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A Survey on Back EMF Sensing Methods for Sensorless Brushless DC Motor Drives

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ABSTRACT

This paper provides a technical review of Back EMF Sensing Methods for Sensorless Brushless Direct Current (BLDC) motor drives. Brushless DC (BLDC) motors and their drives have been proven to be best type of motors in recent years because of their long life, high efficiency, reliability, compact form, low maintenance and low heat dissipation. To improve the performance and reliability of BLDC motor drive system, sensorless technology is preferred. The study includes an overview of back-EMF sensing methods, which includes Back-EMF Zero Crossing Detection Method, PWM schemes, Third Harmonic Voltage Integration, Back-EMF Integration and Free-wheeling Diode Conduction method.

Keywords: Back electromotive force (BEMF), back-EMF sensing, brushless dc (BLDC) motor, sensorless.

1. INTRODUCTION

BLDC motors, are one of the motor types that have more popularity, mainly because of their superior characteristics and performance. These motors are used in industrial sectors because their architecture is suitable for any safety critical applications. The brushless DC motor is an electronically commutated motor that, having a linear relationship between current and torque, voltage and speed. BLDC motors have much precedence over brushed DC motors and induction motors, such as a superior speed versus torque characteristics, high dynamic response, high efficiency and reliability, higher speed ranges, and reduction of electromagnetic interference [1].

BLDC motors are electronically controlled and require rotor position information for proper commutation of currents in its stator windings. It is not desirable to use the sensors for applications where reliability is of utmost importance because a sensor failure may cause instability in the control system. These limitations of using sensors have spurred the development of sensorless control technology [2].

Basically, two types of sensorless control technique are there [3]. The first method is the position sensing using back EMF of the motor, and the other one is position approximation using terminal voltages, currents, and motor parameters. The second scheme usually needs DSPs to do the computation, and makes the system relatively expensive. So the position sensing using back EMF of the motor is the most commonly used method. The back EMF voltage in the unenergized winding can be measured to maintain a switching sequence for commutation in the three-phase inverter. In conventional back EMF detection method a virtual neutral point is build and senses the difference between the virtual neutral and the voltage at the floating terminal [4]. However, when using a chopping drive, the neutral is not a standstill point, creating large common mode. Also, the PWM signal is superimposed on the neutral voltage, causing a large amount of electrical noise on the sensed signal. A lot of attenuation and filtering is required to sense the back EMF properly. Filtering cause's unwanted delay in the signal, results is a poor signal to noise ratio. To reduce the switching noise, the back EMF integration and third harmonic voltage integration were introduced [5], [6]. The integration approach has the advantage of reduced switching noise sensitivity. However, they still have the problem of high common voltage in the neutral. An indirect sensing of zero crossing of phase back EMF by detecting conducting state of free-wheeling diodes in the unexcited phase was also discussed [7]. The implementation of this method is complex and expensive, while its low speed operation is also a problem. The true back EMF can be detected directly from terminal voltage by properly choosing the PWM and sensing strategy [8]. This back EMF detection method does not require the motor neutral voltage. As a result there are no common mode voltage issues.

The organization of the paper is as follows: Part 1 deals with the sensorless BLDC motor drives. Part 2 explains the background of back EMF sensing methods. Part 3 discusses about the back EMF sensing techniques, and finally, the work is summarized in the conclusion part.

2. SENSORLESS BLDC MOTOR DRIVES

The BLDC motor is an AC synchronous motor with permanent magnets on the rotor and windings on the stator. Rotor flux is created by permanent magnets and electromagnet poles are created by the energized stator windings. The permanent magnets are attracted by the energized stator phase. A rotating field on the stator is generated and maintained, by using the appropriate sequence to supply the stator phases. This action of permanent magnets on the rotor chasing after the electromagnet poles on the stator is the fundamental action used in permanent magnet motors. By controlling the currents in the stators, a magnetic field of arbitrary magnitude and direction can be produced. Torque is the result of the forces of attraction and repulsion between the rotor and the stator field acting on the rotor shaft. The angle at which force is applied to the rotor field affects the amount of torque produced. To produce the most torque, the stator field must be orthogonal to the rotor field. This in turn means that the position of the rotor relative to the stators is a crucial data in a BLDC motor control system [2].

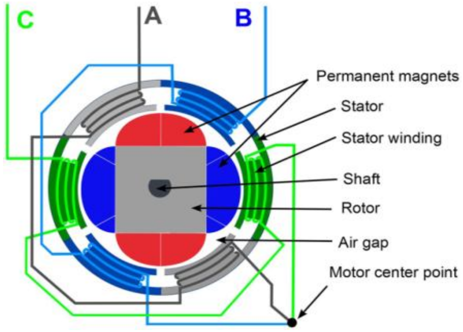

Figure 1: Structure of A BLDC Motor

Figure 1 shows the structure of a BLDC motor [2]. On the stator side, three phase motors are the most usual. These offer a good settlement between accurate control and the number of power electronic devices required to control the stator currents. For the rotor, for the same level of current a greater torque is created by a greater number of poles. By adding more number of poles, a point is reached where, the torque no longer increases, because of the space needed between poles. The manufacturing cost also increases with the number of poles. As a result, the number of poles is a compromise between manufacturing cost, torque and volume.

The key to successive torque and speed control of a BLDC motor is based on simple torque and Back EMF equations. The Back EMF magnitude can be written as:

$$E = 2NlrB\omega \qquad (1)$$

and the torque term as:

$$T = \left(\frac{1}{2} i^2 \frac{dL}{d\theta}\right) - \left(\frac{1}{2} B^2 \frac{dR}{d\theta}\right) + \left(\frac{4N}{\pi} Brl\pi i\right) \qquad (2)$$

where N is the number of turns in winding per phase, l is the length of the rotor, r is the internal radius of the rotor, B is the rotor magnet flux density, ω is the rotor's angular velocity, i is the phase current, L is the phase inductance, θ is the rotor position, R is the phase resistance. The first and second terms in the torque equation are parasitic reluctance torque components. The third term creates mutual torque, which is the torque production technique used in BLDC motors. To summarize, the Back EMF is directly proportional to the motor speed and the torque production is almost directly proportional to the phase current.

The BLDC motor control consists of generating DC currents in the motor phases. This control is split into two distinct operations: stator and rotor flux synchronization and current control. Both operations are perceived through the three phase inverter illustrated in the figure 2.

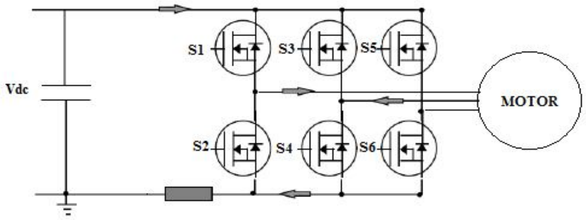

Figure 2: Three Phase Inverter

The flux synchronization is derived from the position information using sensors, or using sensorless techniques. From the position information, the controller decides the suitable pair of transistors (Q1 to Q6) which must be driven. The control of the current to a fixed 60 degrees reference can be perceived in either of the two modes:

- The Pulse Width Modulation (PWM) Mode
- The Hysteresis Mode

The speed of the BLDC motor is directly proportional to the applied voltage. The commutation logic specifies the windings that need to be energized for every 60 degree of electrical revolution based on position information. The Pulse Width Modulation logic specifies the time intervals during which the switches should be ON and OFF to average the DC Bus voltage applied thereby controlling the speed.

3. BACKGROUND OF BACK EMF SENSING METHODS

When a BLDC motor rotates, according to the Lenz's law, each winding generates BEMF which opposes the main voltage supplied to the windings. The polarity of this BEMF opposes the energizing voltage polarity. BEMF is mainly dependent on the following motor parameters:

- Number of stator windings turns
- Motor's Angular Velocity
- Magnetic field created by rotor magnets

BEMF can then be calculated using the given expression:

$$BEMF = NlrB\omega$$

Where,
N = number of windings per phase
l = length of the rotor
r = internal radius of the rotor
B = rotor magnetic field
ω = rotor angular velocity

As from the equation, the only variable term is the rotor angular speed. Therefore, the BEMF is proportional to the rotor speed, as the speed increases the BEMF increases. The BEMF of the motor varies as both a function of the rotor's position and speed

4. BACK EMF SENSING METHODS

Back-EMF sensing methods for the BLDC motors are split into two categories; direct and indirect back-EMF detection,

•Direct Back-EMF Sensing Methods: The back-EMF of floating phase is sensed and its zero crossing is detected by comparing it with neutral voltage. This technique suffers from high common mode voltage and high frequency noise due to the PWM switching, so it requires voltage dividers and low-pass filters to reduce the common-mode voltage and the higher harmonics. These methods can be classified as [8]:

- Back-EMF Zero Crossing Detection (ZCD) or Terminal Voltage Sensing.
- PWM strategies.

•Indirect Back-EMF Sensing Methods: Since filtering introduces commutation delay at high speeds and attenuation causes reduction in signal sensitivity at low speeds, the speed range is limited in direct back-EMF sensing methods. In order to reduce high frequency noise due to the PWM switching, the indirect back-EMF sensing methods are used. These methods are the following [8]:

- Back-EMF Integration.
- Third Harmonic Voltage Integration.
- Free-wheeling Diode Conduction or Terminal Current Sensing.

4.1 Back-EMF Zero Crossing Detection Method (Terminal Voltage Sensing)

The open phase voltage sensing method is one of the easiest approaches of back-EMF sensing, and is based on estimating the rotor position indirectly by finding the instant at which the back-EMF in the unenergized phase crosses zero. The terminal voltage sensing method is commonly used for low cost industrial applications where frequent speed variation is not required. The commutation points can be estimated by shifting 30^0 from the zero crossing of the back-EMFs. The drawbacks of this method are noise sensitivity in detecting the zero crossing, poor performance over wide speed ranges unless the timing interval is programmed as a function of rotor speed. And the estimated commutation points have position error during the transient period. Another drawback is that it requires high operational speed enough to detect the zero crossing point of terminal voltages since back-EMF is zero at standstill and proportional to rotor speed [4].

4.2 Methods Based on PWM Strategies

The zero crossing of the back-EMF can be attained by comparing the terminal voltage with the neutral point voltage. In most cases, the motor neutral point voltage is unavailable. The most commonly used technique is to estimate the back EMF by sensing the terminal voltages with respect to a virtual neutral point, which is theoretically at the same potential as the neutral point of the star-wound motor. The virtual neutral point will not be stable during pulse width modulation (PWM) switching and fluctuates at PWM frequency. This results in a very high common-mode voltage and high-frequency noise. Voltage dividers and low-pass filters are required to reduce the common-mode voltage and the higher harmonics. Filter produces phase delay which is dependent to back-EMF frequency. By eliminating this virtual neutral point, filtering requirement can be minimized, and the zero crossing point of the back-EMF voltage of the floating phase can be obtained directly from the motor terminal voltage with respect to the ground by properly selecting the PWM and sensing strategy. For BLDC drive, only two out of three phases are excited at any time instant. The PWM drive signal can be arranged in three ways:
- On the upper side: PWM is applied only on the upper side switch, the bottom side is on during the step.
- On the bottom side: the PWM is applied on the bottom side switch, the upper side is on during the step.
- On both sides: the upper side and bottom side are switched on/off together.

The back-EMF signal can be detected either during PWM off time or PWM on time. During the PWM off time, terminal voltage of the floating phase is directly proportional to the phase back EMF and during the PWM on time which is directly proportional to back EMF voltage plus the half of dc bus voltage. This terminal voltage is not with respect to the floating neutral point. So, back EMF zero crossing point can be detected without the neutral point voltage information. As a result there are no common mode voltage issues [9].

4.3 Back-EMF Integration Method

In this technique, the position information is extracted by integrating unexcited phase's back-EMF. The integration starts at the zero crossing points of unexcited phase's back-EMF. When the integrated value reaches a threshold value, the integration stops, which gives the corresponding commutation point and the phase current gets commutated.

The integration approach has reduced switching noise sensitivity and automatically adjusts the inverter switching instants for rotor speed changes, but has poor operation at low speeds. This approach suffers from error accumulation and offset voltage problems due to integration [5]

4.4 Third Harmonic Voltage Integration Method

Commutation instants of BLDC motors can be estimated from the third harmonic of the back EMF waveform. This technique removes all the fundamental and other polyphase components through a summation of the terminal voltages. The third harmonic voltage component is then integrated to find the zero crossing, which gives the corresponding commutation points. Since the third harmonic signal has a frequency three times higher than the fundamental signal, there is a reduced filtering requirement and signal detection at low speeds is possible, allowing wide speed range of operation. Simplicity of implementation, exact coincidence of third harmonic zero crossing detection points with current commutation instants, low susceptibility to electrical noise, and robustness, are the key advantages of this technique. The variations of amplitude and phase of harmonic components due to magnetic saturation are the limitations of third harmonic technique. The rotor position is determined based on the stator third harmonic voltage component. The relatively low value of the third harmonic voltage at low speed cause a serious position error, as noise and make this technique not suited to the low speed range applications [6].

4.5 Free-Wheeling Diodes Conduction Detection Method (Terminal Current Sensing)

In this technique, the rotor position information is determined based on the conducting state of antiparallel connected freewheeling diodes in the unexcited phase. Detecting the free-wheeling diode conducting status in the unexcited phase gives the zero-crossing point of the back EMF waveform. A simple starting procedure and uniform control performance over various operating conditions are of key advantages of this technique. This methodology makes it possible to find the rotor position over a wide speed range, especially at a lower speed. Alike other back-EMF based methods; this method has a position error of commutation points in the transient state. Even though it has the above mentioned attractive features, the most serious drawbacks of this method is the use of six isolated power supplies for the comparator circuitry to detect current flowing in each freewheeling diode and requires complicated sensing circuits, which prohibits this method for use in practical applications. However, this technique has proved efficient by outperforming the previous back-EMF methods at low-speeds [7].

5. CONCLUSION

BLDC motors have many advantages over brushed DC motors and induction motors, such as a superior speed versus torque characteristics, high dynamic response, more efficiency and reliability, cheaper, longer life, quieter, higher speed ranges, and reduction of arcing. In addition, the BLDC motor has higher delivered torque to size ratio. All the above advantages make it useful in applications where space and weight are critical factors, particularly in aerospace applications. BLDC motors can be controlled either in sensor or sensorless mode, but to reduce general cost and size of motor assembly, sensorless control techniques are normally employed.

There are many categories of sensorless control strategies, among which the most popular is based on back electromotive forces or back-EMFs. Sensing back-EMF in floating phase is the most cost efficient technique to obtain the commutation sequence in star wound motors. Since back-EMF is zero at standstill and proportional to speed, the measured terminal voltage with large signal-to-noise ratio is unable to detect zero crossing at low speeds. Thus, for all back-EMF-based sensorless methods, one of the limitations is low speed performance and so, an open-loop starting technique is required.

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