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MATHEMATICAL MODELING AND SIMULATION OF DRIVING UNIT OF BRUSHLESS DC MOTOR

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ABSTRACT

This paper presents SIMULINK model of brushless DC motor that is used for industrial purposes (viz. servomotors, linear motors, industrial robots as actuators etc.) as well as for domestic purposes, due to its excellent efficiency, long life, reduced friction and controllability. Also, the controlling of the motor is done in this paper using a PI controller. This paper focuses on the designing of hall sensor in an anticlockwise direction, for BLDC motor. Further, the parameters like Stator current, Back EMF, Rotor Speed and Electromagnetic Torque are evaluated and analyzed for the designed SIMULINK.

Keywords: Brushless direct current motor, Electromotive force, Hall Sensor,

I INTRODUCTION

Since 1970's, BLDC motor is being used in so many applications such as industrial automation, instrumentation, defense and aerospace etc. The BLDC motors have replaced the conventional motors due to their high efficiency and speed. The characteristic of these motors is same as DC motors, except the use of brushes. BLDC motors are brushless hence does not require brushes for commutation purpose and are commutated electronically. Therefore, less maintenance is required and also they possess higher efficiency, better dynamic response and better speed versus torque characteristics as compared to brushed motors. It also delivers higher torque to the motor which makes it useful where space and weight are critical factors. The control algorithm of brushless DC motor is more complex than other motor types due to electronically commutation. The motor works in the single phase, two phase or three phase. But the three phase is mostly used in everywhere. A brushless DC motor is a permanent magnet synchronous motor that uses an inverter and position detectors to control the armature currents. There are two main types of brushless DC motors: sinusoidal type and trapezoidal type. The trapezoidal motor is a more attractive alternative for most applications compared to sinusoidal due to its higher efficiency, lower price, and less complexity. Here state-space based trapezoidal back EMF motor has been taken for modeling and simulation in MATLAB-SIMULINK [1].

II OPERATING PRINCIPLE

In three-phase brushless DC motor operation is done in two phase-ON manners. The highest torque producing phases are energized while the third one is kept OFF i.e. in each commutation sequence there is one winding which is energized as positive power (current enters into the winding), the second winding is negative (current exits the winding) and the third is in a non-energized condition. Torque produce due to the interaction between the permanent magnets and the magnetic field generated by the stator coils. Ideally, when these two fields are at 90° to each other the peak torque occurs and falls off as the fields move together. There should be shift in the position of the magnetic field produced by the windings for the motor to continue running, as the rotor moves to catch up with the stator field. This process is known as "Six-Step Commutation" which defines the sequence of energizing the windings. Rotor position is used for energizing the phase i.e. which phases are kept ON depends on it. The position sensor kept in the rotor produces a three-digit number (H1, H2, and H3) that changes at every 60° (in electrical degrees) as shown in the Fig.1. [2]

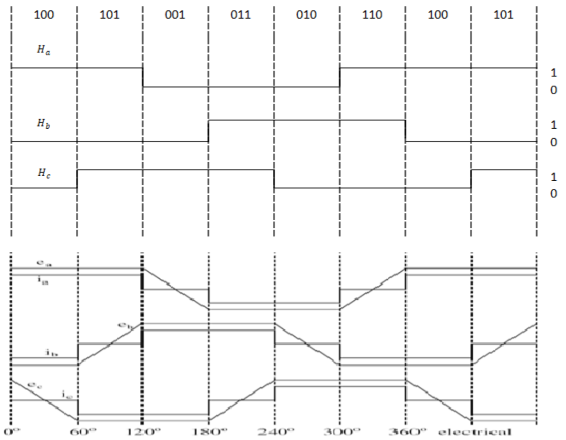


Fig. 1: Back-EMF, phase current and rotor position. [2]

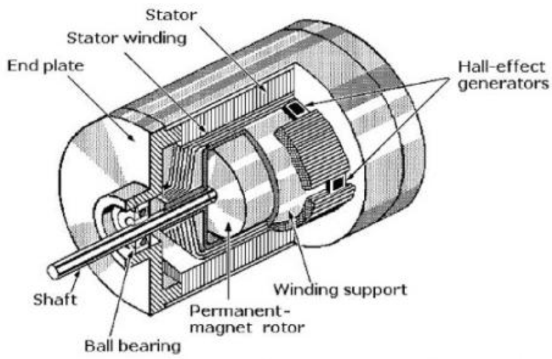
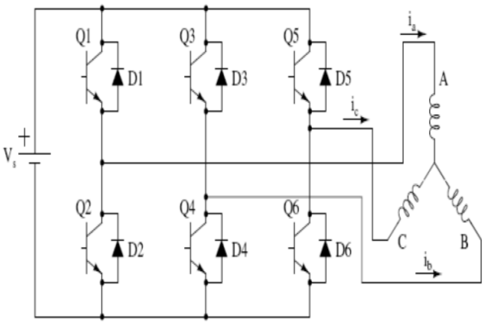


Fig. 2: Cross-sectional view of BLDC motor

Fig.2 shows a cross-sectional view of three phase star connected brushless DC motor along with its phase energizing sequence. Each interval starts with the rotor and stator fields' line 120° apart and ends when they are 60° apart. The torque is maximum when the field lines are perpendicular. Current commutation is done by six-step inverter as shown in a simplified form in Fig.3.



Switching interval in degree	Sequence No.	Position Sensor			Switch Closed		Phase Current		
		H_a	H_b	H_c			A (i_a)	B (i_b)	C (i_c)
0° – 60°	0	1	0	0	Q_1	Q_4	+	-	OFF
60° – 120°	1	1	0	1	Q_1	Q_6	+	OFF	-
120° – 180°	2	0	0	1	Q_3	Q_6	OFF	+	-
180° – 240°	3	0	1	1	Q_3	Q_2	-	+	OFF
240° – 300°	4	0	1	0	Q_5	Q_2	-	OFF	+
300° – 360°	5	1	1	0	Q_5	Q_4	OFF	-	+

Fig. 3: Simplified BLDC drive scheme [2] **Table 1: Switching sequence**

The switches are shown as bipolar junction transistors but MOSFET switches are most common. Table 1 shows the switching sequence, the position sensor signals and the current direction.

III MATHEMATICAL MODEL

The Brushless DC motor's construction is same as permanent magnet synchronous machine. But as the permanent magnets are mounted over the rotor, therefore, there are some differences in the dynamic characteristics. The model of the armature winding for the Brushless DC motor is expressed as follows.

Applying Kirchhoff's law to the considered 3-phase BLDC motor, [3] we will get

$$V_A = i_A R_A + L_A \frac{di_A}{dt} + M_{AB}\frac{di_B}{dt} + M_{AC}\frac{di_C}{dt} + e_A \quad (1)$$

$$V_B = i_B R_B + L_B \frac{di_B}{dt} + M_{BA}\frac{di_A}{dt} + M_{BC}\frac{di_C}{dt} + e_B \quad (2)$$

$$V_C = i_C R_C + L_C \frac{di_C}{dt} + M_{CB}\frac{di_B}{dt} + M_{CA}\frac{di_A}{dt} + e_C \quad (3)$$

Where,

R is stator resistance of all the three phases A, B and C

L is stator inductance of all the three phases A, B and C

I is stator current of all the three phases A, B and C

V is voltage of all the three phases A, B and C

M is mutual inductance

e is back-EMF

In this case, a 3-phase balanced system is assumed,

$$\therefore\ L_A = L_B = L_C = L \quad (4)$$

$$M_{AB} = M_{AC} = M_{BA} = M_{BC} = M_{CB} = M_{CA} = M \quad (5)$$

$$R_A = R_B = R_C = R \quad (6)$$

Arranging equation (1), (2) and (3) according to the equations (4), (5) and (6) and neglecting mutual inductance, We will get,

$$V_A = i_A R + L\frac{di_A}{dt} + e_A \quad (7)$$

$$V_B = i_B R + L\frac{di_B}{dt} + e_B \quad (8)$$

$$V_C = i_C R + L\frac{di_C}{dt} + e_C \quad (9)$$

Arranging the equations (7), (8) and (9) in vector form,

$$\begin{bmatrix} \frac{di_A}{dt} \\ \frac{di_B}{dt} \\ \frac{di_C}{dt} \end{bmatrix} = \frac{1}{L}\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} - \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix} \quad (10)$$

The above equation (10) can be solved by the use of any numerical solution technique (viz. Runge Kutta method) to find the values of i_A, i_B and i_C .

The equation for the generation of back EMF can be given by,

e = Back EMF constant * Mechanical Rotor Speed * Rotor angle

$$e = k \cdot \theta \cdot w \quad (11)$$

Because, the angle difference between each rotor is 120° and, back-EMF is related to the function of the rotor, therefore,

$$e_A = k_e \cdot \theta_e \cdot w_r \quad (12)$$

$$e_B = k_e \cdot (\theta_e - \frac{2\pi}{3}) \cdot w_r \quad (13)$$

$$e_C = k_e \cdot (\theta_e + \frac{2\pi}{3}) \cdot w_r \quad (14)$$

Where,

w_r is rotor speed (rad/sec)

k_e is back EMF constant

Difference across winding = Supply Voltage – Back EMF Voltage

The equation for the generation of torque is given by,

$$T = k_t * I \quad (15)$$

The produced torques are influenced by the permanent magnet because of the trapezoidal flux linkage. Therefore the torque produced is:

$$T_e = T_A + T_B + T_C \quad (16)$$

And here the resultant T_e can be obtained by following equations:

$$T_A = k_t * \theta_e * i_A \quad (17)$$

$$T_B = k_t * \theta_e * i_B \quad (18)$$

$$T_C = k_t * \theta_e * i_C \quad (19)$$

Where,

θ_e *is rotor angle in electrical degree*

w *is rotor speed (rad/sec)*

θ_m *is rotor angle mechanical*

$$\theta_e = \frac{p}{2} \theta_m \quad (20)$$

The equation of the simple motion system (i.e. mechanical torque transfer to the motor shaft) with friction constant, load torque and inertia is

$$T_e - T_l = k_f \cdot w_m + J\frac{dw_m}{dt} \quad (21)$$

Where,

T_e *is Electric Torque*

T_l *is Load (Mechanical) Torque*

k_f *is friction constant*

J *is Rotor Inertia*

IV SIMULINK MODEL

The designed MATLAB-SIMULINK model in Fig. 4 gives a controlled speed of BLDC motor using a PI controller and the simulation results provide necessary waveforms for the analysis of closed loop speed control of BLDC drive.

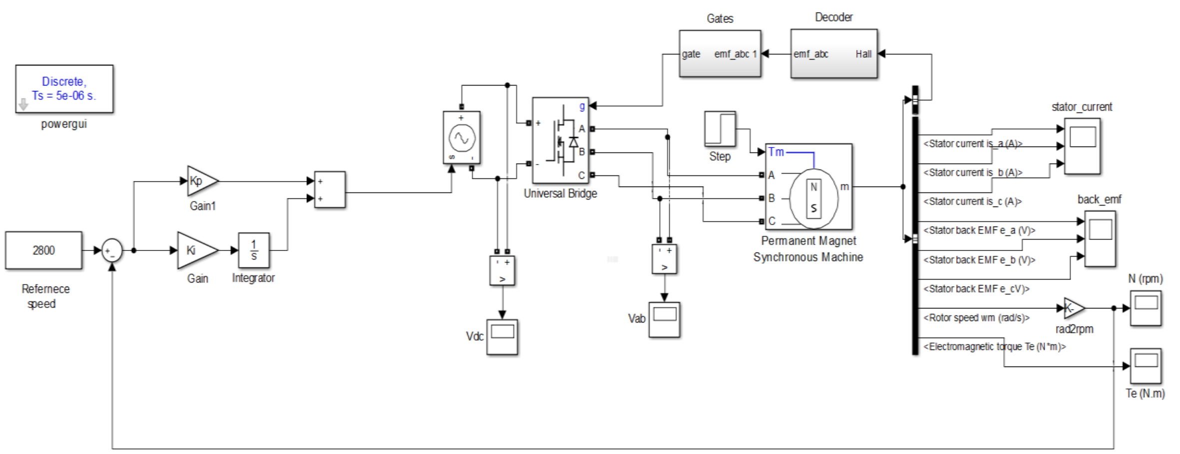


Fig. 4: SIMULINK model of BLDC motor

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The model consists of four main blocks with PI controller. One universal bridge is connected for switching purpose, attached to it is the permanent magnet synchronous machine and two subsystems are there which act as a sensor for the driving unit of the motor. The Controller is used here for regulating the speed of the motor. [4] In order to design BLDC Motor driving unit system, it is necessary to give the precise value of torque to the model because it is related to back-EMF and torque [5].For energizing the stator winding in correct sequence the knowledge of rotor position is necessary since in order to rotate the rotor-stator winding has to be energized sequentially and also commutation has to be done electronically. [6]

Now both the subsystems designed in the SIMULINK Model are discussed below in detail.

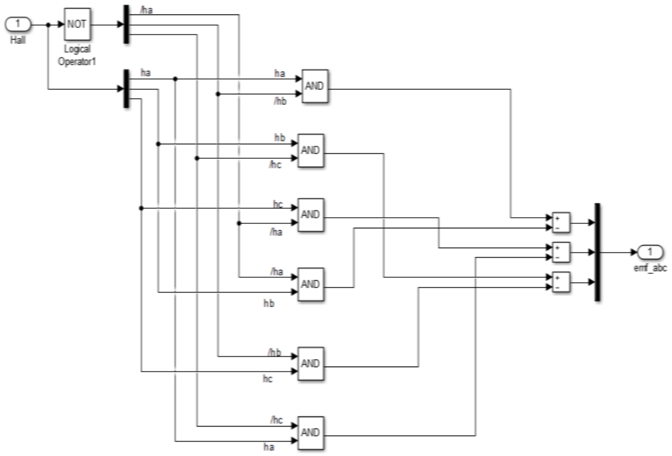

Fig. 5: Detection of EMF from the hall sensor

For the generation of trapezoidal nature of Back EMF from the hall sensor Fig. 5 is designed, whereas Table 2 shows the back EMF detection from hall sensor based on logic sequence. [7]

Based on truth Table 3, a model is developed to generate appropriate commutation signal, as shown in Fig.6. [5]

Table 2: Truth table for back EMF detection from hall sensor

Table 3: Truth table for generation of the Commutation signal

H_a	H_b	H_c	E_a	E_b	E_c	Q_4	Q_5	Q_6
0	0	0	0	0	0	0	0	0
0	0	1	0	+1	-1	0	0	1
0	1	0	-1	0	+1	0	1	0
0	1	1	-1	+1	0	0	0	0
1	0	0	+1	-1	0	1	0	0
1	0	1	+1	0	-1	0	0	1
1	1	0	0	-1	+1	1	1	0
1	1	1	0	0	0	0	0	0

Fig. 6: Commutation signal from back-EMF

The simulation of the designed BLDC motor is done using the software package of MATLAB/SIMULINK. After running the simulation, the Stator Current, Back EMF, Rotor speed and Electromagnetic torque waveforms were evaluated and analyzed.

V SIMULATIONS AND EXPERIMENTAL RESULTS

Speed is set at 2800 rpm and the regulation of the speed is obtained at the set speed. The stator waveform and back-EMF are shown by the simulation waveform and it shows that phase voltage and back-EMF both are displaced by 120° each and stator current are of quasi sinusoidal in nature and also displaced by 120°.

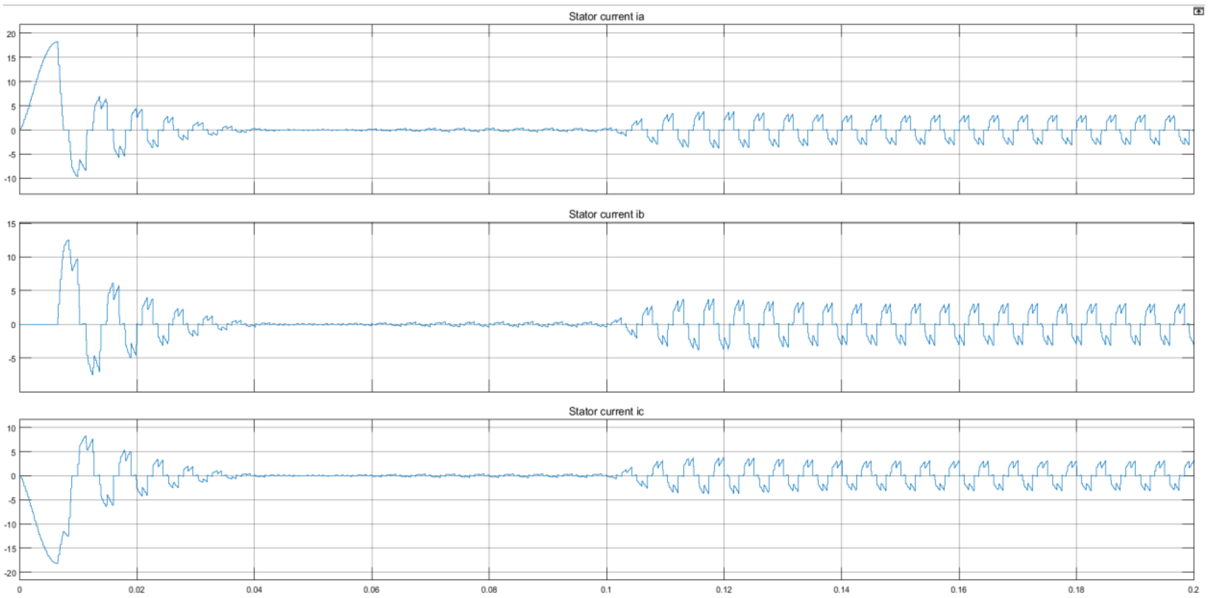

Fig. 7: Stator Current

The stator phase currents of the motor are shown in Fig. 7. Initially, the value of current is high and once the steady value of speed is reached then the current will decrease to the rated value.

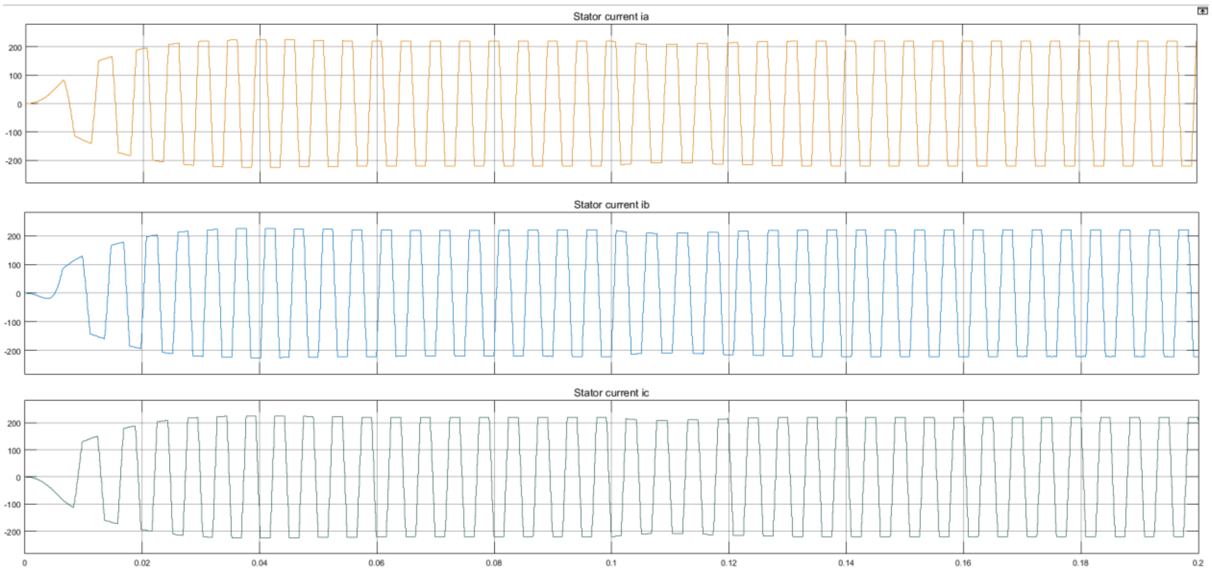

Fig. 8: back-EMF

The 3-phase trapezoidal back-EMF waveform is shown in Fig. 8. The mode of operation considered here is 120°.

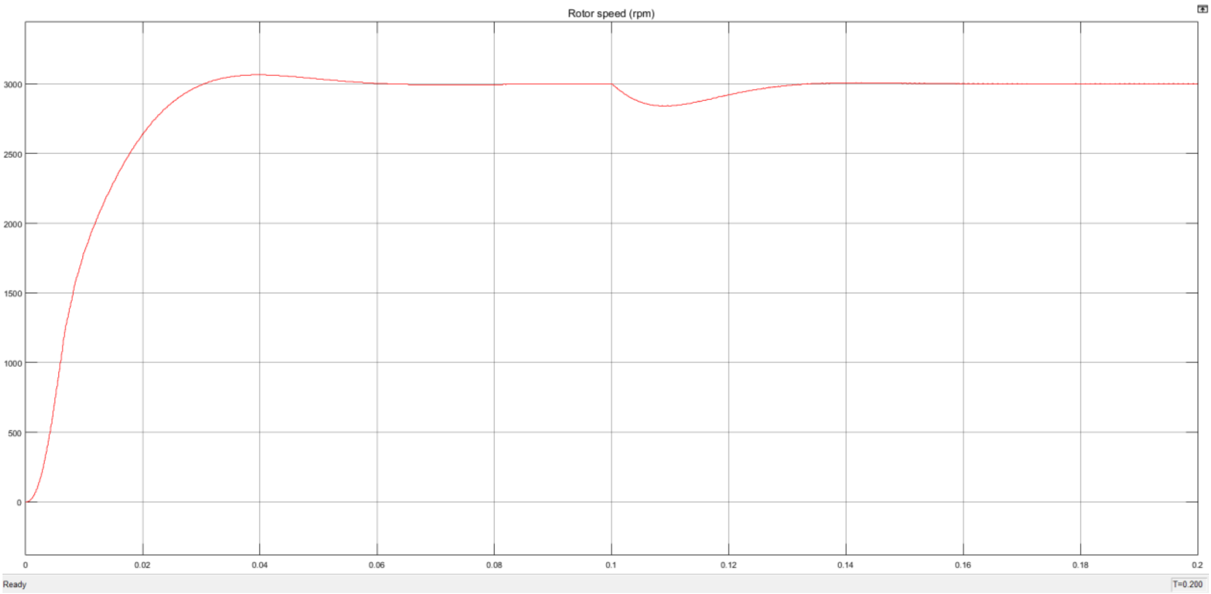

Fig. 9: rotor speed

The rotor speed of the BLDC motor with PI control is shown in Fig. 9. The reference speed taken here is 2800 rpm, with the help of PI controller, motor reaches the reference speed very quickly at 0.06secs.

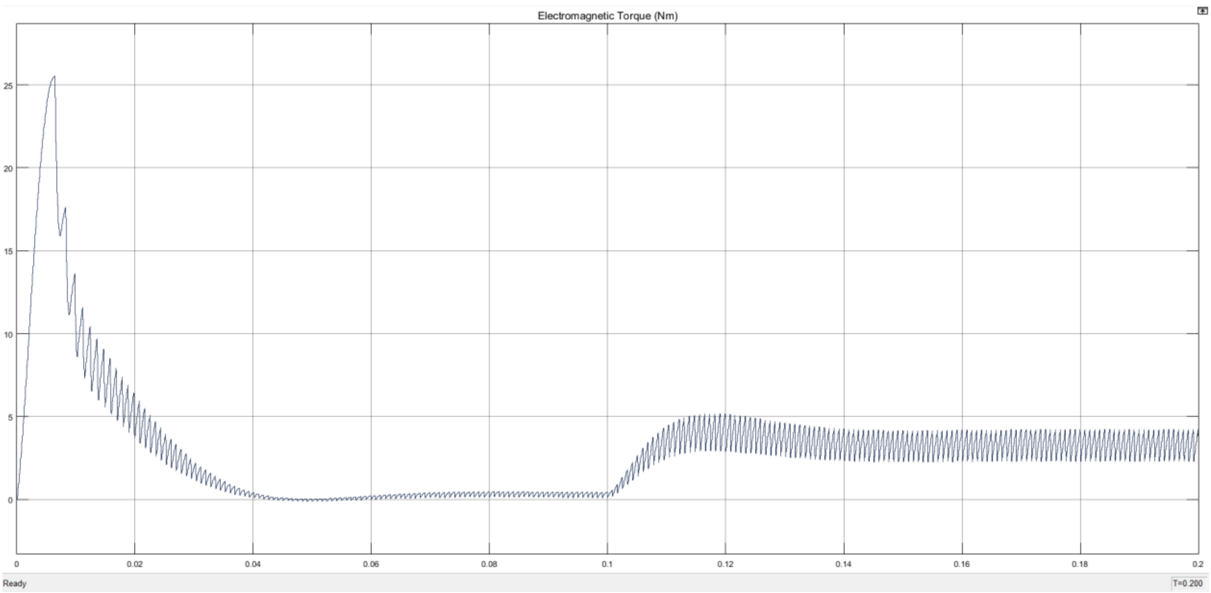

Fig.10: electromagnetic torque

The electromagnetic torque generated by the BLDC motor is shown in Fig. 10. Initially, the value of torque is high, once the steady state speed is reached; the value of torque will decreases as it is in the no-load case, therefore, torque is zero.

VI CONCLUSION

Permanent-magnet brushless dc motors are mostly used in high-performance applications because of their higher efficiency, higher torque in the low-speed range, high power density, low maintenance and less noise than other motors. In this paper mathematical model for Brushless DC motor has been developed, and simulation results are plotted by the use of SIMULINK model, which is reaching the reference speed i.e. 2800rpm at 0.06secs. These results show that this modelling is very useful in studying the high-performance drive before taking up the dedicated controller design concept for evaluation of the dynamic performance of the motor.

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