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A Research on Sensorless Control of Brushless DC Motor using Inductance Variation Technique

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Abstract

Today, brushless DC motors (BLDCM) have been used in many applications replacing to brushed DC motors. Compared to brushed DC motors, BLDCM offer improved reliability, longer life, smaller size, and lower weight. Besides, BLDCM have become more popular in applications where efficiency is a critical concern and, generally speaking, a BLDCM is considered to be a high-performance motor capable of providing large amounts of torque over a wide speed range.

In this paper, a research on sensorless control method which can drive a BLDCM smoothly from standstill to high speeds without position or speed sensors is carried out. Initial rotor position as well as speed of motor at a low speed range is estimated based on the inductance variation principle while at higher speed, the back EMF technique is applied. This sensorless control algorithm is modeled and simulated with MATLAB/SIMULINK software to verify the abilities of the method. The drive control scheme has been implemented on a single-chip controller (STM32F103) and experimental results reveal that the control procedure can work smoothly.

Key Words: Sensorless Control, BLDCM, Inductance Variation, back EMF technique, Matlab/Simulink

1. Introduction

The BLDCM is used in various applications of electromechanical systems because of its high efficiency and good controllability over a wide range of speeds. The drive for the brushless DC motor requires an inverter and a position sensor for providing proper commutation sequence to turn on the power devices in the inverter bridge. However, the position sensor not only increases the cost and encumbrance of the overall drive system but also reduces its control robustness and reliability. Furthermore, it might be difficult to install and maintain a position sensor due to the limited assembly space and rigid working environment with severe vibration and/or high temperature. As a result, many researches have been carried out for sensorless control of BLDCM that can control position, speed and/or torque without shaft-mounted position sensors, which can be categorized into the following:

Back-EMF Sensing Techniques [1]:

These methods include terminal voltage sensing of the motor; detection of the conducting state of freewheeling diode in the unexcited phase; back-EMF integration method; Stator third harmonic voltage components. These methods have been shown to be successful only at medium and high rotor speeds.

Flux Linkage-Based Technique [1]:

In these methods, the flux linkage is calculated using measured voltages and currents. The fundamental idea is to take the voltage equation of the machine and by integrating the applied voltage and current, flux can be estimated. From the initial position, machine parameters, and the flux linkages' relationship to rotor position, the rotor position can be estimated. This method also has significant estimation error in low speeds.

Extended Kalman filters [1]:

The Extended Kalman Filter (EKF) is able to provide optimum filtering of the noises in measurement and inside the system if the covariances of these noises are known. It is an optimal stochastic observer in the least-square sense for estimating the states of dynamic non-linear systems. Hence it is a viable candidate for the on-line determination of the rotor position and speed [22-24]. However, none of the practical industry applications of EKF-based sensorless PMSM control has been reported due to the technical difficulties.

Estimators based on inductance variation due to geometrical and saturation effects [1]:

The rotor position can be estimated by using inductance variations due to magnetic saturation and/or geometrical effects of BLDCM. This method was proposed by Schroedl, which was based on real-time inductance measurements using saliency and saturation effects. During a short time interval, the "complex INFORM reactance" was calculated for estimating flux angle [9]. Corley and Lorenz [10] investigated a high frequency signal injection method in such a way that carrier-frequency voltages were applied to the stator windings of PMSM, producing high-frequency currents of which the magnitude varies with rotor position.

2. BLDCM Drive [3]

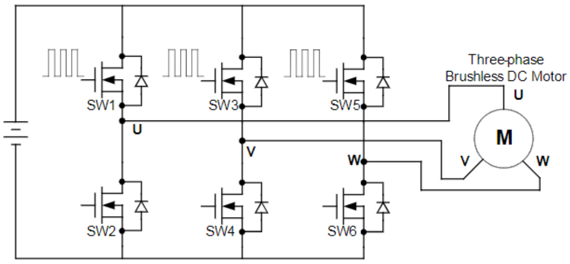


Figure 1. BLDCM Driver

A typical Brushless DC motor is driven by voltage pulses to specific phase of the stator in accordance to the position of the rotor. To generate the maximum torque in the brushless DC motor, these voltage pulses should be applied properly to the active phases of the three-phase winding system so that the angle between the rotor flux and the stator flux is kept close to 90 degrees. Therefore, special controllers are required which control the voltage on the basis of rotor position detected. Once the rotor position is detected, the controller works appropriately to generate a proper commutation sequence of the voltage strokes so that the BLDC motor keeps rotating. The BLDC motor is supplied with the three-phase inverter and the commutation sequence can be simply used to trigger the switching actions of the inverter. There are different control techniques available in the industry for brushless DC motors and are explained below:

- Six step Commutation
- Sinusoidal Commutation
- Field Oriented Control
- Direct Torque Control

3. Sensorless Control Method

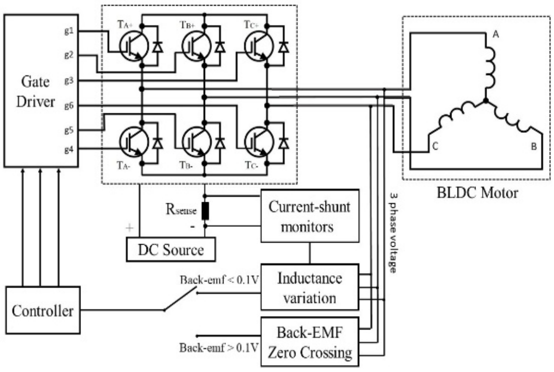


Figure 2. System architecture

The measurement/estimation of rotor position is the most critical step in controlling the BLDC motors. A small error in position estimation for BLDC motor can result in very poor performance and in some cases it may result in a complete motor failure. The estimation of the rotor position can be done by sensored and sensorless approaches. In sensored approach, some types of external sensor are attached with the motor, while for sensorless there are no sensors attached to the motor itself.

The problems associated with the cost and reliability of sensors used to detect the rotor position have motivated research in the area of sensorless position detection for BLDC motor drives. In the last decade, many sensorless drive solution has been offered to eliminate the costly and fragile position sensors for BLDC motor. Below are the main sensorless approaches for controlling the BLDC motors.

3.1. Back-EMF technique [2]

When a brushless DC motor starts rotating, the electromotive force (back-EMF) is generated by each winding which opposes the supplied voltage to the windings in accordance with Lenz's law. Back-EMF is directly proportional to the speed of the motor.

The shape of this back-EMF in brushless DC motor is trapezoidal. The direction of the back-EMF is opposite to the applied voltage, so it is harmful in the normal DC motor. But we can use back-EMF in BLDC to detect the information of rotor position by using "the zero crossing". R is the phase resistance. i_a, i_b, i_c are three-phase current. E_a, E_b, E_c are the back-EMF of three-phases. V_n is the motor neutral voltage, V_a, V_b, V_c are the motor terminal voltage.

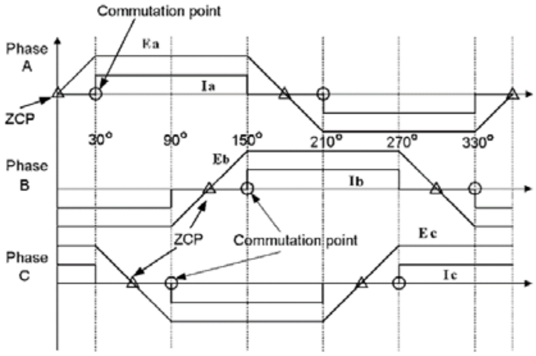


Figure 3. Ideal back-EMF waveforms.

The voltage equations can be written as follows:

$$V_a = Ri_a + L\frac{di_a}{dt} + E_a + V_n \qquad (1)$$

$$V_b = Ri_b + L\frac{di_b}{dt} + E_b + V_n \qquad (2)$$

$$V_c = Ri_c + L\frac{di_c}{dt} + E_c + V_n \qquad (3)$$

Since all three resistors are symmetrical, we have:

$$E_a + E_b + E_c = 0 \qquad (4)$$

And it is obvious that:

$$i_a + i_b + i_c = 0 \qquad (5)$$

At the zero-crossing point of the Back–EMF phase C we have:

$$E_c = \frac{1}{2}V_{dc} \qquad (6)$$

Similarly:

$E_a = \frac{1}{2}V_{dc}$ (at the zero crossing of phase A). (7)

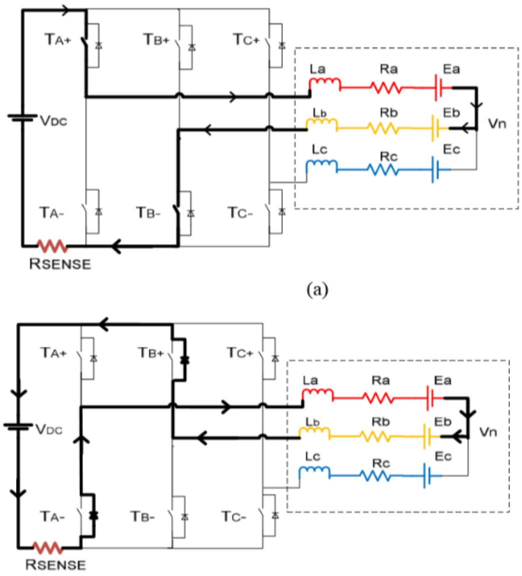
$E_b = \frac{1}{2}V_{dc}$ (at the zero crossing of phase B). (8)

So we can find the zero crossing by feeding the voltage of the un-powered winding with the virtual ground and half the DC bus voltage to comparator.

The Back – EMF sensing is not suitable at the very low speed and at stationary state. So we need a sensorless technique which can control the BLDCM

3.2. Inductance Variation Technique [7]

Three voltage pulses are applied in the rotor position estimation. Voltage pulse injection consists of two intervals: pulse injecting interval and freewheeling interval.



(a)

(b)

Figure 4. Pulse injecting interval (a) and freewheeling interval (b).

This technique consists of two process:

Inductance comparison process:
Two voltage pulses are injected to phases A, B and phases A, C. Based on the mathematical model of BLDCM:

$$V = Ri + L\frac{di}{dt} + e \qquad (9)$$

And *e* = *0* when motor standstill or rotating in low speed, we have:

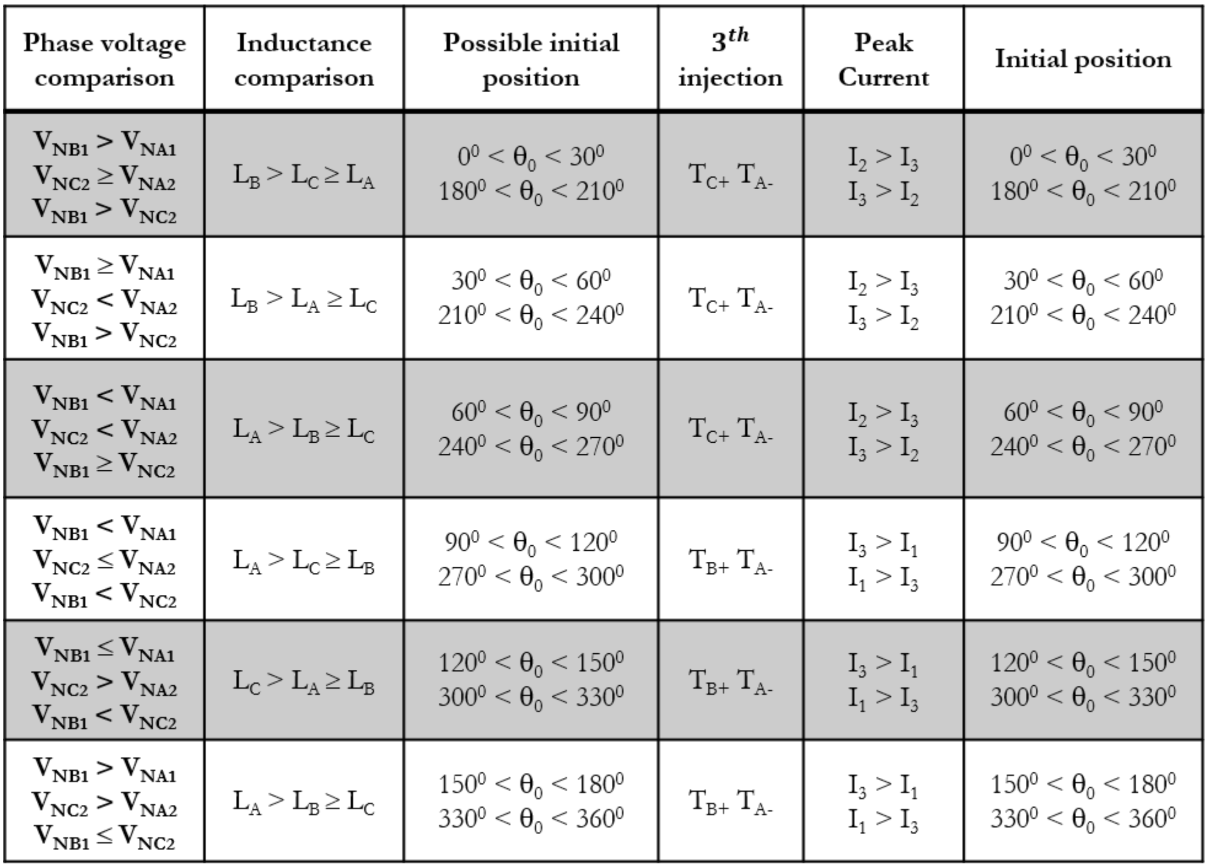
$$V = Ri + L\frac{di}{dt} \qquad (10)$$

$$V \sim L \text{ or } V \sim f(\theta) \qquad (11)$$

With θ is the initial rotor position.

Because *R* is constant and *i* in each phase is same so the:

Polarity determination process [5]:
The third voltage pulse is injected, the direction is based on the initial rotor position (look up column 4 on the Table 1).
The north and south poles of the rotor magnet can be determined from the idea that the winding currents from the injected pulse voltages can further increase or decrease the stator saturation. With this ideal, the sector where the north pole locates can be discriminated.



Phase voltage comparison	Inductance comparison	Possible initial position	3^{th} injection	Peak Current	Initial position
$V_{NB1} > V_{NA1}$ $V_{NC2} \geq V_{NA2}$ $V_{NB1} > V_{NC2}$	$L_B > L_C \geq L_A$	$0^0 < \theta_0 < 30^0$ $180^0 < \theta_0 < 210^0$	$T_{C+}\ T_{A-}$	$I_2 > I_3$ $I_3 > I_2$	$0^0 < \theta_0 < 30^0$ $180^0 < \theta_0 < 210^0$
$V_{NB1} \geq V_{NA1}$ $V_{NC2} < V_{NA2}$ $V_{NB1} > V_{NC2}$	$L_B > L_A \geq L_C$	$30^0 < \theta_0 < 60^0$ $210^0 < \theta_0 < 240^0$	$T_{C+}\ T_{A-}$	$I_2 > I_3$ $I_3 > I_2$	$30^0 < \theta_0 < 60^0$ $210^0 < \theta_0 < 240^0$
$V_{NB1} < V_{NA1}$ $V_{NC2} < V_{NA2}$ $V_{NB1} \geq V_{NC2}$	$L_A > L_B \geq L_C$	$60^0 < \theta_0 < 90^0$ $240^0 < \theta_0 < 270^0$	$T_{C+}\ T_{A-}$	$I_2 > I_3$ $I_3 > I_2$	$60^0 < \theta_0 < 90^0$ $240^0 < \theta_0 < 270^0$
$V_{NB1} < V_{NA1}$ $V_{NC2} \leq V_{NA2}$ $V_{NB1} < V_{NC2}$	$L_A > L_C \geq L_B$	$90^0 < \theta_0 < 120^0$ $270^0 < \theta_0 < 300^0$	$T_{B+}\ T_{A-}$	$I_3 > I_1$ $I_1 > I_3$	$90^0 < \theta_0 < 120^0$ $270^0 < \theta_0 < 300^0$
$V_{NB1} \leq V_{NA1}$ $V_{NC2} > V_{NA2}$ $V_{NB1} < V_{NC2}$	$L_C > L_A \geq L_B$	$120^0 < \theta_0 < 150^0$ $300^0 < \theta_0 < 330^0$	$T_{B+}\ T_{A-}$	$I_3 > I_1$ $I_1 > I_3$	$120^0 < \theta_0 < 150^0$ $300^0 < \theta_0 < 330^0$
$V_{NB1} > V_{NA1}$ $V_{NC2} > V_{NA2}$ $V_{NB1} \leq V_{NC2}$	$L_A > L_B \geq L_C$	$150^0 < \theta_0 < 180^0$ $330^0 < \theta_0 < 360^0$	$T_{B+}\ T_{A-}$	$I_3 > I_1$ $I_1 > I_3$	$150^0 < \theta_0 < 180^0$ $330^0 < \theta_0 < 360^0$

Table 1. Comparison table of position determination

4. Simulation and Experiment Results

4.1. Simulation results

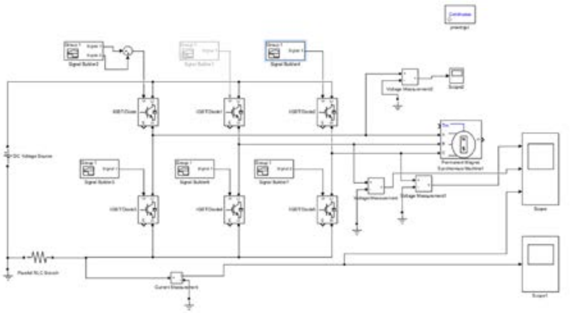


Figure 5. BLDCM Driver in Matlab/Simulink

In order to verify the proposed methods, a simulation is carried out by using Matlab/Simulink software. The parameter of simulation is synthesized in Table 1. The Simulink model is described in Figure 5.

Parameters	**Value**
Polarity poles	4
DC source	25V
Inductance of stator (L)	0.2H
Reluctance of stator (R)	2.8Ω

Table 2. Parameters of BLDCM in simulation

The shape of Back-EMF in the motor is trapezoidal as shown in Figure 6. The Back-EMF detection is made in the floating phase, and the power of detecting circuit is directly supplied by the power unit of driver system.

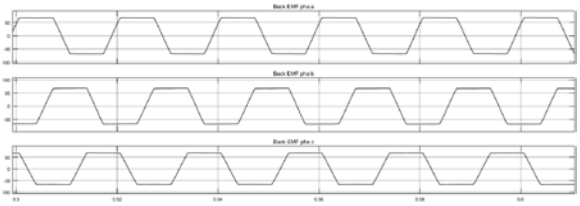


Figure 6. Simulation Back EMF in three-phase

Effectiveness of the method is validated from simulation results. The simulation had been done in Matlab/Simulink platform. The validity of this method is verified by conducting the simulation for $\theta = 35^0$ and $\theta = 280^0$ by adjusting the motor model in simulink. In case of $\theta = 35^0$ after two pulses voltage are injected, we have $V_{NA2} < V_{NC2}$ and $V_{NB1} > V_{NC2}$.

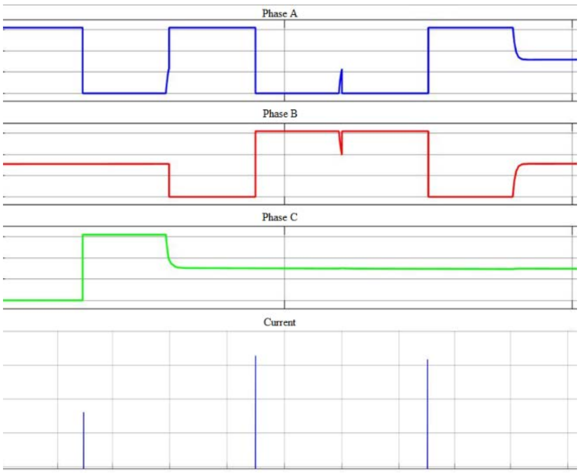


Figure 7. Phase voltage and DC-link current at 35^0

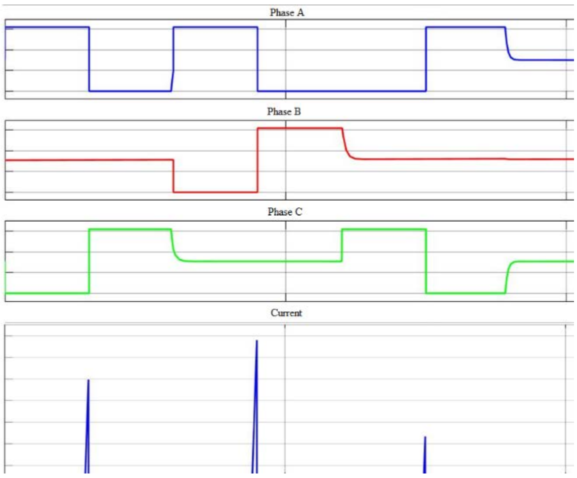


Figure 8. Phase voltage and DC-link current at 280^0

From Table 1, it is clear that the direction of the third pulse voltage is turn on switches T_{C+} and T_{A-} and also the current comparison is between I_2 and I_3. Because $I_2 > I_3$ so the estimated initial rotor position is $30^0 < \theta < 60^0$. Similarly, we also have $V_{NA2} > V_{NC2}$; $V_{NB1} < V_{NC2}$ so the estimated initial rotor position can be between $90^0 < \theta < 120^0$ or between $270^0 < \theta < 300^0$. But the DC- link current, which is measured for the rotor position $\theta = 280^0$, shown that $I_3 < I_1$. Hence from the table 1, it is clear that the rotor position is at sector $270^0 < \theta < 300^0$.

4.2. Experiment results

In order to validate the claims made in the proposed approach, the targeted experimental setup was used to implement the proposed method.

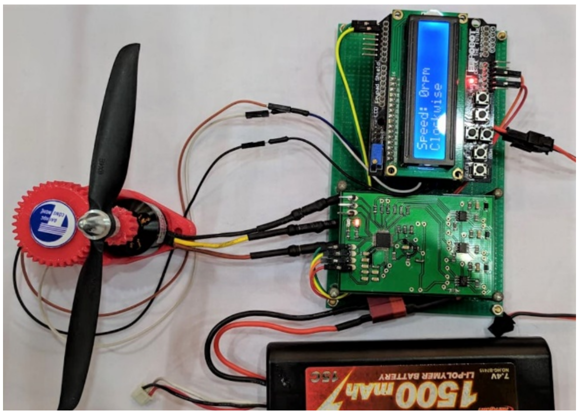


Figure 9. BLDCM Control scheme

BLDCM drive control board includes:

- 6 step control.
- Four-layer PCB.
- IPC-2221 Generic Standard on Printed Board Design.
- STM32F103 microcontroller with RTOS.
- INA214 current-sense amplifiers.
- The phase voltage is measured using ADC pin of the microcontroller.
- 6x IRF7828 power MOSFET.
- UART and CAN communication bus

The proposed method is verified with several tested speed ranging from low to medium (20rpm, 60rpm and 200rpm). Phase voltage, DC-link current and back-EMF waveforms of BLDCM in experiment is same as these in the simulation. The results show that the proposed method can be applied in the real application.

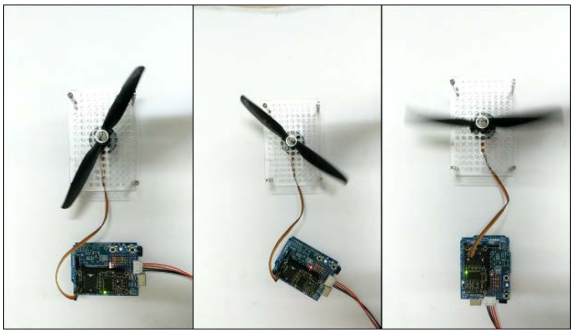


Figure 10. Test at three speed 20rpm, 60rpm and 200rpm.

5. Conclusion

The research studies how to drive a BLDCM smoothly from standstill to high speeds without position or speed sensors is carried out, using one and the only current sensor. Its applications is decreasing the cost of a BLDCM attached system.

This study mainly focuses on rotor position of the BLDCM without controlling the motor moment which might be discussed in another study in the future.

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