Three-Phase Inverter Fed BLDC Motor Drive.

Sneha K.Awaze,
PG G.C.O.E.Amravati *Department of electrical engg.*
G.C.O.E., Amravati *Maharashtra State, India*
sneha.awaze@gmail.com

ABSTRACT: Brushless dc motors have only decades of history. They have been gaining attention from various industrial and household appliance manufacturers because of its high efficiency, high power density and low maintenance cost, silent operation, compact form, and reliability. This paper describes the procedure of deriving a easy model for the brush less dc motor with 120-degree inverter system and its validation in the MATLAB/Simulink platform. In order to evaluate the model, various cases of simulation studies are carried out. Test results thus obtained show that, the model performance is satisfactory.

Keywords: BLDC Motor, Controller, PWM Inverter, Reference Current Generator .

I. INTRODUCTION

Recently, permanent magnet brushless dc motors are widely used in many applications such as motors, sensors, actuators, etc [1]. Permanent magnet motors with trapezoidal back EMF and sinusoidal back EMF have several advantages over other motor types. Most notably, (compared to dc motors) they are lower maintenance due to the elimination of the mechanical commutator and they have a high-power density which makes them ideal for high torque- to weight ratio applications [2]. Compared to induction machines, they have lower inertia allowing for faster dynamic response to reference commands. Also, they are more efficient due to the permanent magnets which results in virtually zero rotor losses [3]. Permanent magnet brushless dc (PMBLDC) motors could become serious competitors to the induction motor for servo applications The PMBLDC motor is becoming popular in various applications because of its high efficiency, high power factor, high torque, simple control and lower maintenance [4]. The major disadvantage with permanent magnet motors is their higher cost and relatively higher complexity introduced by the power electronic converter used to drive them. The added complexity is evident in the development of a torque/speed regulator [5].

II. DESCRIPTION OF THE DRIVE SYSTEM

The complete drive system is shown in Fig.1. It can be categorized into BLDC motor, Inverter, Current Controller, Speed Controller, reference current generator. Each block is modeled separately and integrated together.

A. Analysis Of BLDC Motor Drive System

BLDC motor can be realized mathematically in two ways:- abc phase variable model and d-q axis model. In a BLDC motor, the trapezoidal back EMF implies that the mutual inductance between stator and rotor is non-sinusoidal, thus transforming to d-q axis does not provide any particular advantage, and so abc phase variable model is preferred. In the present model, the motor is assumed to be star connected with isolated neutral. The analysis is based on the following assumptions:

- The motor is not saturated.
- Stator resistances of all the windings are equal and self and mutual inductances are constant.
- Power semiconductor devices in the inverter are ideal.

Under the above assumptions, The electrical and mechanical system is realized as:

$$\frac{di_a}{dt} = -\left(\frac{di_b}{dt} + \frac{di_c}{dt}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\frac{di_b}{dt} = \frac{1}{3L_t}[V_{ca} + 2V_{bc} - 3Ri_b + (e_a + e_c - 2e_b)] \ldots . (2)$$

$$\frac{di_c}{dt} = \frac{1}{3L_t}[V_{ca} - V_{bc} - 3Ri_c + (e_a + e_b - 2e_c)] \ldots\ldots (3)$$

$$E_k = \sum_k K_e w_m f_k(\Theta_r) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (4)$$

And the electromagnetic torque can be express as,

$$T_L\text{-}T_e = J\frac{dw_m}{dt} + Bw_m \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (5)$$

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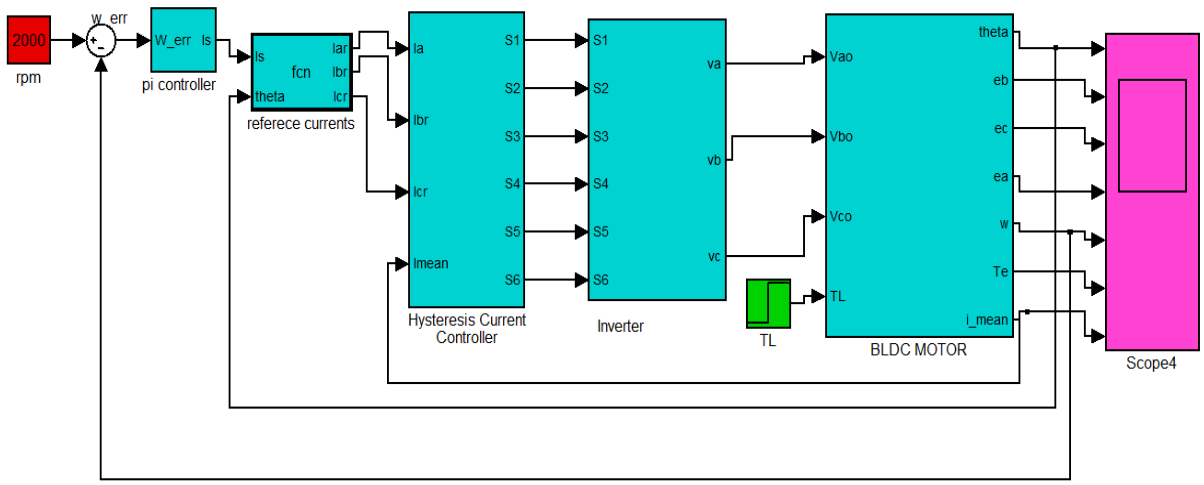

Fig. 1. PMBLDC Motor Drive System

And electrical rotor speed and position are related by

$$\frac{d\theta}{dt} = \frac{p}{2} * w_m \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots.(6)$$

Where **k=a, b, c.**

K_e is torque constant.

J is rotor inertia.

T_e is the electromagnetic torque.

w_m is the mechanical speed of the motor.

$f_k(\theta_r)$ Represents the back-EMF as a function of rotor Position.

Equation (1) to (3) is obtained by solving the loop equation (7) when an inverter is connected to a star load.

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = R_s \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + (L_s + M) \begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} + \begin{bmatrix} e_{an} \\ e_{bn} \\ e_{cn} \end{bmatrix} \ldots\ldots.(7)$$

The back EMF is a function of rotor position (θr) and has the amplitude $E = Ke \cdot \omega m$ (Ke is the back EMF constant). In this paper the modeling of the back EMF is performed under the assumption that all three phases have identical back EMF waveforms. Based on the rotor position, the numerical expression of the back EMF can be obtained as equations (8), (9), and (10), and it is implemented as shown in Fig 2.

B. Closed-Loop Controller

The BLDC motor is fed by a three phase MOSFET based inverter. The PWM gating signals for firing the power semiconductor devices in the inverter is injected from a hysteresis current controller [4] which is required to maintain the current constant within the 60° interval of one electrical revolution of the rotor. It regulates the actual current within the hysteresis band around the reference currents. The reference currents are generated by a reference current generator depending upon the steady state operating mode. The reference currents are of quasi –square wave. They are developed in phase with the back-emf in motoring mode and out of phase in braking mode. The magnitude of the reference current is calculated from the reference torque. The reference torque is obtained by limiting the output of the PI controller. The PI controller processes on the speed error signal (i.e. the difference between the reference speed and actual speed) and outputs to the limiter to produce the reference torque. The actual speed is sensed back to the speed controller and processed on to minimize the error in tracking the reference speed. Thus, it is a closed loop control drive system.

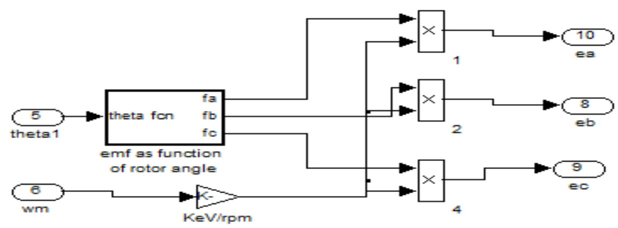

Fig.2.back-EMF generating Block as function of rotor angle

C. Inverter Modeling

The inverter (Fig. 3.) supplies the input voltage for the three phases of the BLDC motor. It comprises of two power semiconductor devices on each phase leg.

Appropriate pairs of FET's (S_1 toS_6) are driven based on the hall sensors input.Three phases are commutated for every 60°.

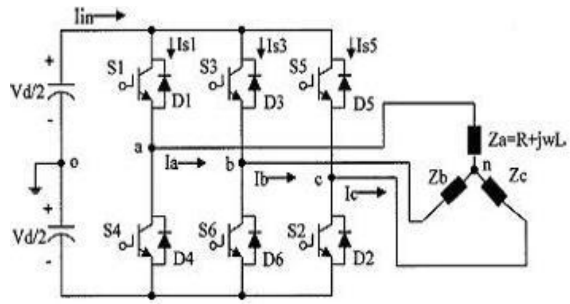

Fig.3. Three Phase Inverter

$\boldsymbol{V_{AN}} = (\boldsymbol{S_1}) * \left(\frac{V_d}{2}\right) - (\boldsymbol{S_4}) * \left(\frac{V_d}{2}\right) - \boldsymbol{V_F}$ _____**(8)**

$\boldsymbol{V_{BN}} = (\boldsymbol{S_3}) * \left(\frac{V_d}{2}\right) - (\boldsymbol{S_6}) * \left(\frac{V_d}{2}\right) - \boldsymbol{V_F}$ _____ **(9)**

$\boldsymbol{V_{CN}} = (\boldsymbol{S_5}) * \left(\frac{V_d}{2}\right) - (\boldsymbol{S_2}) * \left(\frac{V_d}{2}\right) - \boldsymbol{V_F}$ ____**(10)**

Where,
$\boldsymbol{V_{AN}}, \boldsymbol{V_{BN}}$ and $\boldsymbol{V_{CN}}$ are line-neutral voltages.
$\boldsymbol{V_d}$ is the DC-link voltage.
$\boldsymbol{V_F}$ is the forward diode voltage drop.

As sensors are the direct feed back of the rotor position, synchronization between stator and rotor flux is achieved

D. Modeling Of Hysteresis Current Controller

Hysteresis controller [4] limits the phase currents within the hysteresis band by switching ON/OFF the power devices. The switching pattern is given as:

If i_a^{err} >*UL,* S1 is on and S4 is off.

If i_a^{err} < *LL,* S1 is off and S4 is on.

If i_b^{err} >*UL,* S3 is on and S6 is off.

If i_b^{err} < *LL,* S3 is off and S6 is on.

If i_c^{err}>*UL,* S5 is on and S2 is off.

If i_c^{err}< *LL,* S5 is off and S2 is on.

Where $i_k^{err} = i_k^{ref} - i_k^{mean}$ and UL, LL are the upper and lower limits of hysteresis band. Thus, by regulating the current desired quasi-square waveforms can be obtained.

E. Modeling Of Reference Current Generator

The magnitude of the reference current (Is) is determined by using reference torque (T*) and the back emf constant (Kb), Is= $\frac{T*}{K_b}$ Depending on the rotor position, the Kb reference current generator block generates three- phase reference currents (Iar, Ibr,Icr) considering the value of reference current magnitude as Is, - Is and zero. The reference current generation is explained in the Table.I.

Table I. Rotor position signal Vs reference current

θ	**Iar**	**Ibr**	**Icr**
0°-60°	**0**	**Is**	**-Is**
60°-120°	**Is**	**0**	**-Is**
120°-180°	**Is**	**-Is**	**0**
180°-240°	**0**	**-Is**	**Is**
240°-300°	**-Is**	**0**	**Is**
300°-360°	**-Is**	**Is**	**0**

F. Modeling Of Speed Controller

Conventional PI controller is used as a speed controller for recovering the actual motor speed to the reference. The reference and the measured speed are the input signals to the PI controller. The *KP* and *KI* values of the controller are determined by trial and error method for set speed. The controller output is limited to give the reference torque, Its integral term has the effects of accumulation, memorization and delay, which enables PI controller to remove static error. The Saturation block limits the amplitude of outputting three phase reference current to the demanding range.

III. SIMULATION RESULTS

The performance of the developed BLDC system model is examined using motor parameters as listed in Table II.

TABLE II

$\boldsymbol{V_{dc}}$	380V	$\mathbf{K_b}$	0.13658(V/rad/sec)
P	4	**J**	0.0022(kg-m^2)
R	0.7Ω	$\mathbf{w_{rated}}$	4000(rpm)
(L-M)	0.00521H	$\mathbf{T_{max}}$	2.73N-m

The performance of the developed BLDC system model is examined under following conditions.

1. Starting and No-load condition.
2. Load condition.

1. Starting and No-load condition.

Simulation of brushless dc motor during no-load condition has been observed The starting dynamics of the motor is shown in Fig. 4 to 7. The reference speed is set at 2000 rpm. The starting current is limited to 20A by the controller.
The simulation results under no load condition shows the following characteristics.
An electro-magnetic torque Te of 5.43 N-m is developed to start the motor from standstill. With the help of P-I controller the actual speed is maintained at set value. The rotor position is varied from 0 to 2π per electric cycle 0.016sec. As soon as the motor reaches the steady state speed at 0.089s, and the trapezoidal back-emf settles at 29. 05 V. The starting current decreases to no-load value of 1A, an electro-magnetic torque Te decreases to 0.06 N-m.

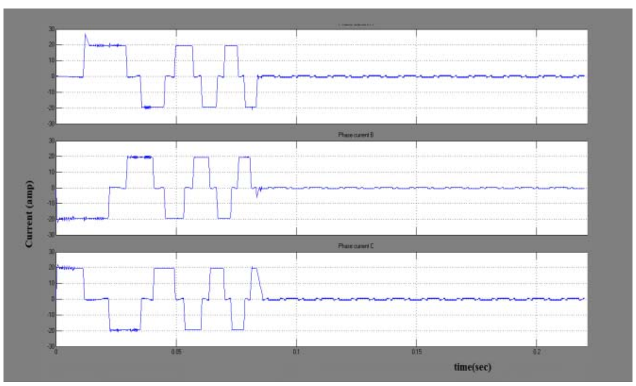

Fig.4 Phase a, b and c currents under no-load condition at 2000 rpm

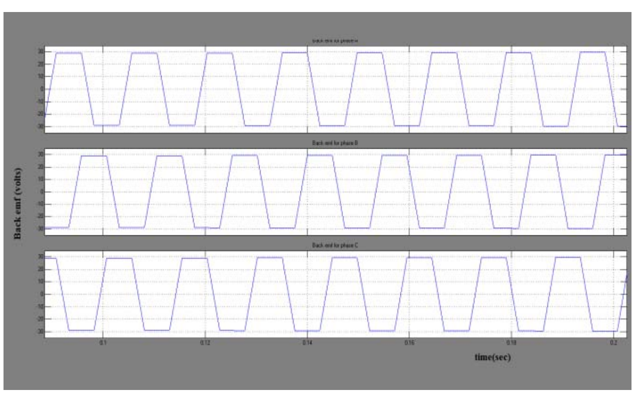

Fig.5. Back emf waveforms for no-load condition at 2000 rpm

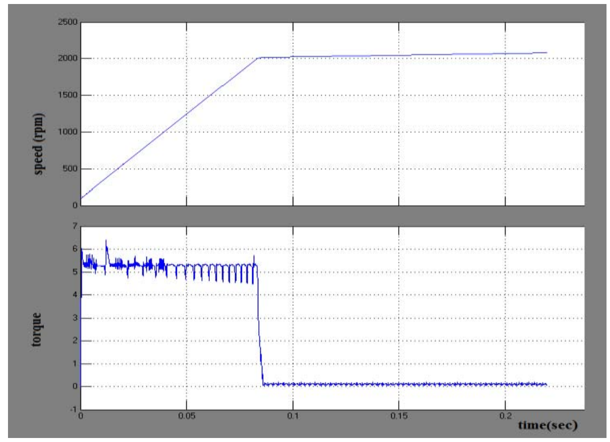

Fig.6 Speed and torque characteristics under no-load condition

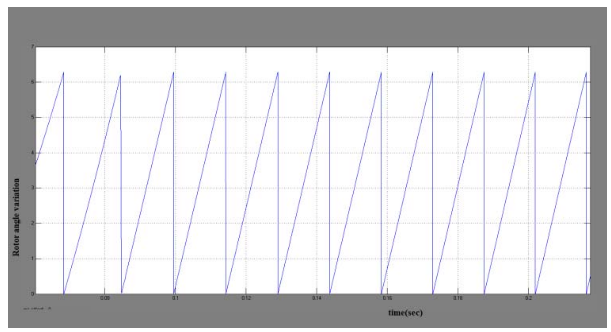

Fig.7.rotor position

2. Load Condition

When a step load of 1 N-m is suddenly applied, there is small change in the speed, but the controller recovers the speed to set value and there is no appreciable change in back-emf. The simulation results under load condition shows the following characteristics in fig 8 to 10.
The current increases to 4 A to meet the extra load with increases in electromagnetic torque T_e to 1.1 N-m. The motor reaches to steady state speed at 0.1sec and the back emf settles at 29.05 V. Once the load is removed all the parameters returns to no-load condition state.

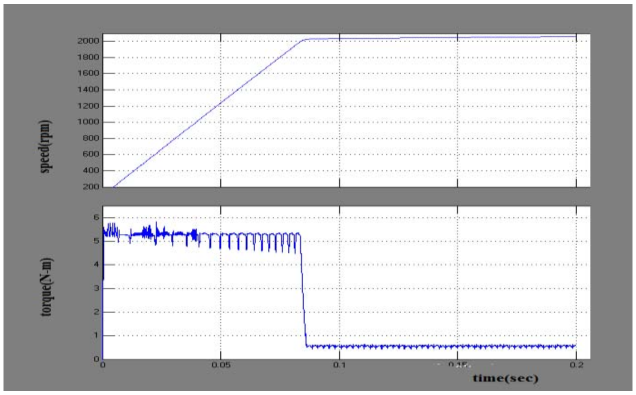

Fig.8 Speed and torque characteristics under load condition at 2000 rpm

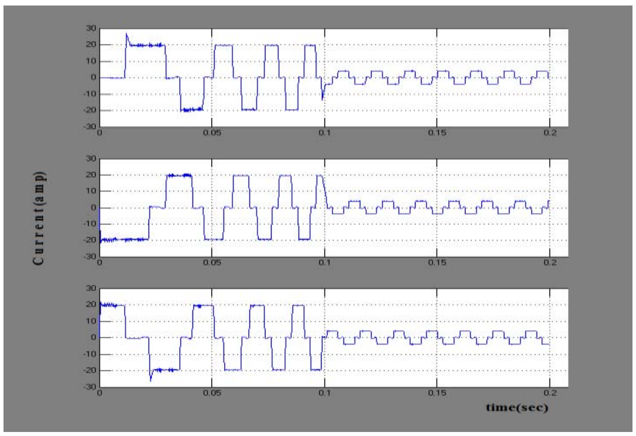

Fig.9 Phase a , b and c currents under load condition at 2000 rpm

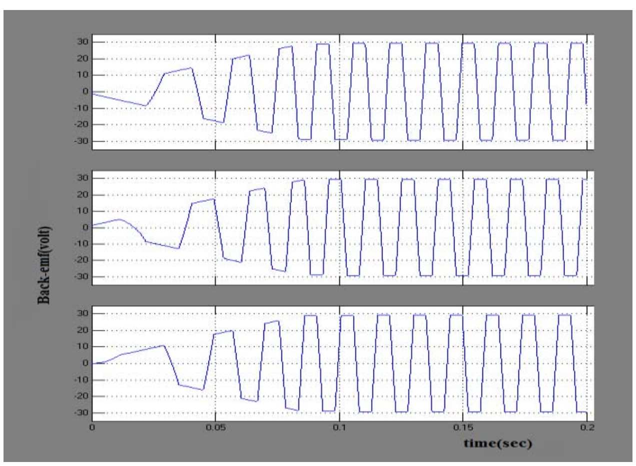

Fig10. Back emf waveforms under load condition

IV. CONCLUSION

The non-linear simulation model of the BLDC motor drive system with PI control based on MATLAB/Simulink platform is presented. The control structure has an inner current closed-loop and an outer-speed loop to govern the current. The speed controller regulates the rotor movement by varying the frequency of the pulse based on signal feedback from the Hall sensors. The behavior and performance of BLDC motor drive are shown in above figs. Results show that, such a modeling is very useful in studying the drive system.

The application of this work is on the basis of simulation and analysis carried out can be to select the proper motor specifications to match the load requirements. The simulation is used to predict the behavior of actual system. These predicted results can be used to determine the range of parameters of controller while designing the system.

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