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Optimized Design Of The Bldc Motor For Higher Efficiency

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Abstract: The applications of brushless DC (BLDC) motors and drives have grown significantly in recent years in the appliance industry and the automotive industry. Sensorless BLDC drive is very preferable for compact, low cost, low maintenance, and high reliability system. The conventional sensorless method based on neutral motor point has limited its application since it has relative speed range, suffering from high common mode voltage noise and high frequency switching noise. In this paper a novel back EMF sensing technique, direct back EMF sensing, without motor neutral voltage for BLDC drives is proposed, analyzed, and extended, overcoming the drawbacks of the conventional scheme.

Keywords: sensorless system, transition, floating winding, overall period, current freewheels.

I. INTRODUCTION

For three-phase BLDC motor, typically, it is driven with six-step 120 degree conducting mode. At one time instant, only two out of three phases are conducting current. For example, when phase A and phase B conduct current, phase C is floating. This conducting interval lasts 60 electrical degrees, which is called one step.

A transition from one step to another different step is called commutation. So totally, there are 6 steps in one cycle. Usually, the current is commutated in such way that the current is in phase with the phase back EMF to get the optimal control and maximum torque/ampere. The commutation time is determined by the rotor position. Since the shape of back EMF indicates the rotor position, it is possible to determine the commutation timing if the back EMF is known. In Fig.1, the phase current is in phase with the phase back EMF. If the zero crossing of the phase back EMF can be measured, we will know when to commutate the current.

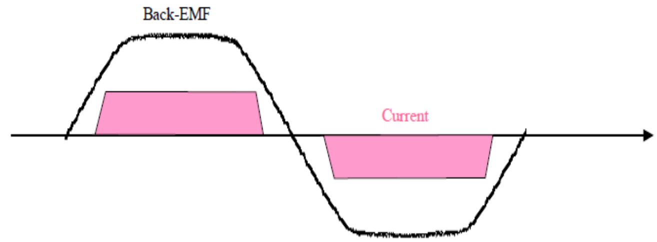

Fig.1 The phase current is in phase with the back EMF in brushless dc motor.

As mentioned before, at one time instant, since only two phases are conducting current, the third winding is open. This opens a window to detect the back EMF in the floating winding. The terminal voltage of the floating winding is measured. This scheme needs the motor neutral point voltage to get the zero crossing of the back EMF, since the back EMF voltage is referred to the motor neutral point.

II. ZERO CROSSING BACK EMF DETECTION

The terminal voltage is compared to the neutral point, then the zero crossing of the back EMF can be obtained. In most cases, the motor neutral point is not available. In practice, the 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. The virtual neutral point is built by resistors, which is shown in Fig 2 (B).

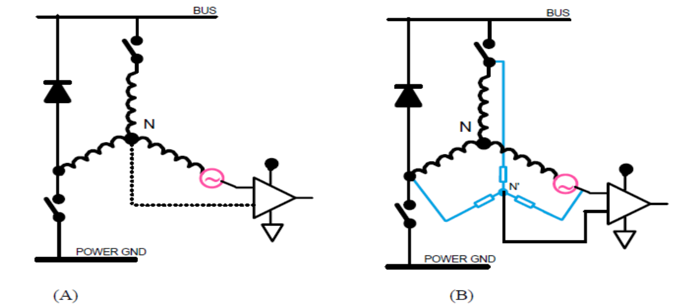

Fig.2 (A) Back EMF zero crossing detection scheme with the motor neutral point available; (B) back EMF zero crossing detection scheme with the virtual neutral point.

This scheme is quite simple. It has been used for a long time since the invention. However, this scheme has its drawbacks. Because of the PWM drive, the neutral point is not a standstill point. The potential of this point is jumping up and down. It generates very high common mode voltage and high frequency noise. So we need voltage dividers and low pass filters to reduce the common mode voltage and smooth the high frequency noise, shown in Fig.3 For instance, if the dc bus voltage is 300 V, the potential of the neutral point can vary from zero to 300 V.

The allowable common mode voltage for a comparator is typically a few volts, i.e. 5 V. We will know how much attenuation should be required. Obviously, the voltage divider will reduce the signal sensitivity at low speed, especially at start-up where it is needed most. On the other hand, the required low pass filter will induce a fixed delay independent of rotor speed. As the rotor speed increases, the percentage contribution of the delay to the overall period increases. This delay will disturb current alignment with the back EMF and will cause severe problems for commutation at high speed. Consequently, this method tends to have a narrow speed range.

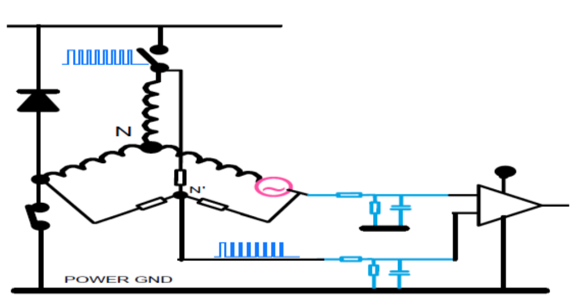

Fig.3 Back EMF sensing based on virtual neutral point

The back EMF integration approach has the advantage of reduced switching noise sensitivity and automatically adjustment of the inverter switching instants to changes in the rotor speed. The back EMF integration still has accuracy problems at low speeds. The rotor position can be determined based on the stator third harmonic voltage component. The main disadvantage is the relatively low value of the third harmonic voltage at low speed. The rotor position information is determined based on the conducting state of free-wheeling diodes in the unexcited phase. The sensing circuit is relatively complicated and low speed operation is still a problem.

III. DIRECT BACK EMF DETECTION

As described before, the noisy motor neutral point causes problems for the sensorless system. The proposed back EMF detection is trying to avoid the neutral point voltage. 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. 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 step.
- On the low side: the PWM is applied on the low side switch, the high side is on during the step.
- On both sides: the high side and low side are switched on/off together.

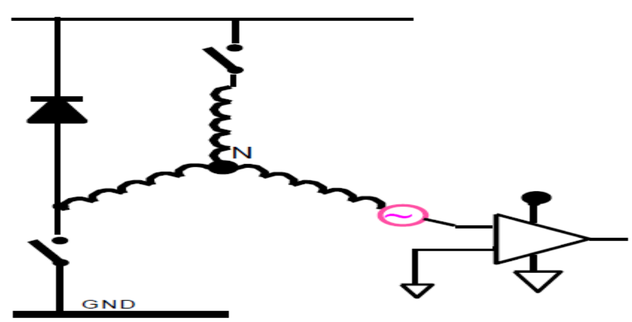

Fig.4 Proposed back EMF zero crossing detection scheme.

In the proposed scheme, the PWM signal is applied on high side switches only, and the back EMF signal is detected during the PWM off time. Fig.4 shows the concept detection circuit. The difference between Fig.4 and Fig.2 is that the motor neutral voltage is not involved in the signal processing in Fig4. 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

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step. The terminal voltage V_C is measured. Fig.5 shows the PWM signal arrangement.

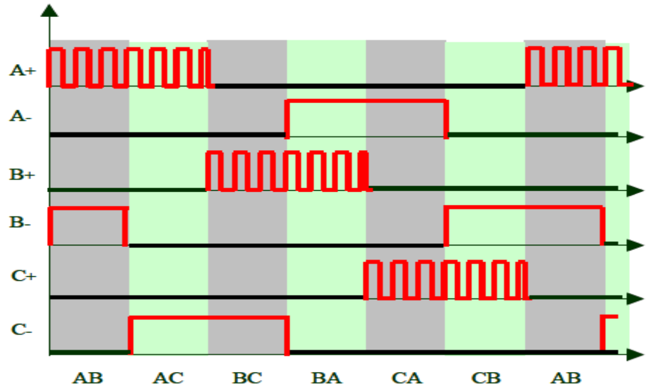

Fig.5 Proposed PWM strategy for direct back EMF detection scheme

IV. BACK EMF VOLTAGE WITHOUT ANY SUPERIMPOSED SWITCHING

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.

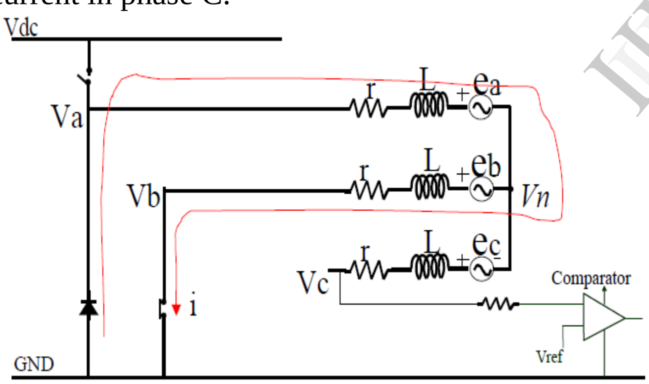

Fig.6 Circuit model of proposed Back EMF detection during the PWM off time moment

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, ec 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

$$v_n = 0 - ri - L\frac{di}{dt} - e_a$$

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

$$v_n = ri + L\frac{di}{dt} - e_b$$

Adding both we get

$$v_n = -\frac{e_a + e_b}{2}$$

Assuming a balanced three-phase system, if we ignore the third harmonics, we have

$$e_a + e_b + e_c = 0$$

Or, if we don't ignore the third harmonics, we will have

$$e_a + e_b + e_c = e_3$$

where e_3 is the third harmonics. Let's first finish the analysis without considering the third harmonics.

$$v_n = \frac{e_c}{2}$$

So, the terminal voltage Vc,

$$v_c = e_c + v_n = \frac{3}{2}e_c$$

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 directly proportional to the back EMF voltage without any superimposed switching noise. It is also important to note that this terminal voltage is 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, and we don't need to worry about the common mode voltage. 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. If we consider the third harmonics,

$$v_n = \frac{e_c}{2} - \frac{e_3}{2}$$

So, the terminal voltage Vc,

$$v_c = e_c + v_n = \frac{3}{2}e_c - \frac{e_3}{2}$$

Therefore, the terminal voltage will see the third harmonics. However, since the zero crossing of the fundamental wave will coincide with the zero crossing of the third harmonics, the third harmonic won't affect the zero crossing of the fundamental wave. A few tests have been conducted to show the relationship between fundamental and third harmonics.

V. ZERO CROSSING OF THE THIRD HARMONICS

Fig.7 and Fig.8 show the test result for motor A. Fig.9 and Fig.10 show the result for motor B. The shapes of back EMF are different from two motors. Nevertheless, the zero crossing of the third harmonics is overlapping with that of fundamental for both motors, which means that the third harmonics will not affect the zero crossing of fundamental wave. For motor B, there is slightly unbalance for three phase. Even under this situation, zero crossings of fundamental wave and third harmonic are still well overlapping.

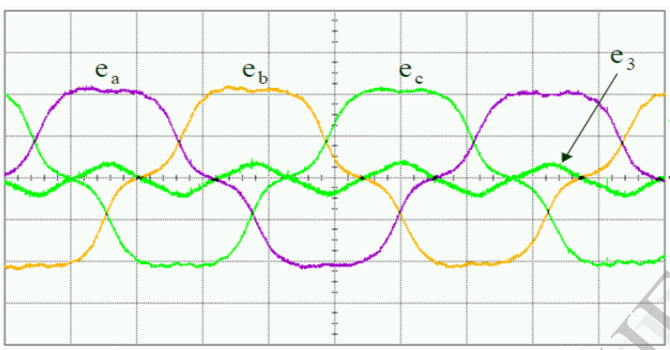

Fig.7 Fundamental wave and third harmonics of back EMF for motor A

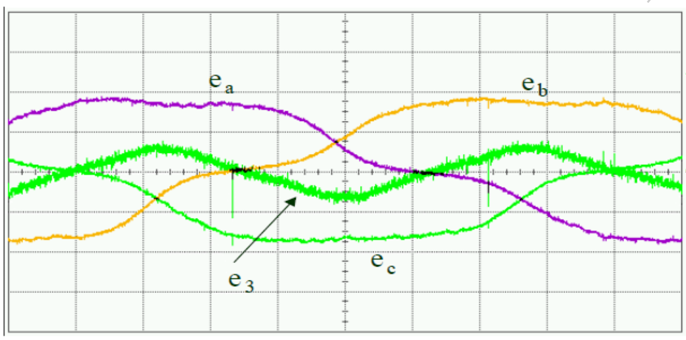

Fig.8 Expanded waveform of Fundamental wave and third harmonics of back EMF for motor A

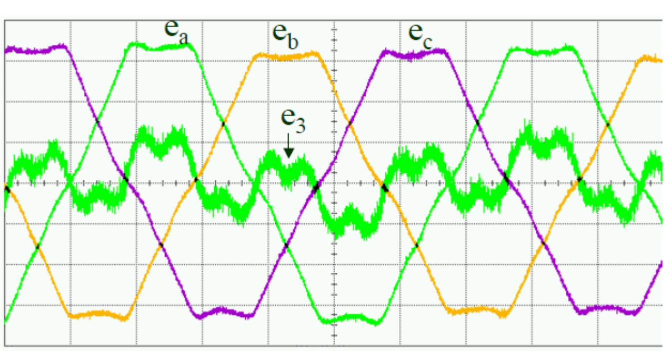

Fig.9 Fundamental wave and third harmonics of back EMF for motor B

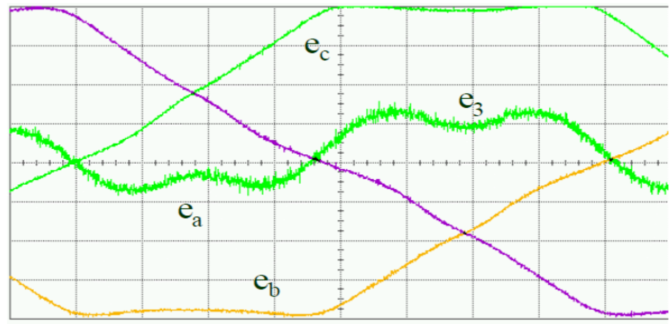

Fig.10 Expanded waveform of Fundamental wave and third harmonics of back EMF for motor B

Therefore, we can neglect the third harmonics content in the terminal voltage for zero crossing detection. To illustrate the scheme, Fig.11 shows the terminal voltage waveform of the scheme. From this waveform, it is clear that the back EMF signal can be extracted from the terminal voltage when the phase is floating. From time T1 to T2, the winding is floating; from time T2 to T3, the winding is conducting; and from time T3 to T4, the winding is floating again. The back EMF signal can be detected when PWM is "off". If the back EMF is negative, it is clamped to about minus 0.7V by the diode paralleled with the switch in the inverter. When the back EMF is positive, it shows up in the terminal voltage. Between time T1 and T2, rising edge of zero crossing is detected; and between T3 and T4, falling edge of the zero crossing can be detected.

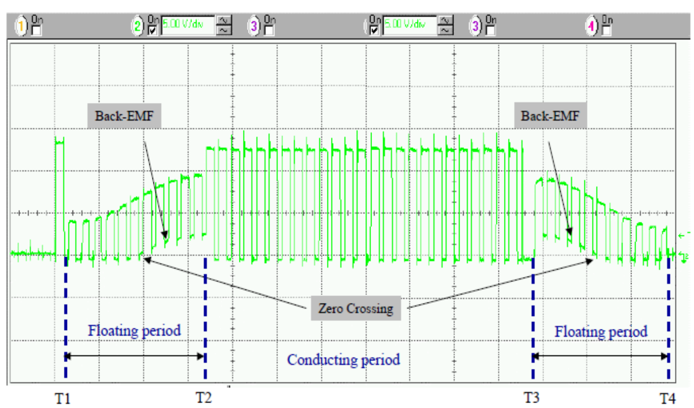

Fig.11 Phase terminal voltage and the back EMF waveform.

As a summary, several advantages of the proposed back EMF sensing technique over the conventional schemes can be listed as following:

- It has high sensitivity. First, since we don't use voltage divider, there is no attenuation. It still has good resolution even at low speed operation. Second, the high frequency switching noise can be rejected because the back EMF is sampled during the PWM off time. The synchronous sampling can easily get rid of the switching noise. Third, because the back EMF is referenced to the ground now, the common mode voltage is minimized.
- It is instant value because there is no filtering in the circuit, which will be good for high-speed operation.
- This sensing technique can be easily used to either high voltage or low voltage systems without much effort to scale the voltage.
- Fast motor start-up is possible because of precise back EMF zero crossing detection without attenuation.

VI. CONCLUSION

A synchronous sampling circuit for the back EMF sensing is developed, and the circuit is integrated with a standard low cost 8-bit microcontroller to be a dedicated BLDC sensorless drive controller. This microcontroller has been commercialized and applied in real applications such as automotive fuel pumps and home appliances. An improved version of the direct back EMF sensing, detecting the back EMF signal during PWM on time, is presented. Since the original method detects back EMF signal during PWM off time, it can't go to 100% duty cycle. The improved method will overcome the duty cycle limit. The complementary PWM algorithm can eliminate the offset voltage in the back EMF signal caused by the voltage drop of the diode, and also increase the system efficiency by reducing the conduction loss. The pre-conditioning circuit not only compensates the offset voltage, but also amplifies the back EMF signal to be stronger.

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