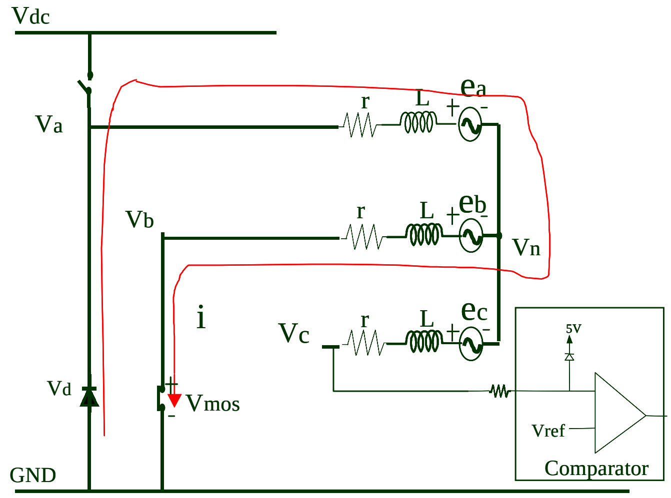

Fig.3. Proposed Back EMF detection during the PWM off time moment

Assuming at a particular step, phase A and B are conducting current, and phase C is floating. The upper switch of phase A is controlled by the PWM and lower switch of phase B is on during the whole step. The terminal voltage Vc is measured.

When the upper switch of phase A is turned on, the current is flowing through the switch to winding A and B. When the upper transistor of the half bridge is turned off, the current freewheels through the diode paralleled with the bottom switch of phase A. During this freewheeling period, the terminal voltage Vc is detected as Phase C back EMF when there is no current in phase C.

From the circuit, it is easy to see $v_c = e_c + v_n$, where Vc is the terminal voltage of the floating phase C, e_c is the phase back EMF and Vn is the neutral voltage of the motor.

From phase A, if the forward voltage drop of the diode is ignored, we have

$$v_n = 0 - ri - L\frac{di}{dt} - e_a \qquad (1).$$

From phase B, if the voltage drop on the switch (MOSFET) is ignored, we have

$$v_n = ri + L\frac{di}{dt} - e_b \qquad (2).$$

Adding (1) and (2), we get

$$v_n = -\frac{e_a + e_b}{2} \qquad (3).$$

Assuming it is a balance three-phase system, we know

$$e_a + e_b + e_c = 0 \qquad (4).$$

From (3) and (4),

$$v_n = \frac{e_c}{2} \qquad (5)$$

So, the terminal voltage Vc,

$$v_c = e_c + v_n = \frac{3}{2} e_c \qquad (6).$$

From the above equations, it can be seen that during the off time of the PWM, which is the current freewheeling period, the terminal voltage of the floating phase is proportional to the back EMF voltage without any superimposed switching noise. It is also important to note that this terminal voltage is directly referred to the Ground instead of the floating neutral point. So, the neutral point voltage information is not needed to detect the back EMF zero crossing. Since the true back EMF is extracted from the motor terminal voltage, the zero crossing of the phase back EMF can be detected very precisely. Several advantages of the proposed back EMF sensing technique are 1) precise BEMF zero crossing detection without low pass filtering and voltage dividing; 2) this sensing technique can be used to either high voltage or low voltage systems without effort to scale the voltage; 3) fast motor start-up is possible because of precise BEMF zero crossing detection; 4) simple and low cost to implement.

IV. SYSTEM IMPLEMENTATION

The proposed back EMF sensing technique has been implemented in a hardware macro cell in the microcontroller ST72141 [6], which is dedicated to the sensorless BLDC driver. The system block diagram of the sensorless BLDC driver is drawn in Figure 4. The motor terminal voltage is directly fed into the microcontroller through current limit resistors.

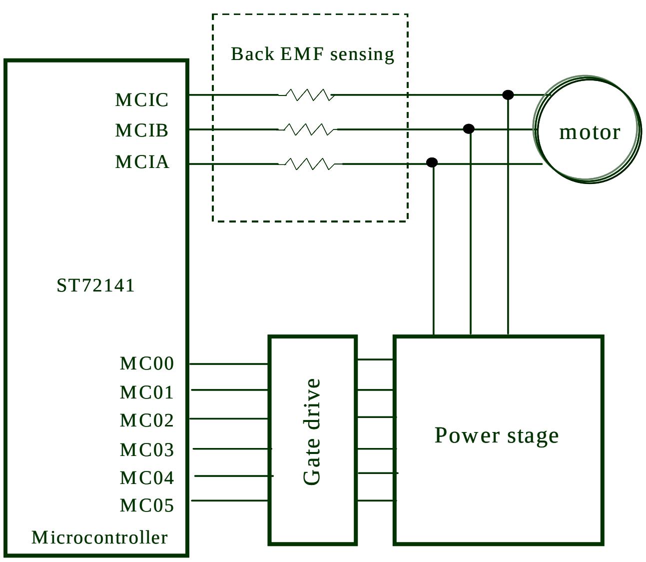

Fig.4. Proposed microcontroller-based BLDC driver

A hardware back EMF zero crossing detection circuitry is embedded in the macro cell. Figure 5 shows the hardware implementation for the back EMF zero crossing detection.

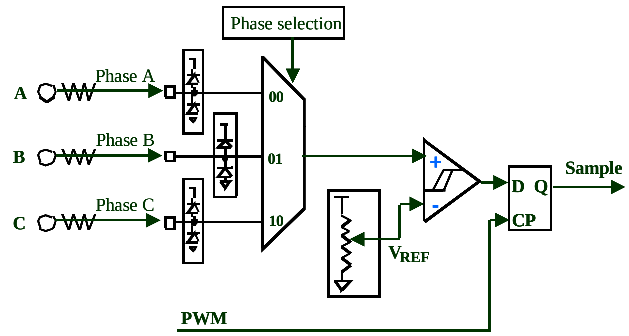

Fig.5. Back EMF zero crossing detection

The back EMF signals go through a multiplexer, and the controller selects the input to be sensed according to the motor commutation stages. Since only the zero crossing is of interest, the peak voltage is internally clamped at 5v thereby keeping the voltage within the common mode range of the sense amplifier. The selected signal is compared to a fixed voltage reference, which is close to zero. During the off time, the back EMF is compared with reference voltage. The rising edge of the PWM, at the beginning of the PWM on time, will latch the comparator output to capture the zero crossing information.

The commutation algorithm used is the standard BLDC control algorithm. The commutation will happen 30 electrical degrees after the back EMF zero crossing. Thanks to the programmability of the microcontroller, the system has much flexibility, running the motor in speed open loop or speed close loop depending on applications. Also it is very convenient to adjust the control parameters. For example, the time between the zero crossing and commutation can be easily adjusted by software. Usually, the delay from phase back EMF zero crossing to commutation is 30^{O} to keep the phase current in phase with phase back EMF. For some high-speed applications, commutation can be done in advance to compensate for the delay caused by the motor winding inductance.

V. EXPERIMENTAL RESULTS

The proposed sensorless BLDC drive has been successfully applied to some home appliance 300v/20,00rpm applications and automotive 6v-48v applications.

The following waveforms show some key operating waveforms of a low voltage system. Figure 6 shows the terminal voltage and back EMF waveforms. The phase back EMF of the floating winding is extracted from the winding terminal voltage during the PWM off time. Figure 7 shows the three phase terminal voltages and the back EMFs, and the zero crossing signal. Each toggling edge of zero-crossing signal corresponds to the zero crossing of the back EMF. Figure 8 shows phase back EMF and the phase current. The sequence from back EMF zero crossing to commutation is clearly demonstrated.

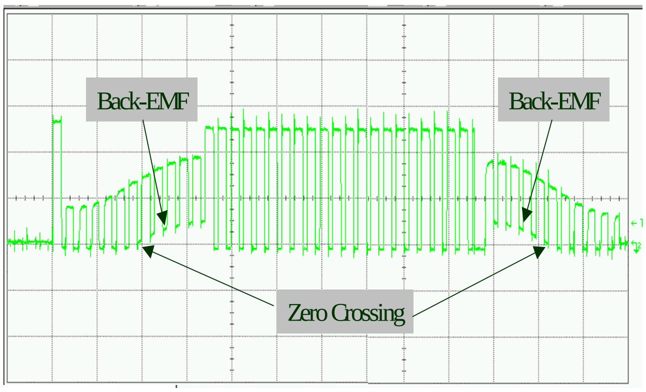

Fig.6. Phase terminal voltage and back-EMF waveform

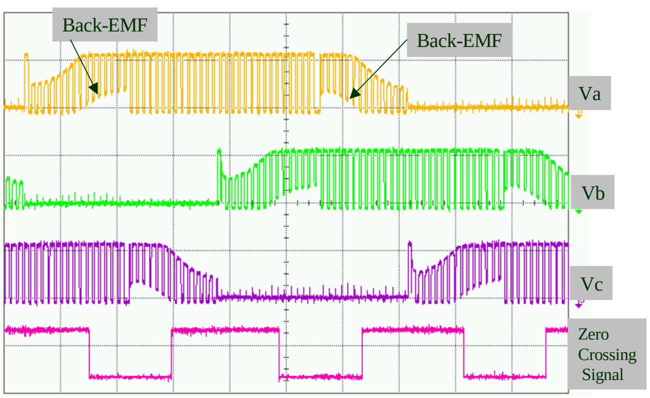

Fig.7. Three phase back EMFs and the zero-crossings of back EMFs

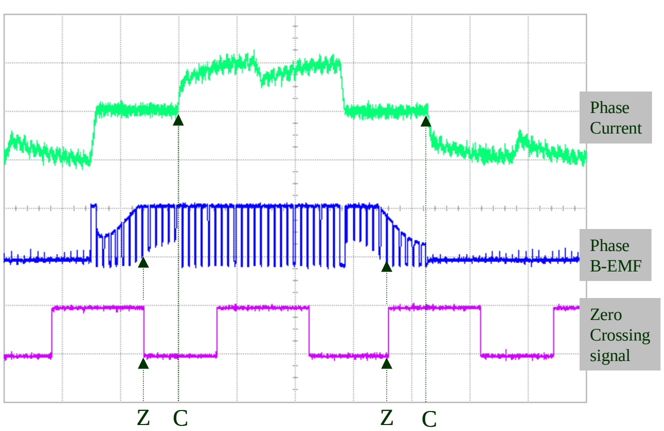

Fig.8. Sequence of zero crossing of back EMF and phase commutation

As described before, this zero crossing detection has very good resolution. Thus it can be used in applications where the motor speed is low, when the amplitude of back EMF is low. Figure 9 shows the waveforms of back EMF and zero crossing signals at low motor speed. The system can function very well even when the peak of back EMF is less than 1V. From the picture, the zero crossing is not evenly distributed. The threshold voltage for zero crossing is 0.2v, and if the amplitude of the back EMF is low, the comparison output has this offset effect. The software will do the compensation for the commutation. If the speed needs to go very low, an OP AMP can be used to amplify the signal and compensate for the detection offset. In this way, the motor speed can be extended to very wide range.

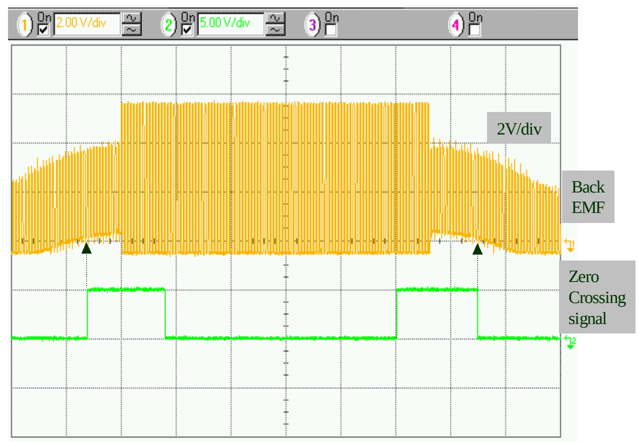

Fig.9. Back EMF and zero crossing of low speed

Due to the high precision back EMF detection by the ST72141, quick starting of the BLDC motor can be accomplished. Starting the motor is very critical for the sensorless drive system. When the motor is not running, there is no back EMF. Usually, the motor is driven by open loop commutation for the start-up. The forced commutation time should be carefully tuned according to motor and load characteristics. When the motor generates enough back EMF, the controller automatically switches to synchronized commutation mode. Using this new back EMF sensing system system, , it is possible to switch to close loop synchronous operation when the peak back EMF is as little as 0.5V. Figure 10 shows that the start-up procedure can be finished within 200ms.

VI. CONCLUSIONS

A novel back EMF sensing technique for BLDC driver is presented in this paper. The true back EMF can be detected during off time of PWM because the terminal voltage of the motor is directly proportional to the phase back EMF during this interval. Also, the back EMF information is referred to ground without any common mode noise. Therefore, this back EMF sensing method is immune to switching noise, and suitable for high voltage or low voltage, and high speed or low speed applications. This unique back EMF sensing method has superior performance to others which rely on neutral voltage information, providing much wider motor speed range with low cost. Thanks to the precise detection of back EMF, a quick motor starting is also possible. The applications of this sensorless BLDC can include hard disk drive, fans, pumps, blowers, scanners, home appliances, etc.

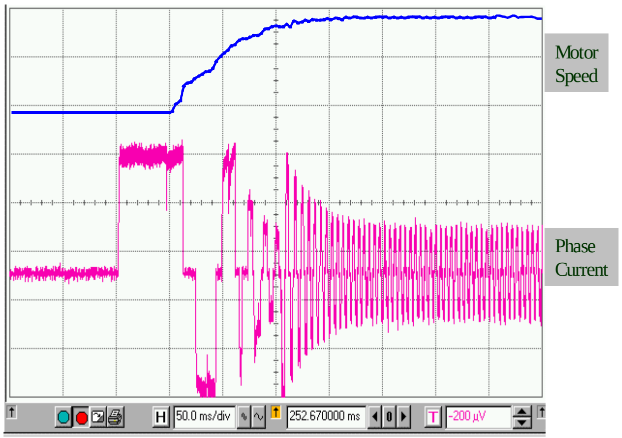

Fig.10. Motor speed and current at starting

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