

# State Space Modeling and Simulation and Analysis of Sensor-less BLDC motor Using MATLAB/SIMULINK

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**Abstract-** This paper represents sensorless state space model of BLDC motor. The BLDC is modeled as sub-blocks and these blocks are either logical or S-function blocks. The BLDC main block is designed using state space model. The Zero cross detection control technique of back-emf is used for commutation of power switching device in 3 phase inverter. Modeling is done using MATLAB/SIMULINK and no built in Simpower system tool box is used. Motor's speed is controlled with PID controller and for current control, hysteresis current controller is used. By reading instantaneous position of the rotor as a one of the output of the state space model, different variables of the motor can be controlled without any external sensors hence motor is operating as sensorless.

**Index Terms-** BLDC, Sensorless, Back-emf, State Space Model, Zero Cross detection.

## I INTRODUCTION

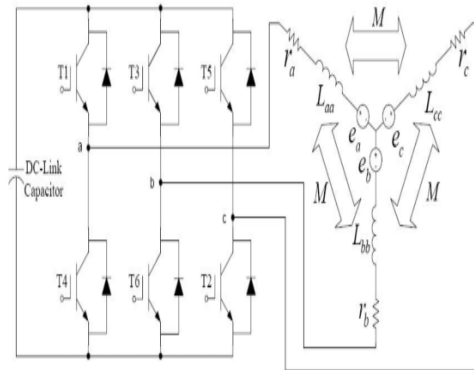
The PMLBDC motors are normally powered by conventional three phase inverter, controlled by the rotor position information obtained from hall sensors. But these position sensors have numerous drawbacks like increase in cost, complexity in control, temperatures sensitivity requiring special arrangements. These sensors reduce the system reliability and acceptability.

The sensorless technique used in this paper is based on sensing the back-emf. In PMLBDC motors, only two out of Three Phases are excited at any time leaving the third winding floating. The back-emf in the floating winding can be measured to determine the switching sequence for commutation of power switching device in the 3 phase inverter. The terminal voltage of the floating winding back-emf with respect to neutral point of the motor is needed to get the zero crossing time of the back-emf. The sensorless technique Based on zero cross detection of back emf has been widely used. In the ZCP method the back-emf cannot be obtained when the BLDC is operating nearly zero speed. Therefore special starting control is needed for smooth starting and reliable transfer to sensorless control. In this paper a MATLAB[1]/SIMULINK model of the PMLBDC motor suitable for sensor less operation is developed. Using this model the dynamic behavior of the motor with sensorless technique is studied.

## II MODELLING OF PMLBDC MOTOR

The modeling is based on the following assumptions:

- (1) The motor is not saturated.
- (2) Stator resistances of all windings are equal and self and mutual inductances are constant.
- (3) Power semiconductor devices in the inverter are ideal.
- (4) Iron Losses are negligible. The voltage equation of a BLDC motor can be expressed as:



**Figure 1: Basic PMLBDC Motor Drive Scheme**

The Voltage equation of a BLDC motor can be expressed as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R \begin{bmatrix} I_a(t) \\ I_b(t) \\ I_c(t) \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} I_a(t) \\ I_b(t) \\ I_c(t) \end{bmatrix} + \begin{bmatrix} e_a(t) \\ e_b(t) \\ e_c(t) \end{bmatrix} \quad (1)$$

Where  $V_a, V_b, V_c$  are the stator phase voltages;  $R$  is the stator resistance per phase;  $I_a, I_b, I_c$  are the stator phase currents;  $e_a, e_b, e_c$  are the back electromotive forces. Back-emf equation of each phase is given below. Back-emf of the BLDC motor is trapezoidal in nature and is function of speed  $\omega$  and position  $\theta$  with a peak value of  $E_p$ . The instantaneous induced emfs can be expressed as,

$$e_a = f_a(\theta) \lambda \omega \quad (2)$$

$$e_b = f_b(\theta) \lambda \omega \quad (3)$$

$$e_c = f_c(\theta) \lambda \omega \quad (4)$$

The peak value,  $E_p$  is derived as,

$$E_p = (B l v) N = N (B l r \omega) = N \phi \omega = \lambda \omega \quad (5)$$

N is number of turns per phase, B is flux density of the field, l is gathered in above steps by adopting any of below suitable approaches: N is number of turns per phase is flux density of the field ,l is length of rotor,v is velocity,r is radius of rotor bore, ω is angular speed in rad/sec , φ is flux linkage=(Blr) , λ represent the total flux linkage as the product of number of turns and flux linkage/conductor.

Total Torque output can be represented as summation of each phase

$$T_e = \frac{e_a I_a + e_b I_b + e_c I_c}{\omega} \quad (6)$$

Where  $T_e$  is total torque output[Nm]  
Also

$$T_e = J \frac{d\omega_m}{dt} + B \omega_m + T_L \quad (7)$$

Where  $T_L$ =load torque[Nm], J= inertia of rotor and coupled shaft[kgm<sup>2</sup>], B is Friction constant.

The rotor speed and its position are related as follows:

$$\frac{d\theta}{dt} = \frac{p}{2} \omega \quad (8)$$

where p is number of machine poles.

### III State Space Modeling

The general equations for state space modeling are:

$$\dot{X} = Ax + Bu \quad (9)$$

$$Y = Cx + Du \quad (10)$$

Where state vector  $x = [I_a \quad I_b \quad I_c \quad \omega \quad \theta]^T$   
(11)

$$u = [V_{an} \quad V_{bn} \quad V_{cn} \quad T_L]^T \quad (12)$$

The Matrix A,B are given as:

$$A = \begin{bmatrix} -\frac{R}{L} & 0 & 0 & \frac{f_a(\theta)\lambda}{L} & 0 \\ 0 & -\frac{R}{L} & 0 & \frac{f_b(\theta)\lambda}{L} & 0 \\ 0 & 0 & -\frac{R}{L} & \frac{f_c(\theta)\lambda}{L} & 0 \\ \frac{f_a(\theta)\lambda}{J} & \frac{f_b(\theta)\lambda}{J} & \frac{f_c(\theta)\lambda}{J} & -\frac{B}{J} & 0 \\ 0 & 0 & 0 & \frac{P}{2} & 0 \end{bmatrix} \quad (13)$$

$$B = \begin{bmatrix} \frac{1}{L} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{L} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{J} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (14)$$

### IV Simulation blocks and operations:

The BLDC control system is divided into isolated function modules. In MATLAB/SIMULINK environment, these function modules are established respectively and then combined effectively to form the integrated simulation model for BLDCM. This Simulink model has several main blocks i.e. BLDC motor block, Reference current block, switching logic block ,Initial control block, Controller block, Inverter block etc.

The BLDC motor block contains state space sub block and S-function sub block.

The reference current controller block starts with calculating the error in speed and uses PID controller to estimate the torque and is calculated by

$$T_{req} = \left[ E \times \left( K_p + (K_i \times 0.5 \times t_s) + \frac{K_d}{t_s} \right) + \left[ E_{-1} \times \left( 0.5 \times t_s \times K_i - \frac{K_d}{t_s} \right) \right] \right] \quad (15)$$

Where E is the angular speed error, E is the previous time step error in angular speed, t is the sampling time,  $K_p, K_i, K_d$  are proportional, integral and derivative constants. The total current command is evaluated from estimated torque. Then it is converted by means of an approximated Park's Transformation to three phase currents. The approximated park's transformation gives the corresponding phase current to every stator phase according to the rotor's position[6].

A Trigger block is used to hold on both the required and instantaneous current values in the open loop. Once the changer block closes the control loop, the Trigger block will give an access to the current values to pass to the present controller scheme. In this simulation, hysteresis controller function is chosen. In hysteresis type control[7]the controller is switched on and off according to whether the current generated is greater or less then reference current. Usually, the controller is used to fire the gates of six step inverter switches, as in [8].

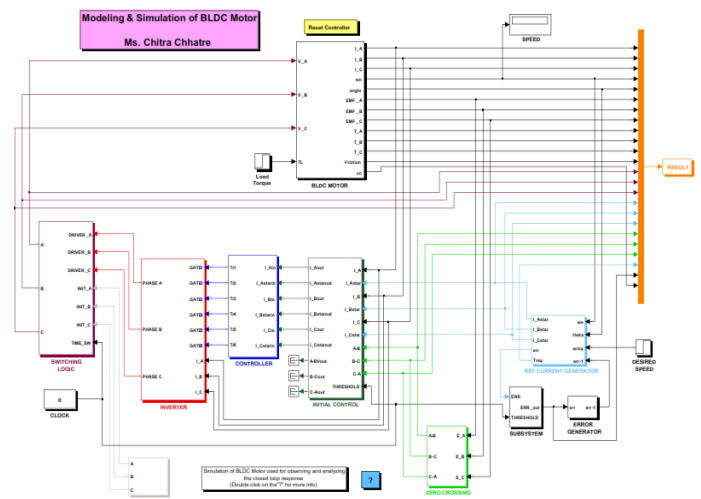
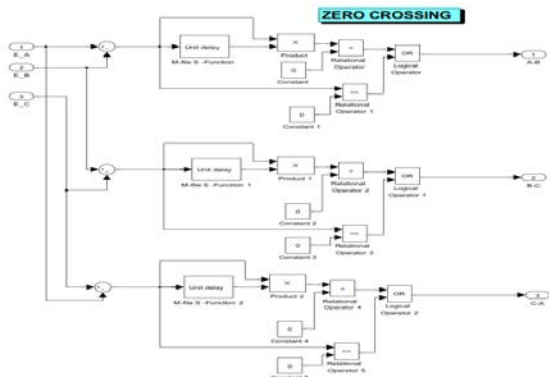


Figure 2:Simulation Model of BLDC motor

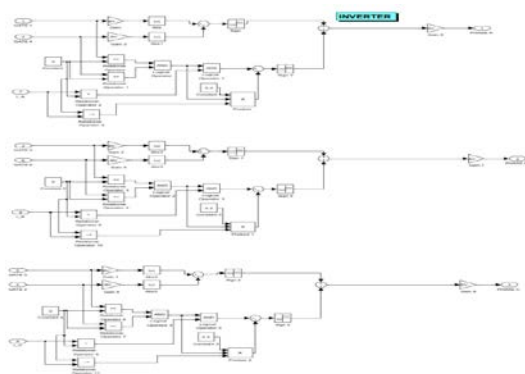
**Zero Crossing Block:**

This block evaluates the zero crossings of BEMF A - BEMF B (A-B), BEMF B - BEMF C (B-C) and BEMF C - BEMF A (C-A). These signals can be used to synchronize the controller or the inverter.



**Figure 3: Inside of Zero Crossing Block**

**Inverter Block:**



**Figure 4: Inside of the inverter Block**

This is a logical version of the power electronics 6 transistor inverter. As the core module BLDC MOTOR.mdl is written as a set of differential equations, the voltages that are impressed upon the module are signals derived from the general sources in SIMULINK. Hence, the inverter block is a completely logical unit.

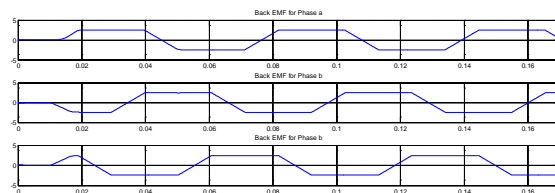
The logic used is straight forward, If the gate of transistor T4 is negative, the phase A is connected to the negative terminal of the voltage source. If however T1 is activated, the phase A is connected to the positive terminal of the voltage source. If however both the transistors are off, then depending upon the sign (i.e. direction) of the current  $I_A$ , the phase A may be connected to either side of the voltage source. This is to simulate freewheeling. If the switches are off and the current is +ve, then the phase A is connected to the -ve side of the voltage source and vice versa. Similar logic is followed for the other legs. THE INPUTS TO THE BLOCK ARE:

- GATE1, GATE2, . . . . . , GATE6 are the logical signals (zero/non-zero) that activate the transistors

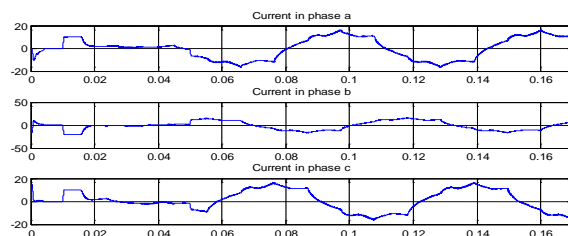
- $I_A$ ,  $I_B$  and  $I_C$  are the values of the phase currents that are required to decide the freewheeling logic. THE OUTPUTS OF THE BLOCK ARE:
- PHASE A, PHASE B and PHASE C are the signal voltages of the respective phases.

**V Simulation Results**

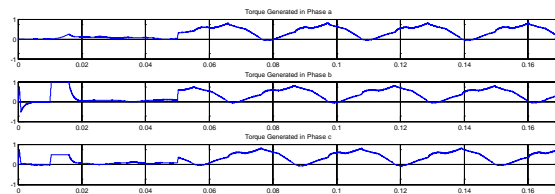
The motor specifications used in this simulation are shown in Table. 1. The simulation was run for 0.17 seconds (simulation time). When the reference speed equals 3600 rpm, the simulation curves of 3 $\Phi$  back emfs (Fig. 5), 3 $\Phi$  currents (Fig. 6), 3 $\Phi$  torques (Fig. 7) and rotor position are shown in, Fig. 9. Load torque is applied at 0.01 seconds. The motor speed stabilizes in 0.058 seconds with 0% overshoot. From Fig. 5 and Fig. 6, the back emf is almost trapezoidal with 120° phase difference.



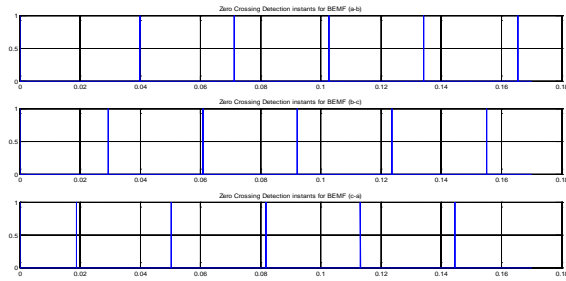
**Figure 5: Back-emf**



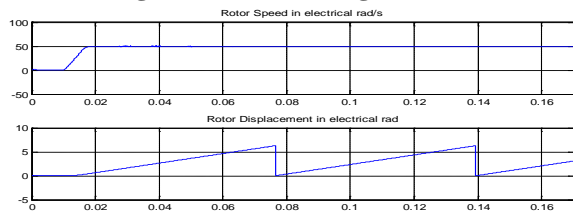
**Figure 6: Phase currents**



**Figure 7: Torque generated**



**Figure 8:Zero crossing instance**



**Figure 9:Rotor speed and Rotor Position**

<b>Current</b>	<b>20A</b>	<b>Rotor length</b>	<b>30cm</b>
<b>Torque</b>	<b>0.45N.m</b>	<b>Rotor radius</b>	<b>20cm</b>
<b>Self-inductance per winding</b>	<b>2.72mH</b>	<b>No.of turns per Phase</b>	<b>120</b>
<b>Mutual inductance</b>	<b>-1.5mH</b>	<b>Flux density</b>	<b>.8167wb</b>
<b>Motor inertia</b>	<b>.0002kg-m<sup>2</sup></b>	<b>Coulomb friction</b>	<b>.0178 N</b>
<b>Rated speed</b>	<b>3600 RPM</b>	<b>Static Friction</b>	<b>.089N</b>
<b>Number of poles</b>	<b>4</b>	<b>Viscous friction</b>	<b>.002N</b>
<b>Number of phases</b>	<b>3</b>	<b>Input dc voltage</b>	<b>160V</b>
<b>Winding resistance per phase</b>	<b>.29Ω</b>	<b>No of slots per pole per phase</b>	<b>120</b>

TABLE I: BLDC MOTOR SPECIFICATIONS

## VI CONCLUSION

In this study MATLAB\SIMULINK based modeling and simulation of the BLDCM is presented, for the specified motor. The simulation results satisfy the theoretical analysis. This model can provide a guide in the modelling of the PMLDC for investigators. State space model, the performance characteristics of the BLDC motor can be evaluated for different machine parameters which can be easily varied in the simulation study and useful information can be obtained. This model has a flexible structure and enables to users to change motor parameters easily.

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