Position Sensorless Control of Permanent Magnet Brushless DC Motor

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Abstract - This paper presents a back Electromotive Force (EMF) sensing scheme, indirect back EMF detection, for sensorless control of Brushless DC (BLDC) motor drive from the terminal voltages. Using this scheme, the motor neutral voltage is not needed to measure the back EMF. Instead the method utilizes difference of line voltages measured at the terminals of the motor. The difference of the line voltages shows an inverted and amplified version of the back EMF. Since the motor neutral is not needed, the developed back EMF sensing method is immune to switching noise and common mode voltage. The effectiveness of the proposed drive system is clarified from simulation results.

Index Terms—Back Electromotive Force (EMF) detection, Brushless DC (BLDC) motor, Sensorless control, Zero crossing.

I. INTRODUCTION

With rapid developments in power electronics, power semiconductor technologies, modern control theory for motors and manufacturing technology for high performance magnetic materials, the brushless DC motors (BLDCM) have been widely used in various areas such as automotive, computer, industrial, and household products, etc., and its market is rapidly growing. This is mainly due to the advancement of small size, good performance, simple structure, high reliability and large output torque. BLDC motors have attracted increasing attention.

An inverter-driven three-phase BLDC motor, as shown in Fig. 1, needs rotor position information to ensure stable operation by synchronizing the phase excitation to the rotor position. This information is generally available by using position sensors. Therefore, the application of position sensor makes the motor body heavy, as well as lots of wires are needed, which in turn brings complication and interference in the design. Thus the position sensorless control technology attracts increasing research interest and currently becomes one of the most promising trends of BLDCM control system.

During the last two decades, a lot of researches on sensorless control techniques for brushless dc motors (BLDCMs) have been conducted. This research can be divided into four categories [1]–[3]. 1) Back electromagnetic force (EMF) integration method [4]. 2) Sensing of the third harmonic of the back EMF [5]. 3) Detection of freewheeling diode conduction and related extended strategies [6]. 4) Detection of the back emf zero crossing point (ZCP) of the motor with a precise phase shift circuit [7]–[7]. Among the various techniques, the back EMF zero crossing detection method is the most popular.

In [4] T. M. Jahns, R. C. Bema, and M. Ehsani, proposed the method where position information is extracted by integrating the back-emf of the unexcited phase. Here the integration of the back-emf starts when the open phase's back-emf crosses zero. A threshold is set to stop the integration which corresponds to a commutation instant. Due to integration it suffers from offset error and not applicable at low speeds.

In [5] J.X. Shen and S. Iwasaki, used the third harmonic back emf method to determine the switching instants of the inverter. The three terminal voltages with respect to neutral point is added to obtain the third harmonic back emf. Then the third harmonic back emf is integrated to find the third harmonic rotor flux. The zero crossings of the third harmonic rotor flux provide the commutation instant of the inverter. The motor neutral terminal is used and hence they could be affected by common mode noise.

In [6] S. ogarawara and H. Akagi, describes the method of detecting the free-wheeling diode conduction in the open phase gives the zero-crossing point of the back EMF waveform. This method of sensing the rotor-position works over a wide speed range, especially at lower speed. The main drawback of this scheme is the requirement of six additional power supplies for the comparator circuits to detect current flowing through the free-wheeling diode.

Back EMF estimation methods typically rely on the zero crossing detection of the EMF waveform. The technique of estimating back EMF by sensing the terminal voltages with respect to a virtual neutral point is proposed in [7]. The neutral point will not be stable during pulse width modulation (PWM) switching. Low pass filters have been used to eliminate the higher harmonics and to convert the terminal voltages into triangular waveform signals. Delay is introduced in the sensed signal due to heavy filtering, which also varies with the operating speed. Therefore, this method is well suited only for a narrow speed range.

A flux linkage function was proposed by [8] depending on the measured voltage, current, and derivative of currents which indicates the switching instants. The speed independent function is obtained by dividing one line to line function by another line to line function. This method requires digital implementation and could be affected by sensor noise.[9] Proposed the digital filtering procedure to determine the true and false zero crossing point of the back emf. However the starting method was not discussed and it involves complex calculations.[10] Proposed a method for speed controller which uses the recursive least square (RLS) is used to calculate the J and B parameters which acts as inputs to the torque observer. The torque observer generates load torque which is substituted in the mechanical angle to determine the rotor speed.
In [11] used the terminal voltage to measures the commutation interval also calculates the PWM duty ratio using commutation interval to suppress the torque ripple and applies to the calculated duty ratio only during next commutation. It is not applicable at low speeds, [12], J. Shao, uses a specific kind of PWM to achieve both high and low speed i.e., both PWM on and PWM off time are used to sample the motor back EMF. To start PWM off time is used and during high speeds PWM on time is used to detect back EMF. [13] C.-H. Chen and M.-Y. Cheng, used the average line to line voltage which is obtained by filtering the PWM. The filter used to remove the high switching frequency noise signal caused by PWM which results in time delay and thereby reducing the performance. Also they do not discuss about the sensorless starting of the motor.

In [14], C. T. Lin, C. W. Hung, proposed four switch inverter. The position information is detected from the floating line. This scheme is also called as asymmetric PWM scheme. Here the four switches determines the two zero crossing points and other four commutation instants are attained through interpolation and shift delay software. However the commutations may cause commutation torque ripples. In [15], W.-J. Lee and S.-K. Sul, proposed the starting delay software. However the commutations may cause commutation torque ripples and during high speeds PWM on time is used to detect back EMF. In [16] and [17], C.-H. Chen and M.-Y. Cheng, used the average line to line voltage which is obtained by filtering the PWM. The filter used to remove the high switching frequency noise signal caused by PWM which results in time delay and thereby reducing the performance. Also they do not discuss about the sensorless starting of the motor.

In the proposed method, the zero crossings of the back EMF are estimated indirectly from the terminal voltages measured with respect to dc negative terminal. The method does not involve any integration. Further, since line voltages are used, the requirement of neutral potential has been eliminated.

The organization of this paper is as follows. Section II discusses the review of traditional sensorless methods for BLDC motors. Section III describes the modelling of BLDC motor. Section IV describes the proposed back EMF zero-crossing estimation method. Section V presents the simulation results of the proposed method and Section VI presents the conclusion.

II. REVIEW OF TRADITIONAL SENSORLESS METHODS FOR BLDC MOTORS

Sensorless BLDC motor control has been a research topic for the last two decades. Many papers have been published on this topic [2] and [3]. The main method published in literature on this topic especially for the trapezoidal back emf type of BLDC motors can be classified as follows

A. Back- EMF Sensing Technique

The brushless DC motor has the trapezoidal shape of the induced back EMF in the stator winding. Monitoring the phase back EMF measured from terminal voltage in the silent phase, the zero crossing of the back EMF is detected. Since the hall sensor signals advances the back EMF by 30 degree, the zero crossing point of the back EMF is detected and a phase shift of 30 degree is given to produce the virtual hall sensor signals. This virtual hall sensor signal provides the rotor position information which are used to determine the switching signals of the inverter. The figure 2.1 shows the back EMF waveform with the zero crossing point of the back EMF and the commutation point (which are advanced by 30 degrees).

B. Back- EMF Integration Technique

In this method position information is extracted by integrating the back-emf of the unexcited phase. Integration starts when the open phase’s back EMF crosses zero. A threshold is set to stop the integration that corresponds to a commutation instant. The drawback is this method also has a problem at low speeds because of the error accumulation problem. It also suffers from offset error due to integration.
\[
\begin{align*}
V_a &= \begin{pmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{pmatrix} + \begin{pmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} e_a \\ e_b \\ e_c \end{pmatrix} \\
V_b &= \begin{pmatrix} 0 & R & 0 \\ R & 0 & 0 \\ 0 & 0 & R \end{pmatrix} + \begin{pmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} e_a \\ e_b \\ e_c \end{pmatrix} \\
V_c &= \begin{pmatrix} 0 & 0 & R \\ 0 & 0 & R \\ R & 0 & 0 \end{pmatrix} + \begin{pmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} e_a \\ e_b \\ e_c \end{pmatrix}
\end{align*}
\] (1)

They can also be written as follows:
\[
\begin{align*}
V_a &= (L-M) \frac{di_a}{dt} + i_a * R + E_a \\
V_b &= (L-M) \frac{di_b}{dt} + i_b * R + E_b \\
V_c &= (L-M) \frac{di_c}{dt} + i_c * R + E_c
\end{align*}
\] (2, 3, 4)

Based on the above equations, the equivalent circuit of motors can be obtained. From the above voltage equation the phase current flowing through each winding can be expressed as
\[
\begin{align*}
i_a &= \frac{1}{L-M} \int (V_a - E_a - R i_a) \, dt \\
i_b &= \frac{1}{L-M} \int (V_b - E_b - R i_b) \, dt \\
i_c &= \frac{1}{L-M} \int (V_c - E_c - R i_c) \, dt
\end{align*}
\] (5, 6, 7)

Where \(V_a, V_b, V_c\) are the phase voltages, \(E_a, E_b, E_c\) are the phase back emf, \(p\) is the differential operator, \(i_a, i_b, i_c\) are the phase currents.

The electromagnetic torque of BLDCM is generated by the interaction of the current in stator windings and the magnetic field in rotor magnet. The electromagnetic torque equation is
\[
T_e = \frac{c_{ia} + c_{ib} + c_{ic}}{\omega_n} = \frac{4 P_m N \Phi_{mld}}{\pi n}
\] (8)

Where, \(P_m\) is pole numbers, \(N\) is total conductor numbers, \(\Phi_{mld}\) is main magnetic flux, \(n\) is motor speed.

The equation indicates that the developed torque of BLDCM is proportional to the magnetic flux and inverter input current, which is similar to that of a separately excited DC motor, where the developed torque is proportional to the armature current. Therefore, the torque of BLDCM will be controlled so long as the rectangle wave current amplitude is done. When inputting the three-phase rectangle wave current of 120° electrical angle and making it in phase with the EMF of each phase, the ripple of torque for BLDCM will be equal to zero.

The equation of motion can be expressed:
\[
T_e = T_L + J \frac{d\omega_n}{dt} + B \omega_n
\] (9)

Where, \(T_e\) is the load torque, \(J\) is the rotational inertia of rotor and load, \(B\) is the viscous damping coefficient.

**IV IMPROVED INDIRECT BACK EMF ZERO CROSSING SENSING SCHEME**

Consider a BLDC motor having three stator phase windings connected in star. Permanent magnets are mounted on the rotor. The BLDC motor is driven by a three phase inverter in which the devices are triggered with respect to the rotor position as shown in Fig. 5.1. The phase A terminal voltage with respect to the star point of the stator Van, is given in (1)
\[
V_{an} = R_{ia} \frac{di_a}{dt} + e_{an}
\] (10)

Where \(R_i\) is the rotor resistance, \(L_m\) is the phase inductance, \(e_{an}\) is the back EMF, and \(i_a\) is the phase current of the “A” phase. Similar equations can be written for the other two phases, as in (2) and (3)
\[
\begin{align*}
V_{bn} &= R_{ib} \frac{di_b}{dt} + e_{bn} \\
V_{cn} &= R_{ic} \frac{di_c}{dt} + e_{cn}
\end{align*}
\] (11, 12)

From this, the line voltage \(V_{ab}\) may be determined from the equation (1) and (2).
\[
V_{ab} = V_{an} - V_{bn} - R(\frac{di_a}{dt} + \frac{di_b}{dt}) + L \frac{d(\frac{di_a}{dt} + \frac{di_b}{dt})}{dt} + e_{an} - e_{bn}
\] (13)

Similarly
\[
\begin{align*}
V_{ac} &= R(\frac{di_a}{dt} + \frac{di_c}{dt}) + L \frac{d(\frac{di_a}{dt} + \frac{di_c}{dt})}{dt} + e_{an} - e_{cn}
\end{align*}
\] (14)

These line voltages can, however, be estimated without the need for star point by taking the difference of terminal voltages measured with respect to the negative dc bus. Subtracting (5) from (4) gives
\[
V_{abc} = R(\frac{di_a}{dt} - 2 \frac{di_b}{dt} + \frac{di_c}{dt}) + L \frac{d(\frac{di_a}{dt} - 2 \frac{di_b}{dt} + \frac{di_c}{dt})}{dt} + 2e_{bn} - 2e_{cn}
\] (16)

**Figure 4.1 Block diagram for Line voltage difference method**

Consider the interval when phases A and C are conducting and phase B is open as indicated by the mode II in Fig. 2.1. In this interval, phase A winding is connected to the positive terminal of the
dc supply, phase C to the negative terminal of the dc supply and phase B is open. Therefore,

\[ i_a = -i_c \]  \hspace{1cm} (17)

and \( i_b = 0 \).  \hspace{1cm} (18)

It can be seen from Fig. 5.1 (mode III) that the back EMF in phases A and C are equal and opposite. Therefore, in that interval (7) may be simplified as

\[ V_{abc} = V_{ab} - V_{bc} = e_a - 2e_b + e_c = -2e_b. \]  \hspace{1cm} (19)

Similarly for \( V_{bca} \) and \( V_{cab} \) the equations are given as

\[ V_{bca} = V_{bc} - V_{ca} = e_b - 2e_c + e_a = -2e_c. \]  \hspace{1cm} (20)

\[ V_{cab} = V_{ca} - V_{ab} = e_c - 2e_a + e_b = -2e_a. \]  \hspace{1cm} (21)

The difference of line voltages waveform is, thus, an inverted representation of the back EMF waveform. The EMF values would be those in a resistance, inductance, EMF (RLE) representation of the phase (not referred to ground). It may also be noted that the subtraction operation provides a gain of two to the EMF waveform thus amplifying it. It is again evident from Fig. 5.1 that during this interval (mode II) the back EMF \( e_b \) transits from one polarity to another crossing zero.

Therefore, the operation \( V_{ab} - V_{bc} \) \((V_{abc})\) enables detection of the zero crossing of the phase B EMF. Similarly, the difference of line voltages \( V_{bca} \) enables the detection of zero crossing of phase C back EMF when phase B and A back EMFs are equal and opposite. The difference of line voltages \( V_{cab} \) waveform gives the zero crossing of phase A back EMF where phases C and B have equal and opposite back EMFs. Therefore, the zero-crossing instants of the back EMF waveforms may be estimated indirectly from measurements of only the three terminal voltages of the motor.

V SIMULATION RESULTS

The permanent magnet brushless DC motor is driven by the six switch inverter. The mathematical modelling of brushless DC motor is used. The terminal voltage with respect to negative terminal is used to determine the line voltages. The line voltage differences are used which represents the inverter and amplified version of back emf. The zero crossings of the line voltage differences are used to find the commutation instants of the inverter.

5.1. SIMULATION BLOCK DIAGRAM IN OPEN LOOP

The motor is started by using the zero crossings of the line voltage differences without any phase shift. After 0.5 seconds the motor runs with sensorless commutation. Also after 0.5 seconds the loads are varied gradually. Therefore up to 0.5 seconds the motor runs at no load and after 0.5 seconds the motor runs with load variations. The simulation results are shown with the no load and with load variations.
Simulation block diagram in closed loop

Figure 5.5 Simulation Block diagram for line voltage difference method

Figure 5.6 Zero crossings of line to line voltage differences

The motor is started by using the zero crossings of the line voltage differences without any phase shift. After 0.5 seconds the motor runs with sensorless commutation. Also after 1 second the loads are varied gradually.

Therefore up to 0.5 seconds the motor runs at no load and after 1 second the motor runs with load variations. The simulation results are shown with the no load and with load variations.

CONCLUSION

A simple technique to detect back EMF zero crossings for a BLDC motor using the line voltages is proposed. It is shown that this method uses the line to line voltage differences represents an amplified version of the back EMF. Only three motor terminal voltages need to be measured thus eliminating the need for motor neutral voltage. The simulation model is developed for the open loop and closed loop drive of PMBLDC motor. The motor performances with no load and with load variations are observed and the simulation results are obtained.

REFERENCES
