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Modeling and Simulation of Open Loop Model of Brush Less DC Motor by Using MATLAB Based Software

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ABSTRACT

In this paper, an open loop model of a Brushless Direct Current (BLDC) Motor Drive supplied from a two-level voltage source inverter (VSI) under 120-degree conduction mode has been simulated in MATLAB command platform. BLDC motors are currently growing popularity and replacing brush motor in so many applications, as it can be operated for both low and high-speed vehicle system and also in servo drives. The high reliability, torque to inertia ratio, high efficiency, high power density, ease of control and mainly the brushless operation make the BLDC motors superior to others. But this type of motor cannot run without any power electronics converter. It has a permanent magnet as a rotor with a balanced 3-phase armature in its stator. The armature winding is driven by a power electronics inverter which is operated in synchronism with the rotor position, sensed by an optical encoder or a Hall Effect sensor. The inverter is obviously two level inverter because BLDC is never concerned with large power high voltage application. The 2-level VSI two-level voltage source inverter operates for positive half voltage and negative half voltage for controlling the speed and torque of this drive. It is found that by tuning the value of rotor position, no load condition, and trapezoidal armature phase current, the torque ripple can be minimized. The different performance parameters of the BLDC motor like phase voltages, phase currents, speed response, electromagnetic torque, d and q axis current, and rotor position, etc. are determined in MATLAB environment.

Keywords

Brushless DC motor, Open loop model, voltage source inverter (120 degree mode), position sensor (encoder), MATLAB.

1. INTRODUCTION

Brushless DC motor is one type of Permanent Magnet Synchronous Machine (PMSM) where the stator has a balanced three- phase armature and the rotor is made of permanent magnet. As BLDC motor is the Synchronous motor, so the stator and rotor field is always operating at the same frequency, and it means there is no slip[1].But unlike Synchronous motor, BLDC motors have trapezoidal back emf. Basically, with the availability of different types of permanent magnet materials and solid state power semiconductors, the conventional brushed DC motors were the source of an idea to develop BLDC motors[2].

A standard DC motor has so many advantageous satisfying characteristics such as real effectiveness, smooth speed control, and linear torque-speed features. But there are some disadvantages too, which are because of the existence of brushes. The reliability is limited at any time, the operation can be hampered, and the replacement of brushes may be required as the brushes have limited longevity. Mainly, this type of BLDC motors has been used to minimize such problem. This motor does not need any extra dc supply like a conventional dc motor as the flux is generated from a stationary, permanent magnet rather than an electromagnet in the case of a DC motor. Also, DC motors are having lesser reliability compared to other motors as there is the use of brushes may be made of carbon or any metal. But this problem is solved by using electronic commutation, and so the need of maintenance or replacement of brushes is not required anymore[3]. Thus BLDC motor has a long operating life and higher speed range and is also designed with the

compressed body. It is robust and has high efficiency[4]. BLDC motors have some other highlighting further advantages such as high torque to inertia ratios, greater speed capabilities and better operational speed versus torque characteristics[5]. As mentioned earlier the BLDC motors electrically commutated which involves six steps, wherein each step any two phases will be either positively or negatively energized and the rest one phase is floating[6]. The BLDC motor is electronically commutated and so to control the rotation of the motor, a particular sequence should be maintained to energize the stator windings. The information about the position of the rotor is important to know as depending this information the order of sequence energizing the winding may be understood. This Rotor position can be known by using a sensor, basically, a Hall effect sensor which is implanted into the stator[7]. In this paper, an open loop model for BLDC motor is analyzed by programming in MATLAB, considering the supply to the armature from a three phase two-level voltage source inverter (VSI) which operates under the 120° conduction mode of the inverter switches by the rotor position information. In open loop manner, the speed control of such a machine can be done in a way similar to that of a conventional dc machine by changing the equivalent conceptual" brush" position with varying the sensor position concerning the rotor frame[5].

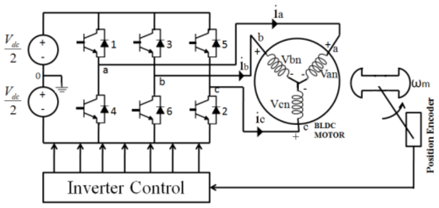

Fig-1. Schematic diagram of two level three phase voltage inverter fed BLDC motor drive

Figure-1 shows the drive system for which the proposed model is developed. The three phase supply is given to the three-phase armature winding of BLDC motor by a two-level voltage source bridge inverter which operates under the 120º mode of conduction. There are six self-controlled switches viz. IGBT's with anti-parallel diodes in the inverter. As mentioned earlier, the switching of the inverter devices is done by the rotor position information. Now to avail the rotor position information one sensor or transducer is placed on the rotor. A set of three infrared emitting diodes (IRED) and a Gray-coded disc is required to combine and put together and also a corresponding set of three receptor photodiodes positioned on a stationary frame. The position sensor system generates three electrical pulses in digital form which are considered as a three-bit binary word and this bit value change automatically after each 60° rotation of the rotor. Hence, the information of the rotor position is delivered after every 60° rotation[6]. Now, as the information is in both form and so a simple decoder logic is used to interpret this information to provide the switching signals of the six self-controlled inverter devices as per the 120º conduction logic. Inverter, on the whole, converts a DC voltage to its equivalent AC voltage as per requirement. Thus, here, a controllable DC voltage source, Vdc, is connected to the inverter to achieve speed control in an open-loop configuration as shown in figure-1.The different values of Vdc may be chosen for the system. The same way the armature voltage control, done in a usual DC machine with a mechanical commutator to control the speed of the machine. The in general open loop model of the BLDC motor drive is shown in fig.2.

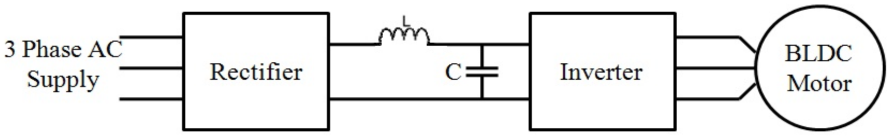

Fig-2: Overall open loop model of BLDC motor drive

The overall open loop model of BLDC motor drive consist of three main blocks, i.e. the inverter block which is of voltage source type, ABC-DQ transformation block and the BLDC motor i.e. the machine block. This model of BLDC motor can be derived by assuming the inverter to be operated 120° conduction mode.

2. THREE-PHASE VOLTAGE SOURCE INVERTER

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Voltage source inverter, a dc voltage source with minimum internal impedance is used as input of the inverter. The dc side terminal voltage is constant, but the alternating current side output voltage may be constant or variable irrespective of load current. For one cycle of 360º, each step should be on the 60º interval for six step inverter. In inverter expressions, a step means the change in the firing from one switch to the next switch in proper sequence. There are two ways of gating the switch. One way is the 180º conduction mode where each switch conducts for 180º, and the other is the 120º mode of conduction where each switch operates for 120º. But in both these cases, the same 60º interval of the output voltage waveform is kept to provide and to remove the gating signal[5]. Here, in the case of BLDC motor 120º conduction mode is applied as the voltage pattern is trapezoidal. Now, for the switching of a sequence of the switches, the rotor position is monitored by a fixed position encoder and this encoded information is passed on to the controller block which controls the process of the inverter. This inverter controller blocks processor decodes this information and from there generates the switching signals accordingly for the inverter [8].

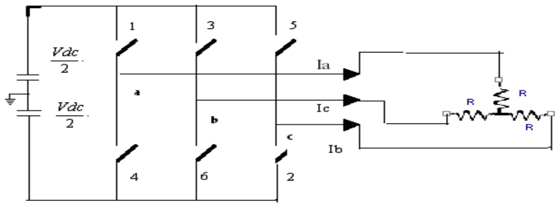

Fig-3: Schematic Diagram of Three Phase VSI

There are some important points to be remembered in case of 120° conduction mode of inverter operation. Always either one switch of the upper three inverter devices and one switch out of the lower three inverter devices are ON simultaneously.

120 Degree Conduction: There are six switching sequences. Each SCR conducts for 120 degree of a cycle. The switching sequence is 61, 12, 23,34,45,56.

From table-1 we can highlight that the total of phase voltage is always nil and thus if one voltage is positive, another one is negative, and the other phase voltage is zero. This is valid for all the switching sequence. As it is a 120 Degree conduction mode, so always two phases will carry voltage the other one will be of zero value.

	61	12	23	34	45	56
V_{an}	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	0	$\frac{-V_{dc}}{2}$	$\frac{-V_{dc}}{2}$	0
V_{bn}	$\frac{-V_{dc}}{2}$	0	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	0	$\frac{-V_{dc}}{2}$
V_{cn}	0	$\frac{-V_{dc}}{2}$	$\frac{-V_{dc}}{2}$	0	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$

Table-1: Phase voltage

	61	12	23	34	45	56
V_{ab}	V_{dc}	$\frac{V_{dc}}{2}$	$\frac{-V_{dc}}{2}$	$-V_{dc}$	$\frac{-V_{dc}}{2}$	$\frac{V_{dc}}{2}$
V_{bc}	$\frac{-V_{dc}}{2}$	$\frac{V_{dc}}{2}$	V_{dc}	$\frac{V_{dc}}{2}$	$\frac{-V_{dc}}{2}$	$-V_{dc}$
V_{ca}	$\frac{-V_{dc}}{2}$	$-V_{dc}$	$\frac{-V_{dc}}{2}$	$\frac{V_{dc}}{2}$	V_{dc}	$\frac{V_{dc}}{2}$

Table-2: Line voltage

3. THE ABC-DQ TRANSFORMATION BLOCK

The BLDC motor with trapezoidal back EMF is analyzed and module using d-q reference frame theory[9]. The d-q reference frame theory is well-known, where a three -phase system called a-b-c frame of reference of current or voltage or flux linkage is transformed into an equivalent two phase system called a d-q reference frame, actually d-q-0 frame. But zeroes sequence neglected, finally, assuming stable operation of current or voltage or flux linkage, using a transforming relationship, known as Park's transformation.

The slip ring to commutator transformation as introduced by Park transformation and others (a, b, c to d, q, 0) will now be considered. This is because the permanent magnet has distinct d and q axis. D-Axis is taken along the axis of the PM flux, and q-axis lead d-axis by 90^0.

Thus, we may write

$$[V_{d,q,0}] = K[V_{a,b,c}] \quad \text{......} [1]$$

Then, $[i_{a,b,c}] = K^T [i_{d,q,0}]$ .... [2]

Where $K = \begin{bmatrix} \cos\theta & \cos(\theta-2\pi/3) & \cos(\theta+2\pi/3) \\ -\sin\theta & -\sin(\theta-2\pi/3) & -\sin(\theta+2\pi/3) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$ ....[3]

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos(\theta-120^o) & \cos(\theta+120^o) \\ -\sin\theta & -\sin(\theta-120) & -\sin(\theta+120) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \text{...[4]}$$

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos(\theta-120^o) & \cos(\theta+120^o) \\ -\sin\theta & -\sin(\theta-120) & -\sin(\theta+120) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \text{...[5]}$$

Where θ is the angle between the d-axis of the rotor and q-axis at any instant of time. We may obtain vd, vq, and v_o as shown in above equation-4, using voltage, the current equation in the d-q axis reference frame. We can also find out the d-axis and q-axis current from equation-5 and also obtain the torque equation in the same reference.

4. MODELING OF BLDC MOTOR

The mathematical modeling of BLDC motor is analyzed by "D-Q axes rotor reference frame theory"[10]. The 'Machine' block of the developed model accepts different components of the BLDC motor stator (armature) voltage, like the D-axis (Vds) and Q-axis (Vqs), the instantaneous rotor position value and the details of load torque (Tl, fn) as inputs. The other parameters viz. the stator currents and the flux linkages in the stator in the d-q frame and the electromagnetic torque (Tem) are then calculated from those inputs. The fundamental equations related to the machine are shortened next, where symbols have their usual meanings. The stator voltage and flux equation in the rotor reference frame are given below.

$$\psi_{qs}^r = L_q i_{qs}^r \text{ ....[6]}$$

$$\psi_{ds}^r = L_d i_{ds}^r + \psi_0^{'r} \text{ ....[7]}$$

Where, ψ_0 is the flux linkage due to the permanent magnet

$$v_{qs}^r = r_s i_{qs}^r + \omega_r \psi_{ds}^r + p\psi_{qs}^r \text{ ....[8]}$$

$$v_{ds}^r = r_s i_{ds}^r - \omega_r \psi_{qs}^r + p\psi_{ds}^r \text{ ....[9]}$$

The d and q axis voltage may be represented in a matrix form, which is given below

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} r + L_{d\rho} & -\omega L_q \\ \omega L_d & r + L_{q\rho} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \text{..[10]}$$

$$T_{em} = \frac{3}{2}\frac{P}{2}(\psi_{ds}^r i_{qs}^r - \psi_{qs}^r i_{ds}^r) = \frac{3}{2}\frac{P}{2}(\psi_0^{'r} i_{qs}^r - (L_d - L_q) i_{qs}^r i_{ds}^r) \text{ .... [11]}$$

$$T_{em} = \frac{d\omega_m}{dt} + f_n \omega_m + T_l \text{ .... [12]}$$

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5. SIMULATION RESULTS AND DISCUSSIONS

Different parameters of BLDC motor at no load condition has been simulated using MATLAB software and the simulation result i.e. the nature of different responses are discussed. The figure-4 represents speed vs. time for input voltage 48volt It has been seen from the figure 4 that the speed is increased from zero in transient condition and found to settle finally to a steady state value. The speed response has no tendency of instability at no load condition i.e. TL=0. The electromagnetic torque vs. time response for the same condition of BLDC motor drives for open loop model is shown in figure-5. From this response, it has been noticed that torque is initially higher for high current passing through the process without connected to load in output side and finally achieve a condition of the steady state with some ripples in the output. figure-6 and figure-7 represent as a phase voltage and phase current vs. time plot for the same terms of open loop model of BLDC motor drives respectively. The phase voltage response has identified a six-step waveform in which a two-level vsi is operating under 120 degree conduction mode in a balancing condition. The frequency of this waveform as well as phase current is found to gradually increase from starting point because speed gradually builds up and it is self-synchronized with the rotor position. It has been seen from figure-7 that the current waveform is not a pure sinusoidal. figure-8 and figure-9 represent as a q axis and d axis current vs. time response to the same condition of open loop model of BLDC motor drives. It is found that the q axis current waveform is almost similar to the electromagnetic torque waveform because q-axis current is responsible for the production of the torque component of this model. It has been seen from the figure-9 the d axis current initially increased and finally settled at steady state value with some ripples.

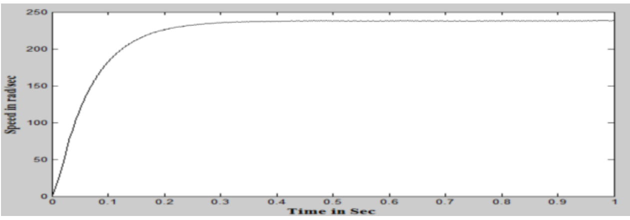

Fig-4 Speed vs Time characteristics of a BLDC Motor drive for Vdc=48V and Tl=0.

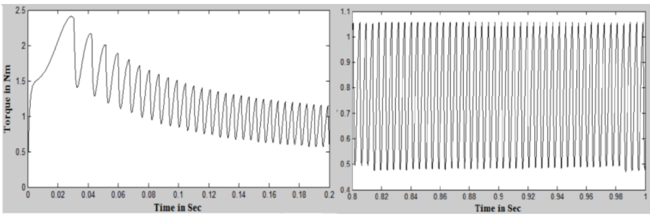

Fig-5 Electromagnetic torque vs Time characteristics of a BLDC Motor drive for Vdc=48V and Tl=0

The rotor position vs time is shown in figure-10. It is starting from negative position and goes upto the positive maximum position due to the change of the position of switching sequence of six step VSI.

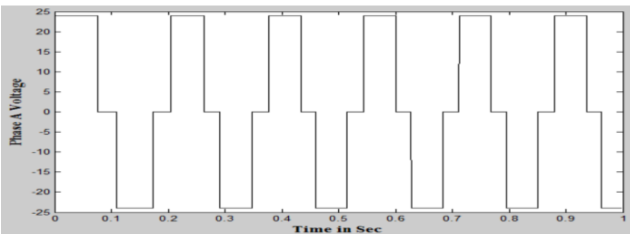

Fig-6 A-Phase Voltage vs. Time characteristics of a BLDC Motor drive for Vdc=48V and Tl=0

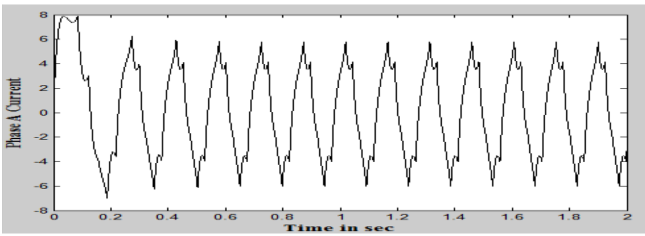

Fig-7 A-Phase Current vs. Time characteristics of a BLDC Motor drive for Vdc=48V and Tl=0

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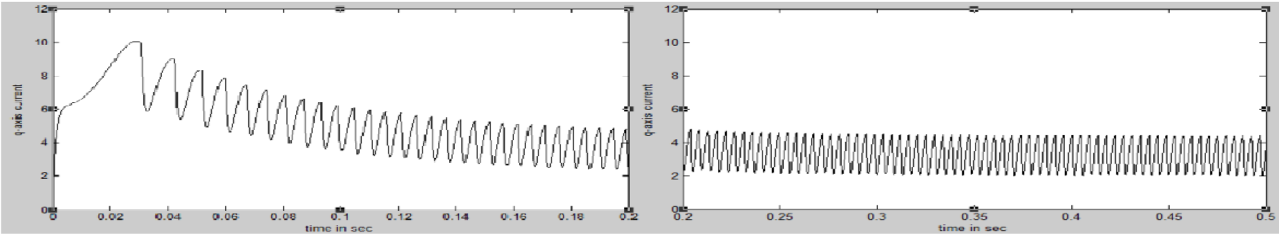

Fig-8 q-axis current vs. Time characteristics of a BLDC Motor drive for Vdc=48V and Tl=0

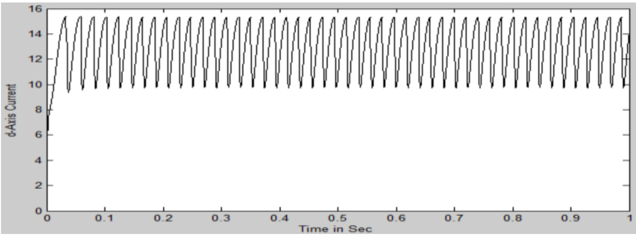

Fig 9 d-axis current vs. Time characteristics of a BLDC Motor drive for Vdc=48V and Tl=0

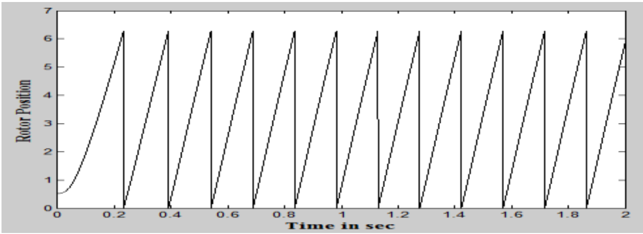

Fig 9 Rotor Position vs. Time characteristics of a BLDC Motor drive for Vdc=48V and Tl=0

6. CONCLUSIONS

In this paper different block of open loop model of BLDC motor has been discussed. The MATLAB-software based program is developed for a trapezoidal back EMF based permanent magnet synchronous machine, operated through a three phase self-synchronous 1200 conduction mode two level bridge voltage source inverter. This paper completely determines the different response characteristics of BLDC motor drive i.e. speed response, rotor position, electromagnetic torque, phase voltages, phase currents, d-q axis currents under no load conditions. The inverter DC link voltage can be controlled to accomplish the speed control, in a way, similar to the armature voltage control of a separately excited conventional DC motor.

7. APPENDIX

The parameters of the Brush-less DC motor (BLDC), on which the studies are made in this paper, are: Number of poles, P = 4, armature resistance, r_s = 3.2Ω, D-axis synchronous inductance, L_d= 0.002524H, Q-axis synchronous inductance, L_q = 0.002524H, rotor peak permanent flux linkage referred to stator, $\psi_0'^r$ = 0.418 Wb-turns, combined moment of inertia, J = 0.001372 kg-m^2.

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