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Advanced Sensorless Control of Brushless DC Motor using Terminal Voltage Sensing Method

E.Sumathi[1*], M. Santhosh Sheela[2] and B.Arunkumar[3]

[1*,2,3] *Department of EEE, V.R.S. College of Engineering and Technology, India*

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***Abstract*—** Brushless DC (BLDC) motor drives are popularly used in both consumer and industrial applications owing to its compact size, controllability and efficiency. BLDC motor is usually operated with one or more rotor position sensors, since the electrical excitation must be synchronous to the rotor position. To reduce cost and complexity and also to improve reliability of the drive system, sensorless drive is preferred. This paper presents the development of sensorless control system for brushless DC motor using terminal voltage sensing method without using any position sensors such as hall sensors or encoders. The simulation for proposed system is done using MATLAB.

***Keywords*—** Brushless DC sensorless control, Terminal Voltage Sensing, Low Pass Filter and Comparator

I. INTRODUCTION

BLDC motors are very popular and are replacing brush motors in numerous applications due to their high efficiency, high power density and large torque to inertia ratio. Brushless DC (BLDC) motor is inherently electronically controlled, and requires rotor position information for the proper commutation of the current, this information can be obtained using hall sensors mounted on a rotor. This results in a high costs as well as poor reliability.

During last two decades, numerous researches on sensorless control approaches for BLDC motor have been conducted. In order to obtain an accurate and ripple-free instantaneous torque of BLDC motor, the rotor position information for stator current commutation must be known, which can be obtained using hall sensors mounted on a rotor [1,2]. This results in a high costs as well as poor reliability. To cope with the above mentioned restriction, many position sensorless algorithms have been considered as potential solutions. The zero-crossing of the back-EMF measured from the stator winding is detected and the commutation points can be estimated by shifting 30° from the zero crossing of the back-EMFs [3].

The performance of the sensorless drive deteriorates with the phase shifter in the transient state. Also, it is sensitive to the phase delay of the low pass filter (LPF) especially at high speed [4,5]. Several phase shifters are used to compensate for phase error induced by the LPF of back-EMFs are proposed [7]. They require an additional compensation circuit including timers.

The third harmonic back-EMF and phase-locked loop for BLDC motor are proposed [11]. The commutation drifts of the motor are away from the required phase angle owing to the transmission of the freewheel diode. As well, the drift angle and speed changes according to the motor factors and load conditions. Access to the motor neutral point is mandatory, that will make difficult the motor design and increase the cost of overall system.

Most of the sensorless speed control techniques are based on the back-EMF evaluation [12]. However, when a motor is at stand still or very low speed, it is well known that the back-EMF is too low to detect the specific rotor position. Therefore, a specific start-up method in sensorless drive system is needed [13]. The common answer to the problem of open-loop start-up technique called open loop *I-f* starting method, where the current is specified and maintained constant during accelerating the motor, is proposed at the back-EMF based sensorless control of a permanent magnet synchronous motor.

Some drawbacks of the above mentioned sensorless and open loop start-up technique are not applicable to some applications, which require the good reliability and various speed ranges with the high starting torque for the sensorless BLDC motor drive systems. To satisfy these requirements, this paper proposes a sensorless speed control using terminal voltage sensing with comparator and zero cross detection technique in BLDC motor. The terminal voltages can be used to detect the commutation points of the BLDC Motor instead of using the back-EMFs. The *v/f* starting method is used in this paper, which is suitable for the BLDC motor.

II. MODELLING AND SENSORLESS CONTROL PRINCIPLES OF BLDC MOTOR

A three-phase brushless DC motor has three phase stator windings and is driven by an inverter. Following sections gives mathematical modeling with equivalent circuit of BLDC motor and working principle.

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A. Mathematical Modeling of BLDC Motor

BLDC motor is the kind of permanent magnet motor. The modeling of BLDC motor is similar to three-phase synchronous machine modeling. The model is developed, in which the permanent magnet enclosed with the rotor and it contains different dynamic characteristics. Figure 1 shows the equivalent circuit of a star connected BLDC motor and the Inverter topology. The BLDC motor is fed to a three-phase voltage source through inverter, which is not necessary to be sinusoidal or square wave can be applied.

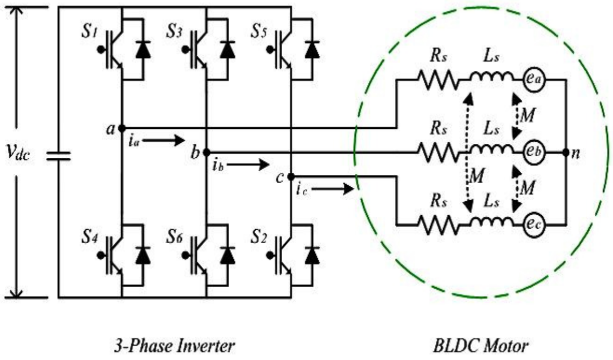

Figure 1. Three Phase Inverter and Equivalent circuit of star connected BLDC Motor

The modeling of BLDC motor drive system is based on the following assumptions

I. The motor is not saturated
II. All the stator phase windings have equal resistance per phase and constant self and mutual inductances.
III. Power semiconductor devices are ideal.
IV. Iron losses are negligible and the motor is unsaturated.

Based on the above assumptions the three phase input voltages are expressed as follows

$$V_a = Ri_a + Ldi_a/dt + e_a \quad (1)$$

$$V_b = Ri_b + Ldi_b/dt + e_b \quad (2)$$

$$V_c = Ri_c + Ldi_c/dt + e_c \quad (3)$$

Where
L is armature self inductance [H],
R is armature resistance [Ω],
V_a , V_b , V_c are terminal phase voltage [V],
i_a, i_b, i_c are motor input current [A], and e_a, e_b, e_c are motor back-EMF [V].

Back-EMF equation of each phase

$$e_a = K_e f_a(\theta_e)\, \omega \quad (4)$$

$$e_b = K_e f_b(\theta_e - 2\pi/3)\, \omega \quad (5)$$

$$e_c = K_e f_c(\theta_e + 2\pi/3)\, \omega \quad (6)$$

where
K_e is back-EMF constant of one phase [V/rad.s^{-1}],
θ_e is electrical rotor angle [° el.],
ω is rotor speed [rad.s^{-1}].

The electromagnetic torque is expressed as

$$T_e = (e_a i_a + e_b i_b + e_c i_c) / \omega \quad (7)$$

where
T_e is total torque output [Nm],

Also,

$$T_e = J\, d\omega_m/dt + B\, \omega_m + T_L \quad (8)$$

where
T_L is Load torque [Nm],
J is Inertia of rotor and coupled shaft [kgm^2],
B is Friction constant [Nms.rad^{-1}]

B. Principle of Sensorless Control of BLDC Motor

The BLDC motor is also referred to as an electronically commuted motor and, as there are no brushes on the rotor and the commutation is performed electronically depending on the rotor position. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. The rotor is made up of permanent magnet and can vary from two poles to eight poles with alternate North and South poles. Rotor position is sensed using the Hall sensors which are embedded into the stator on the non driving end of the motor. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the North or South pole is passing near the sensors. Based on the combination of these three hall sensor signals, the exact sequence of commutation can be determined.

BLDC motor drives that do not require position sensors but it contains electrical dimensions are called a sensorless drive. The BLDC motor provides sensorless operation based on the nature of its excitation intrinsically suggest a low-cost way to take out rotor position information from motor-terminal voltages. In the excitation of a three-phase BLDC motor, apart from the phase commutation periods, two of the three phase windings are functioning at a time and no conducting phase carries the back-EMF. The advantage of sensorless drives comprises of less hardware cost, increased system reliability, decreased system size and reduced feedback units. And also they are free from mechanical and environmental constraints.

Among various sensorless control methods the zero-crossing detection of back-EMF is the easiest method and it is based on finding the instantaneous at which unexcited phase crosses zero due to back-EMF.

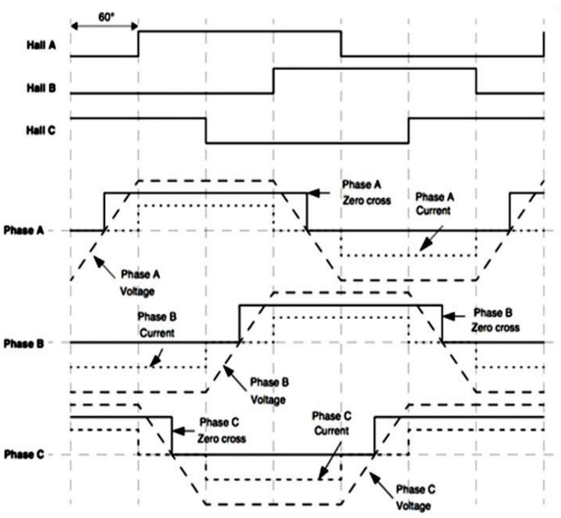

Figure 2. Waveforms of back-EMF and phase current

In BLDC motor for its distinctive operation, the back-EMF and phase current should be associated to generate constant torque. As a result the interval for every phase of a BLDC motor is conducted at 120 electrical degrees. Hence, in BLDC motor only two phases conduct current at whichever time. The third phase is called floating phase. In order to produce greatest torque, the inverter is to be commutated at every 60° by calculating zero crossing of back-EMF on the floating phase of the motor, therefore the current is in phase with the back-EMF.

III. PROPOSED SENSORLESS CONTROL USING TERMINAL VOLTAGE SENSING

A. Terminal Voltage Sensing

The Hysteresis comparator with zero cross detection technique is achieved by sensing the terminal voltage. Figure.3 shows the block diagram of a sensorless control by using terminal voltage method. It consists of the Low Pass Filters (LPFs) for suppressing the high switching frequency ripples and comparators for compensating phase lag of terminal voltage if occurred at high speed. Motor neutral point voltage information is not used in this method. After sensing the three-phase terminal voltages, each of the three phase terminal voltages is fed into an LPF to suppress the high switching frequency ripple or noise. As only two phases of the BLDC motor are energized at any time, the back-EMF can be measured from its terminal voltage in the period of an open phase (60°). During the two phase conduction period (120°), the only difference between the back-EMF and its terminal voltage is a stator impedance voltage drop, which may be considerably small as compared with the dc voltage source. Therefore, the waveform of the terminal voltage is nearly the same as that of the back-EMF. The terminal voltages can be used to detect the commutation points of the BLDC motor instead of the back-EMFs.

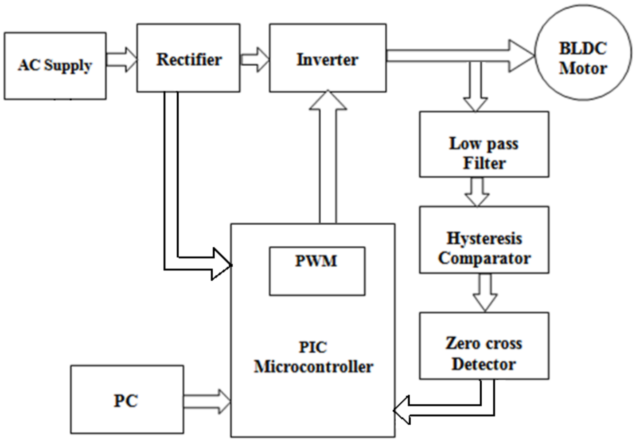

Figure 3. Block diagram of proposed sensorless control scheme

B. Low Pass Filter (LPF)

Each of the three phase terminal voltages is fed into an LPF to suppress the high switching frequency ripple or noise. Hence there are three low-pass filters (LPFs) are utilized to eliminate higher harmonics in the phase terminal voltages caused by the inverter switching.

C. Hysteresis Comparator with Zero Cross Detection

The hysteresis comparator is used to compensate for the phase lag of the back-EMFs due to the LPF in order to determine the proper commutation sequence of the inverter according to the rotor position. Also, it can prevent multiple output transitions by high frequency ripples in the terminal voltages. There are three hysteresis comparators are used, each terminal voltage output from LPF are fed into comparator.

As the rotor speed increases, the percentage contribution of the phase lag to the overall period increases. The lag will disturb current alignment with the back-EMF and will cause serious problems for commutation at high speed. The phase lag in commutation can produce significant pulsating torques in such drive which may cause oscillations of the rotor speed, and generate extra copper losses. The output of hysteresis comparator is fed into zero cross detector.

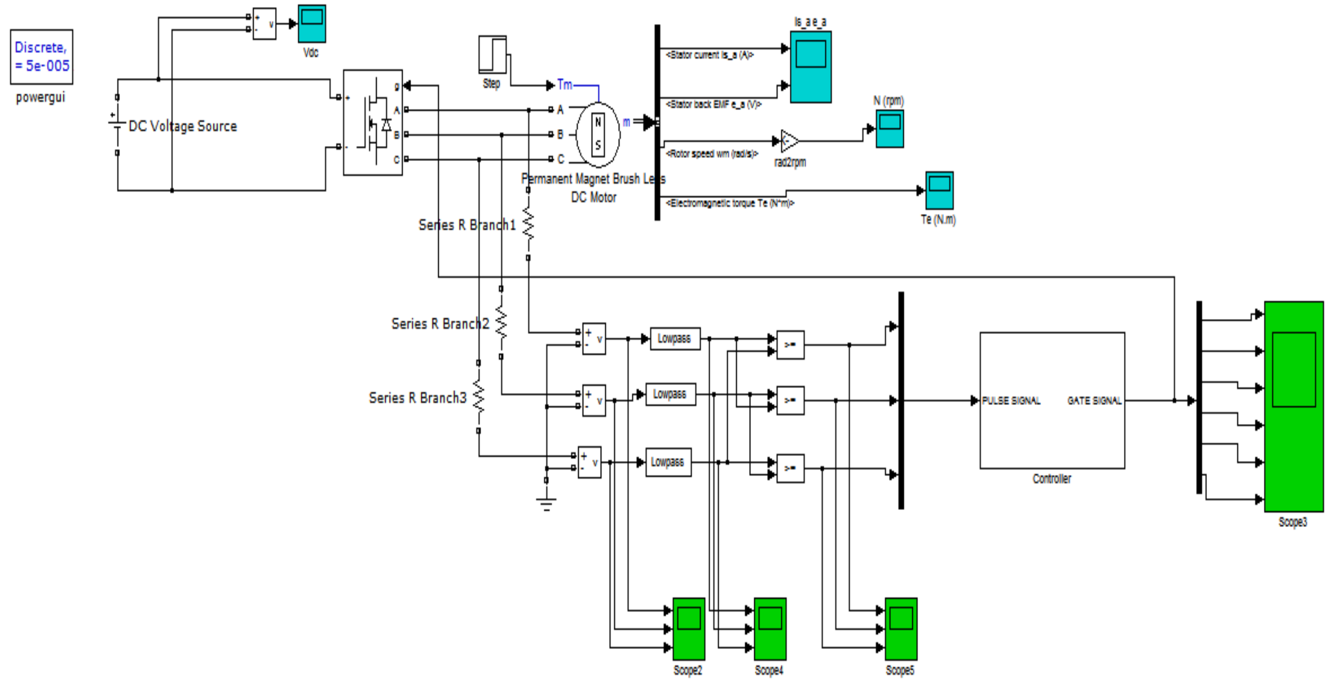

Figure 4. MATLAB/SIMULINK Model for sensorless control of BLDC Motor

The outputs from the three-phase hysteresis comparators become three commutation signals, and then six gating signals called six step PWM signals can be generated by PWM technique.

According to the falling and rising edge of commutating signals inverter switches are controlled and other commutating instances are obtained. The gating signals generated from every commutating instants from hysteresis comparator. By properly choosing the PWM and sensing, the true phase back-EMF signal could be directly obtained from the motor terminal voltage without using motor neutral point voltage information.

III. SIMULATION AND RESULTS

The MATLAB/SIMULINK model for the sensorless control of BLDC motor is shown in figure 4. A three phase star connected BLDC motor with six step commutation is used for the analysis. Permanent Magnet Synchronous motor with trapezoidal back-EMF is modeled as a Brushless DC Motor. The closed loop controller for a three phase brushless DC motor is modeled using MATLAB/SIMULINK. Figure 5 and 6 shows simulated output of stator back-EMF and phase current. Figure 7 and 8 shows zero crossing output and Rotor speed

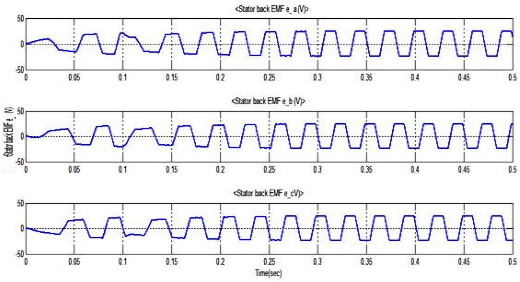

Figure 5. Stator Back-EMF wave form

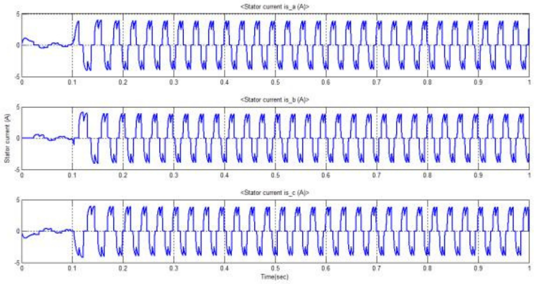

Figure 6. Stator current waveform

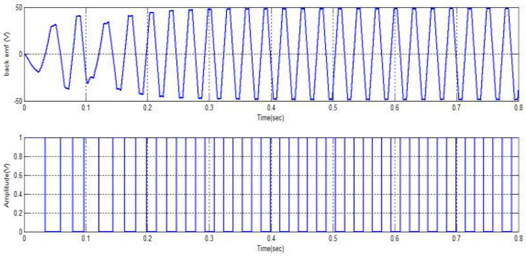

Figure 7. Zero crossing output

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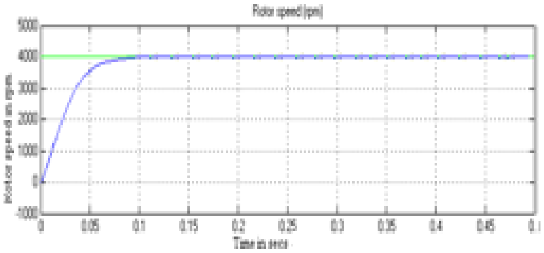

Figure 8. Rotor Speed

IV. CONCLUSION

This paper presents the simulation of sensorless control of BLDC motor using terminal voltage sensing method. In order to reduce the cost of BLDC motor drive and also to improve the reliability of the drive, Hall sensors are removed in this implementation. The performance of the drive is further improved by use of LPF and hysteresis comparator, which suppress high frequency switching noise and also prevent output transitions due to harmonics. MATLAB/SIMULINK is used for simulation modeling and simulation results were observed.

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AUTHORS PROFILE

E. Sumathi was born in Tamilnadu, India in 1989. She received her B.E degree in Electrical and Electronics Engineering from V.R.S college of Engineering & Technology, Anna University, Chennai, India in 2010. She is pursuing her M.E degree in Embedded System Technologies from V.R.S college of Engineering & Technology, Anna University, Chennai. Her area of interest includes Embedded system and Embedded control of Electrical Machines.

M. Santhosh Sheela was born in Tamilnadu, India in 1988. She received her B.E degree in Electronics and Communication Engineering from Dhanalakshmi Engineering College, Anna University, Chennai, India in 2009. She is pursuing her M.E degree in Embedded System Technologies from V.R.S college of Engineering & Technology, Anna University, Chennai. Her area of interest includes Embedded system, Embedded system controllers and Embedded system security using cryptography.

B. Arun Kumar has received his B.E (Electronics and communication) degree from Pallavan college of Engineering, Anna University, Chennai, India, in 2009 and his M.E (Embedded and Real time system) degree from PSG college of Technology, Coimbatore, India, in 2011. In 2011, he joined the Department of Electrical and Electronic Engineering, V.R.S college of Engineering & Technology, as an Assistant Professor. His area of interest includes Embedded system, Microprocessors and ARM Microcontroller.