

## MATHEMATICAL MODELLING AND SIMULATION OF THREE PHASE BLDC MOTOR USING MATLAB/SIMULINK

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### ABSTRACT

*The Brushless DC motors are widely used in many industrial and traction applications because of their high efficiency, high torque, low maintenance, less noise and low volume. The BLDC motor can act as an alternative for traditional motors like Brushed DC motor, induction motor, switched reluctance motors etc. The performance of BLDC motor is analysed using Matlab with motor on no load. The various performance parameters are analysed by Matlab software. The torque characteristics of BLDC motor is very important factor in designing BLDC motor drive system. After development of simple mathematical model of three phase BLDC motor with trapezoidal waveforms of back emf, the motor is modelled by using MATLAB/SIMULINK. The speed, phase current, back emf waveforms are also obtained using this model. In the presented model speed is regulated by PI controller. In this paper the simulation is carried out for 1200 mode of operation and Trapezoidal back emf waveforms are considered. The results obtained using Matlab software are highly acceptable and this gives very important information for designing BLDC motor drive system.*

**KEYWORDS:** Brushless DC motor, Electro motive force, 1200 mode of operation, PI controller.

### I. INTRODUCTION

Conventional DC motors have many properties such as high efficiency and linear torque-speed characteristics. The control of DC motor is also simple and does not require much complex hardware. However, the main drawback of the dc motor is the need of periodic maintenance. The Brushes of the mechanical commutator eventually wear out and need to be replaced. The mechanical commutator has other undesirable effects such as sparks, acoustic noise and carbon particles coming from the brushes. 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 (BLDC) motors have been widely used in many applications. BLDC Motor have many advantages over conventional DC motors like: Long operating life, High dynamic response, High efficiency, Better Speed vs. Torque characteristic, Noiseless operation, Higher speed range and Higher Torque-Weight ratio. Due to high power to weight ratio, high torque, good dynamic control for variable speed applications, absence of brushes and commutator make Brushless DC (BLDC) motor [1], best choice for high performance applications. Due to the absence of brushes and commutator there is no Problem of mechanical wear of the moving parts [2], [3]. As well, better heat dissipation property and ability to operate at high speeds [4-5] make them superior to the conventional dc machine. However, the BLDC motor constitutes a more difficult problem than its brushed counterpart in terms of modelling and control system design due to its multi-input nature and coupled nonlinear dynamics. Due to the simplicity in their control, Permanent-magnet brushless dc motors are more accepted and used in high-performance applications. In many of these applications, the production of ripple-free torque is of primary concern. There are three main sources of torque production in BLDC motor. [6-11]

A BLDC Motor is a permanent magnet synchronous motor that uses position detectors and an inverter to control the armature currents. Its armature is in the stator and the magnets are on the rotor and its operating characteristic resembles those of a DC motor [1]. Instead of using a mechanical commutator as in the conventional DC Motor [2-3], the BLDC motor employs electronic commutation which makes it a virtually maintenance free. The BLDC motor is driven by DC voltage but current commutation is done by solid-state switches. The commutation instants are determined by the rotor position and the position of the rotor is determined either by position sensors like Hall sensor, position encoder and resolver etc [1].or by sensorless techniques. There are two main types of BLDC Motors: Trapezoidal type and Sinusoidal type. The trapezoidal motor is a more attractive alternative for most applications due to its simplicity, lower price and higher efficiency. Here State-Space based trapezoidal back emf motor has been taken for modelling and simulation in MATLAB\SIMULINK [11].

This paper explains introduction and principle of operation of the BLDC motor is explained. Mathematical modelling of three phase BLDC motor is presented and motor performance analysis of BLDC motor such as speed/torque, input power, input current, efficiency etc. This paper also includes the characteristics which have been drawn between load torque, current, back emf, speed etc. using MATLAB package. Finally conclusion, future scope and references are added at the end.

## II. PRINCIPLE OF OPERATION

The three phase BLDC motor is operated in a two phase-ON fashion, i.e. the two phases that produce the highest torque are energized while third phase is off. Which two phases are energized depend on rotor position. The signals from the position sensors produce a three digit number that changes every  $60^\circ$  (electrical degrees) as shown in figure2 below.(H1,H2,H3). The figure also shows ideal current and back emf waveforms [1]

Figure1 shows cross sectional view of three phase star connected BLDC motor along with its phase energizing sequence. Each interval starts with the rotor and stator fields' line  $120^\circ$  apart and ends when they are  $60^\circ$  apart. Maximum torque is reached when the field lines are perpendicular. Current commutation is done by six-step inverter as shown in a simplified form in figure3. The switches are shown as bipolar junction transistors but MOSFET switches are most common. Table1 shows the switching sequence, the current direction and the position sensor signals.

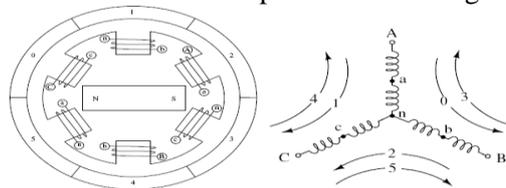


Fig.1:BLDC cross section and phase energizing sequence.

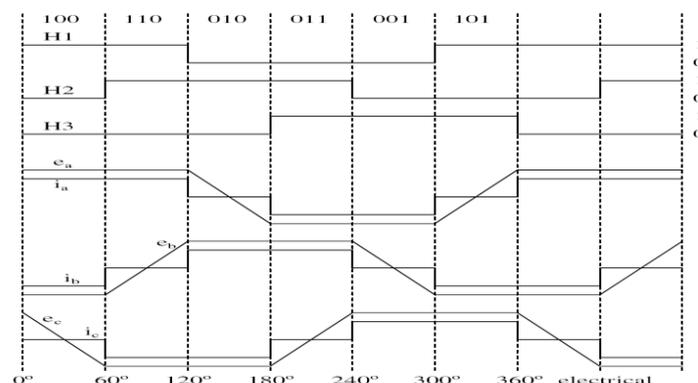


Fig.2: Back emf, phase current and rotor position.

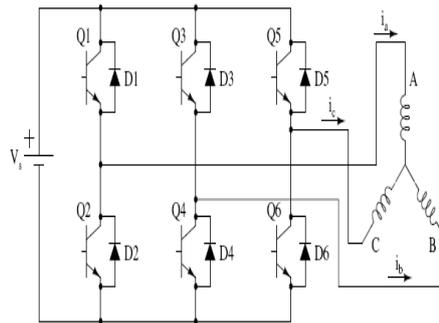


Fig 3: Simplified BLDC drive scheme.

Table.1: Switching Sequence.

| Switching Interval In Degree | Sequence Number | Pos. Sensors |   |    | Switch Closed |    | Phase current |     |     |
|------------------------------|-----------------|--------------|---|----|---------------|----|---------------|-----|-----|
|                              |                 | H1           | H | H3 |               |    | A             | B   | C   |
| 0-60                         | 0               | 1            | 0 | 0  | Q1            | Q4 | +             | -   | Off |
| 60-120                       | 1               | 1            | 1 | 0  | Q1            | Q6 | +             | Off |     |
| 120-180                      | 2               | 0            | 1 | 0  | Q3            | Q6 | off           | +   | -   |
| 180-240                      | 3               | 0            | 1 | 1  | Q3            | Q2 | -             | +   | Off |
| 240-300                      | 4               | 0            | 0 | 1  | Q5            | Q2 | -             | Off | +   |
| 300-360                      | 5               | 1            | 0 | 1  | Q5            | Q4 | off           | -   | +   |

### III. MATHEMATICAL MODELLING

The BLDCM has three stator windings and a permanent magnet rotor on the rotor. Rotor induced currents can be neglected due to the high resistivity of both magnets and stainless steel. No damper winding are modelled. The motor is fed from three phase voltage source, the modelled equations for three armature windings [12] in phase variables are as follows.

$$\begin{bmatrix} V_{ac} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_a & 0 \\ 0 & 0 & R_a \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \dots (3.1)$$

Where  $V_{as}, V_{bs}$  and  $V_{cs}$  are the stator phase voltages;  $R_s$  is the stator resistance per phase;  $i_a, i_b$  and  $i_c$  are the stator phase currents;  $L_{aa}, L_{bb}$  and  $L_{cc}$  are the self-inductance of phases a, b and c;  $L_{ab}, L_{bc}$  and  $L_{ac}$  are the mutual inductances between phases a, b and c;  $e_a, e_b$  and  $e_c$  are the phase back electromotive forces. It has been assumed that resistance of all the winding are equal. It also has been assumed that if there is no change in the rotor reluctance with angle because of a no salient rotor and then

$$L_{aa} = L_{bb} = L_{cc} = L \dots \dots \dots (3.2)$$

$$L_{aa} = L_{ba} = L_{ac} = L_{bc} = L_{cb} = M \dots \dots (3.3)$$

Substituting equations (3.1) and (3.2) in equation (3.3) gives the PMBDC motor model as

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_a & 0 \\ 0 & 0 & R_a \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \dots (3.4)$$

Where  $V_{as}, V_{bs}$  and  $V_{cs}$  are phase voltages and may be designed as

$$V_{as} = V_{ao} - V_{no}; V_{bs} = V_{bo} - V_{no} \text{ and}$$

$$V_{cs} = V_{co} - V_{no} \dots \dots (3.5)$$

Where  $V_{ao}, V_{bo}, V_{co}$  and  $V_n$  are three phase and neutral voltages referred to the zero reference potential at the mid- point of dc link.

The stator phase currents are constrained to be balanced i.e.

$$i_a + i_b + i_c = 0 \dots\dots\dots (3.6)$$

This leads to the simplifications of the inductances matrix in the models as then

$$M_{ib} + M_{ic} = -M_{ia} \dots\dots\dots (3.7)$$

Therefore in state space from

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_a & 0 \\ 0 & 0 & R_a \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + d/dt \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \dots (3.8)$$

It has been assume that back EMF  $e_a, e_b$  and  $e_c$  are have trapezoidal wave from

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \omega_m \lambda_m \begin{bmatrix} f_{as}(\theta_r) \\ f_{bs}(\theta_r) \\ f_{cs}(\theta_r) \end{bmatrix} \dots\dots\dots (3.9)$$

Where  $\omega_m$  is the angular rotor speed in radians per seconds,  $\lambda_m$  is the flux linkage,  $\theta_r$  is the rotor position in radian and the functions  $f_{as}(\theta_r), f_{bs}(\theta_r)$  and  $f_{cs}(\theta_r)$  have the same shape as  $e_a, e_b$  and  $e_c$  with a maximum magnitude of  $\pm 1$ . The induced emfs do not have sharp corners because these are in trapezoidal nature.

The emfs are the result of the flux linkages derivatives and the flux linkages are continuous function. Fringing also makes the flux density function smooth with no abrupt edges. The electromagnetic torque [12] in Newton's defined as

$$T_l = [e_a i_a + e_b i_b + e_c i_c] / \omega_m (N-m) \dots (3.10)$$

It is significant to observe that the phase voltage-equation is identical to armature-voltage equation of dc machine. That is one of reasons for naming this machine the PM brushless dc machine.

The moment of inertia [12] is described as

$$J = J_m + J_l \dots (3.11)$$

The equation of the simple motion system with inertia  $J$ , friction coefficient  $B$ , and load torque  $T_l$  is

$$\frac{d\omega_m}{dt} + B\omega_m = (T_e - T_l) \dots\dots (3.12)$$

The electrical rotor speed and position are related by

$$\frac{d\theta_r}{dt} = \frac{p}{2} \omega_r \dots\dots (3.13)$$

The damping coefficient  $B$  is generally small and often neglected thus the system. The above equation is the rotor position  $\theta_r$  and it repeats every  $2\pi$ . The potential of the neutral point with respect to the zero potential ( $V_{no}$ ) is required to be considered in order to avoid imbalance in the applied voltage and simulate the performance of the drive. This is obtained by substituting equation (3.6) in the volt-ampere equation (3.8) and adding then give as

$$V_{ao} + V_{bo} + V_{co} - 3V_{no} = R_a(i_a + i_b + i_c) + (L - M)(p i_a + p i_b + p i_c) + (e_a + e_b + e_c) \dots (3.14)$$

Substituting equation (3.6) in equation (3.14) we get

$$V_{ao} + V_{bo} + V_{co} - 3V_{no} = (e_a + e_b + e_c)$$

Thus

$$V_{no} = [(V_{ao} + V_{bo} + V_{co}) - (e_a + e_b + e_c)] / 3 \dots\dots (3.15)$$

The set of differential equations mentioned in equations (3.8), (3.12), and (3.13). Defines the developed model in terms of the variables  $i_a, i_b, i_c, \omega_m$  and  $\theta_r$  time as an independent Variable [12].

Combining the all relevant equations, the system in state-space form is

$$X = Ax + Bu + Ce.$$

Where

$$x = [i_a i_b i_c \omega_m \theta_r]^t$$

$$A = \begin{bmatrix} \frac{-R}{L-M} & 0 & 0 & -\frac{\lambda m}{J} fm(\theta r) & 0 \\ 0 & -\frac{R}{L-M} & 0 & -\frac{\lambda m}{J} fm(\theta r) & 0 \\ 0 & 0 & -\frac{R}{L-M} & -\frac{\lambda m}{J} fm(\theta r) & 0 \\ \frac{\lambda m}{J} fm(\theta r) & \frac{\lambda m}{J} fm(\theta r) & \frac{\lambda m}{J} fm(\theta r) & -\frac{B}{J} & 0 \\ 0 & 0 & 0 & \frac{P}{2} & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{L-M} & 0 & 0 & 0 \\ 0 & \frac{1}{L-M} & 0 & 0 \\ 0 & 0 & \frac{1}{L-M} & 0 \\ 0 & 0 & 0 & \frac{1}{L-M} \end{bmatrix}$$

$$C = \begin{bmatrix} \frac{1}{L-M} & 0 & 0 \\ 0 & \frac{1}{L-M} & 0 \\ 0 & 0 & \frac{1}{L-M} \end{bmatrix}$$

$$u = [VasVbsVcsTl]^t$$

$$e = [eaebec]^t$$

#### IV. MATLAB®/SIMULINK® MODEL

The main model of the three phase BLDC motor which is built using Matlab/Simulink in accordance with mathematical model derived previously. The simulink model is as shown in fig 5.

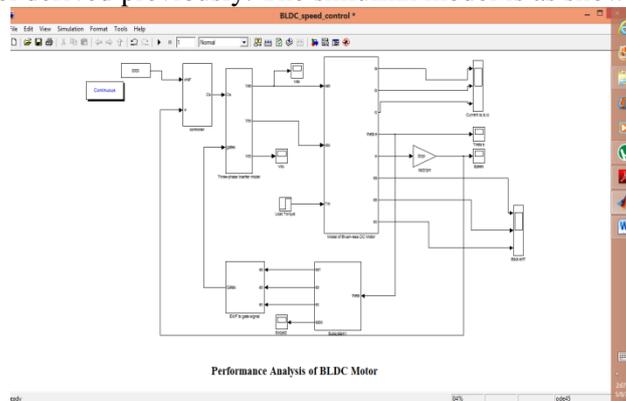


Fig.5: Main SIMULINK model of BLDC Motor.

Figure 5 shows the Maltlab/Simulink model of three phase BLDC motor. This Model consists of four sub blocks named as BLDC block, Inverter block, controller and subsystem 1 for gate signal. The

feedback of actual speed is given to the PI controller along with reference speed. The PI controller adjusts duty cycle of the power electronics devices such as MOSFET,IGBT etc.

## V. PERFORMANCE ANALYSIS OF BLDC MOTOR WITH MATLAB/SIMULINK

### 5.1 Phase currents

The nature of phase currents ia,ib and ic is discussed in this section. Phase currents are sinusoidal in nature and there is phase difference of  $120^\circ$  between each other.Phase current waveforms for three phase BLDC motor is as shown in fig.6.

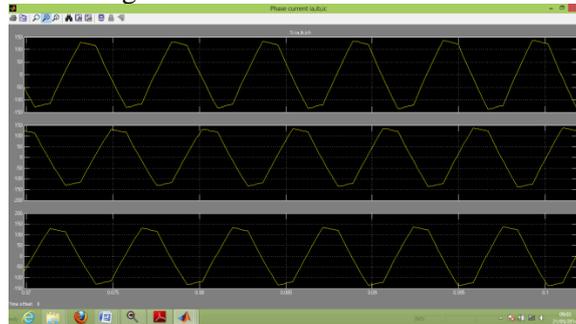


Fig.6: Phase current Waveforms of BLDC motor

### 5.2 Speed/Time characteristics

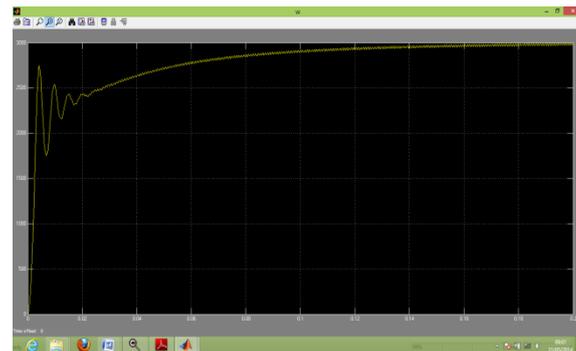


Fig.7: Speed/Time characteristics with closed loop.

Figure 7 shows the no load speed of the BLDC motor. Here reference speed is taken as 3000 rpm, the motor reaches the reference speed at  $t=0.14s$  and remains steady afterwards. In this control desired speed of the motor is achieved very smoothly and this gives basic idea and information about the speed control of the BLDC motor for various applications. This characteristic is very important factor for designing BLDC motor drive system for speed control applications.

### 5.3 Torque/time characteristics

The torque characteristics of BLDC motor presents a very important factor in design of the BLDC motor drive system, so it is necessary to predict the precise value of torque, which is determined by the waveforms of back emf.

The fig.9 Shows Torque/time characteristics of BLDC motor with no load, as the speed reaches to its steady state position at  $t=0.1s$  torque reduces and remain constant. The starting torque of the motor is high at the time of starting of motor.

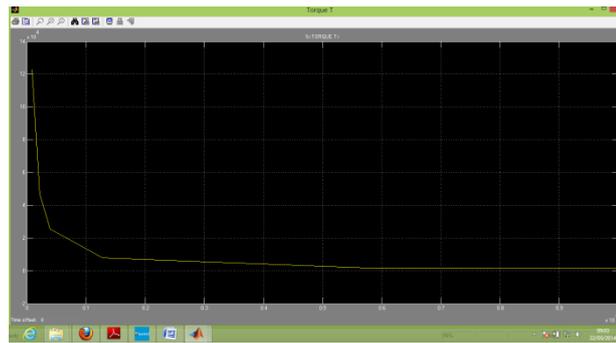


Fig.9.: Torque/time characteristics

### 5.4 Back-emf waveforms

Figure10 shows the trapezoidal back emf wave form. Here we have considered 120° mode of operation. Back emfs are developed in stator winding due to mutual inductance between Permanent magnet and stator winding. Due to trapezoidal back emf torque developed by the BLDC motor is constant and having less ripples than sinusoidal back emf.

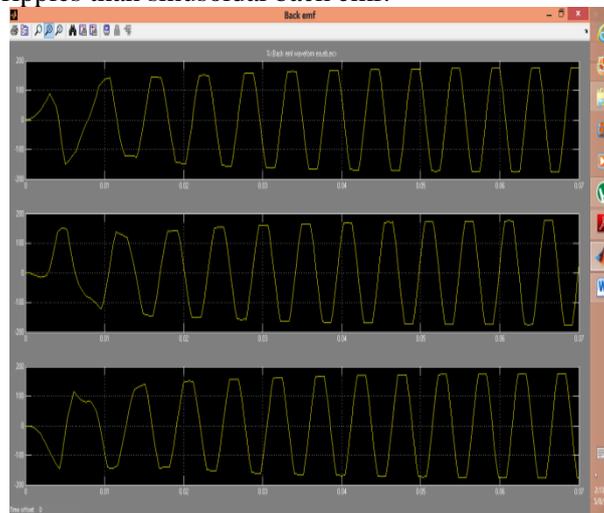


Fig.10: Back-emf waveforms

## VI. CONCLUSION

Permanent-magnet brushless dc motors is more accepted used in high-performance applications because of their higher efficiency, higher torque in low-speed range, high power density, low Maintenance and less noise than other motors. In this paper BLDC motor mathematical model is developed. Finally the performance of BLDC motor is analysed by using Matlab/Simulink and simulation results are presented. The torque characteristics of BLDC motor presents a very important factor in design of the BLDC motor drive system, so it is necessary to predict the precise value of torque, which is determined by the waveforms of back emf. All the simulation results are of theoretical aspect and can be utilized for practical implementation of BLDC motor. In future we can also develop model for performance analysis of BLDC motor for closed loop and open loop control with various loading conditions.

## VII. FUTURE SCOPE

One of the advantages of the BLDC motor model presented here is that it is not overly complicated. Improvement and additions are therefore very easy to make. One additional feature could be to extend the motor operation in four quadrants by using Matlab. Also sensor less control techniques could also be implemented. This could involve a special method to start the motor until the speed becomes high

enough for detection of back emf. Finally, a logical next step would be to try the different control strategies on real BLDC motor by using Matlab.

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