

## Simulation of Brushless DC Motor using Direct Torque Control

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### Abstract—

This paper deals with modelling of three phases brushless dc motor with MATLAB/SIMULINK software BLDC motor have advantages according to brushless dc motor and induction motor's. They have improve speed torque characteristics, high efficiency high transient response and small size. It approaches for reducing the torque ripples of BLDC motor using DTC, by using control technique's ,but present work mainly concentrate on advanced method. The whole drive system is simulated based on the system devices, BLDC motor source inverter, space vector modulation.

**IndexTerms**—Brushlessdc(BLDC)drives,directtorque Control (DTC), permanent-magnetmotor.

### I. INTRODUCTION

The present and future generation is mostly depending on the speed driving systems which have high efficiency and also with a minimum cost. So, for this requirement BLDC motors are very much suitable. Hence the research is also much focusing on BLDC motors. BLDC motors can be classified into two categories as surface mounted permanent magnet BLDC motors and interior permanent-magnet BLDC motors [1]. As these motors provide commutation externally due to presence of converters, hence the wear and tear is not in the picture. To minimize the torque ripples in these motors trapezoidal back-EMF is needed. It is obtained by employing concentrated winding, skewing the stator slots by one slot pitch.

Torque ripples are occurred due to the power electronic commutation, the usage of high frequency switching power devices, imperfections in the stator and the associated control system, the input supply voltage to the motor contains various harmonic components and the pulsating current input due to electronic commutation are also causes for torque ripples [2]. So an efficient controller is required to reduce the harmonics present in the input voltage to

the motor and to reduce the pulsating variation of line current to the motor. Optimal torque control schemes for BLDC motors reducing torque ripples and minimizing copper losses have been proposed [3], [4]. Wang *et al.* proposed a method to minimize the torque ripples generated by non-ideal current waveforms for a BLDC motor without position sensors by adjusting actual phase currents [5]. Luet al. proposed a torque control method to attenuate

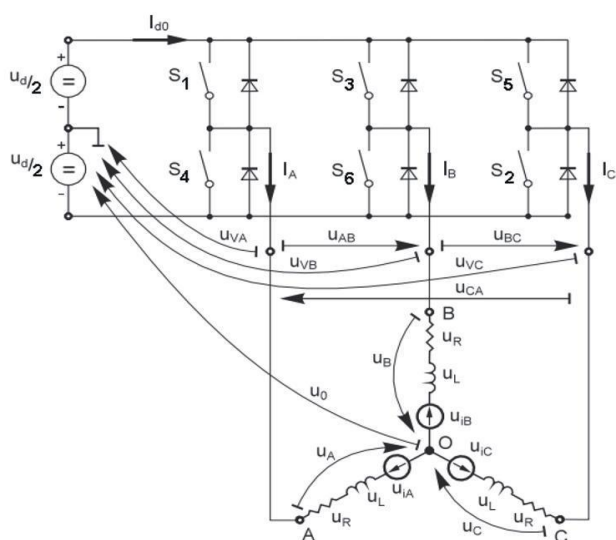
torque ripple of BLDC motors with un-ideal back electromotive force (EMF) waveforms [6].

An instantaneous torque controller based on variable structure control in the d-q reference frame was proposed in [7]–[8]. However, although experimental results showed that it was effective in reducing torque ripple, it was only applicable to three-phase BLDC operating in the 180 conduction mode, and not to the more usual 120 conduction mode. In [9], electromagnetic torque pulsations were reduced with a torque controller in which the torque was estimated from the product of the instantaneous back-EMF and current. However, the winding resistance was neglected and the inverter output voltage had to be calculated, which assumed that the back-EMF waveform was known. The simulation approach for torque ripple minimization of BLDC motor using direct torque control is presented in this paper and more details of this work with experimental realization is given in [10] [11] but the present work is highlighted MATLAB/SIMULINK implementation for torque ripple minimization of BLDC motor with direct torque control and results are compared with BLDC motor without direct torque controller.

### II. CONSTRUCTION AND OPERATING PRINCIPLE

The BLDC motor is also referred to as an electronically commutated motor. There are no brushes on the rotor and the commutation is performed electronically at certain rotor positions. The stator phase windings are inserted in the slots (a

distributed winding), or can be wound as one coil on the magnetic pole. The magnetization of the permanent magnets and their displacement on the rotor are chosen in such a way that the back-EMF shape is trapezoidal. This allows the three-phase voltage system, with a rectangular shape, to be used to create a rotational field with low torque ripples. In this respect, the BLDC motor is equivalent to an inverted DC commutator motor in that the magnets rotates while the conductors remain stationary is reversed by the commutator and the brushes, but in the brushless DC motor, the polarity reversal is performed by semiconductor switches which are to be switched in synchronization with the rotor position. Besides the higher reliability, the missing commutator brings another advantage. The commutator is also a limiting factor in the maximal speed of the DC motor. Therefore the BLDC motor can be employed in applications requiring high speed.



Replacement of a DC motor by a BLDC motor place higher demands on control algorithm and control circuit. Firstly, the BLDC motor is usually considered as a three-phase system. Thus, it has to be powered by a three-phase power supply. Next, the rotor position must be known at certain angles, in order to align the applied voltage with the back-EMF. The alignment between the back-EMF and commutation events is very important. In this condition the motor behaves as a DC motor and runs at the best working point. But the drawbacks of the BLDC motor caused by

necessity of power converter and rotor position measurement are balanced by excellent performance and reliability, and Also by ever falling prices of power components and control circuits.

### III. MATHEMATICAL MODEL OF THE BLDC MOTOR

Figure shows dynamic equivalent circuit of BLDCM. In simulation, the common 'y' connection of stator windings, three phase balanced system and air gap uniform are assumed.

For this model, the stator phase voltage equations is the

$$V_a = i_a R_a + L_a \frac{di_a}{dt} + e_a + m \frac{di_b}{dt} + m \frac{di_c}{dt}$$

$$V_b = i_b R_b + m \frac{di_a}{dt} + L_b \frac{di_b}{dt} + m \frac{di_c}{dt} + e_b$$

$$V_c = i_c R_c + m \frac{di_a}{dt} + m \frac{di_b}{dt} + L_c \frac{di_c}{dt} + e_c$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_a & m & m \\ m & L_b & m \\ m & m & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

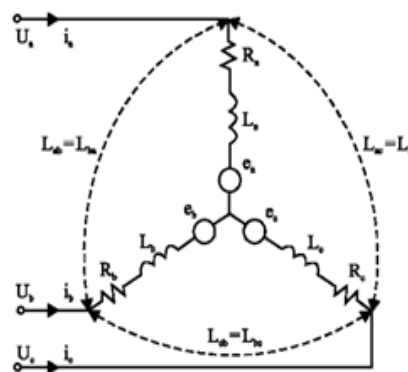
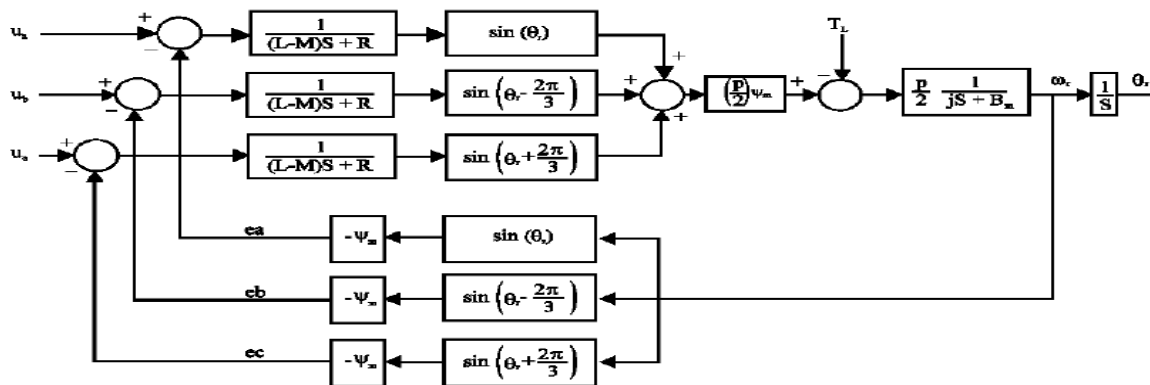


Fig. 1: Equivalent circuit of BLDCM

Back emf is depends to magnetic flux in rotor because of permanent magnet with speed of rotor eqn(2)



$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \begin{bmatrix} -\omega_r & \varphi_m \sin \theta_r \\ -\omega_r & \varphi_m \sin \left( \theta_r - \frac{2\pi}{3} \right) \\ -\omega_r & \varphi_m \sin \left( \theta_r - \frac{4\pi}{3} \right) \end{bmatrix}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \begin{bmatrix} i_a R_a \\ i_b R_b \\ i_c R_c \end{bmatrix} + \begin{bmatrix} L_a \frac{di_a}{dt} + m \frac{di_b}{dt} + m \frac{di_c}{dt} \\ m \frac{di_a}{dt} + L_b \frac{di_b}{dt} + m \frac{di_c}{dt} \\ m \frac{di_a}{dt} + m \frac{di_b}{dt} + L_c \frac{di_c}{dt} \end{bmatrix}$$

Motor equations can be expressed in state- space from eqn(3)

$$\frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{1}{L-m} \left\{ \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \varphi_m \omega_r \begin{bmatrix} \sin \theta_r \\ \sin \left( \theta_r - \frac{2\pi}{3} \right) \\ \sin \left( \theta_r - \frac{4\pi}{3} \right) \end{bmatrix} \right\}$$

$$\begin{bmatrix} V_a - e_a \\ V_b - e_b \\ V_c - e_c \end{bmatrix} = \begin{bmatrix} i_a R_a + L_a \frac{di_a}{dt} + m \frac{di_b}{dt} + m \frac{di_c}{dt} \\ i_b R_b + m \frac{di_a}{dt} + L_b \frac{di_b}{dt} + m \frac{di_c}{dt} \\ i_c R_c + m \frac{di_a}{dt} + m \frac{di_b}{dt} + L_c \frac{di_c}{dt} \end{bmatrix}$$

$$P = e_a i_a + e_b i_b + e_c i_c$$

Electrical magnetic torque is calculated as

$$\text{Torque} = T_e = \frac{P}{\omega_m}$$

$$\text{Dynamic equation } T_e = J \left( \frac{2}{P} \right) \frac{d}{dt} \omega_r + B_m \left( \frac{2}{P} \right) \omega_r + T_L$$

$$\frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{1}{L-m} \left\{ \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} -e_a \\ -e_b \\ -e_c \end{bmatrix} \right\}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_a & m & m \\ m & L_b & m \\ m & m & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

$$\frac{d\omega_r}{dt} = \frac{P}{2J} \left[ T_e - T_L - B_m \left( \frac{2}{P} \right) \omega_r \right]$$

$$\frac{d\theta_r}{dt} = \omega_r \theta_r = \int \omega_r$$

$$S i_a(s) = \frac{1}{L-M} V_a(s) - R$$

$$i_a(s)[S + R] = \frac{V_a(s)}{L-M} - e_a(s)$$

$$i_a(s) = \frac{V_a(s)}{(L-M)[S+R]} - \frac{e_a(s)}{S+R}$$

$$i_a(s)[S + R](L - M) = V_a(s) - e_a(s)(L - M)$$

$$\frac{di_a(s)}{dt} = \frac{V_a}{L - M} - i_a R_a + \varphi_m \omega_r \sin \theta_r \theta_r = 90^\circ$$

$$\frac{di_a}{dt} = \frac{V_a}{L - M} - i_a R + \varphi_m \omega_r$$

By applying the above equation into lapalace transformation

$$Si_a(s) = \frac{V_a(s)}{L - M} - i_a(s)R - e_a(s)$$

$$i_a(s) = \frac{V_a(s)}{(L - M)(S + R)} - \frac{e_a(s)}{S + R}$$

$$i_a(s) = \frac{V_a(s)}{(L - M)(S + R)} + \frac{\varphi_m \omega_r \sin \theta_r}{(S + R)}$$

By solving the equations'ssimilarly we get

$$i_b(s) = \frac{V_b(s)}{(L - M)(S + R)} + \frac{\varphi_m \omega_r (\sin \theta_r - \frac{2\pi}{3})}{(S + R)}$$

$$i_c(s) = \frac{V_c(s)}{(L - M)(S + R)} + \frac{\varphi_m \omega_r (\sin \theta_r - \frac{4\pi}{3})}{(S + R)}$$

Speed of the rotor is proportional position of rotor is

$$\frac{d\theta_r}{dt} = \omega_r$$

Figure shows block diagram of three phase of BLDCM.

#### IV. SIMULINK MODEL OF THE BLDC MOTOR

The simulink model of the BLDC motor is shown in fig.2.

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using hall effect sensors embedded into the stator. Most BLDC motors have three hall sensors embedded into the stator on the non-driving end of the motor.

Whenever the rotor magnetic poles pass near the hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three hall sensor signals,

the exact sequence of computation can be determined.

The converter block was developed using the equations below:

$$V_a = (S_1)V_d/2 - (S_4)V_d/2 \tag{10}$$

$$V_b = (S_3)V_d/2 - (S_6)V_d/2$$

$$V_c = (S_5)V_d/2 - (S_2)V_d/2 \tag{11}$$

Every 60 electrical degrees of rotation, one of the hall sensors changes the state. Given this, it takes six steps to complete an electrical cycle. Corresponding to this, with every 60 electrical degrees, the phase current switching should be updated.

However, one electrical cycle may not correspond to a complete mechanical revolution of the rotor. The number of electrical cycles to be repeated to complete a mechanical rotation is determined by the rotor pole pairs. For each rotor pole pairs, one electrical degree is completed. The number of electrical cycles/rotations equals the rotor pole pairs.

Detailed SIMULINK model of the BLDC motor is:

Fig.3. Detailed SIMULINK model of BLDC motor  
 The sinusoidal back-EMF is given as:

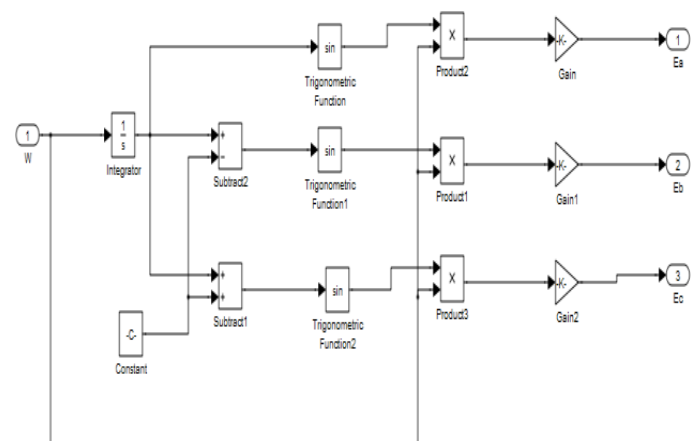
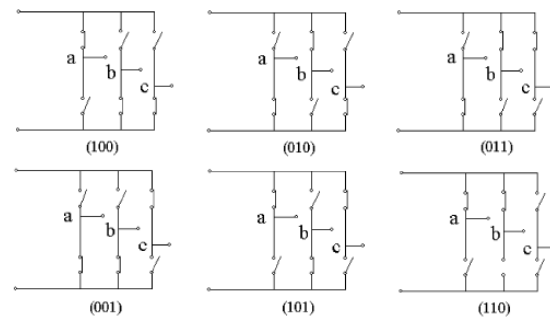
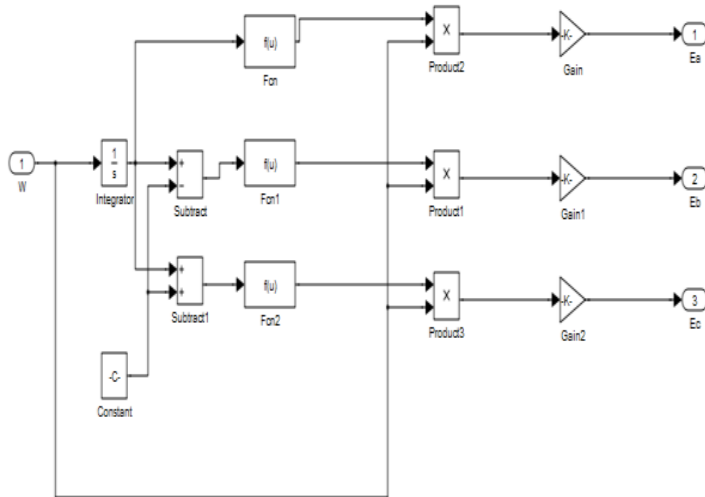


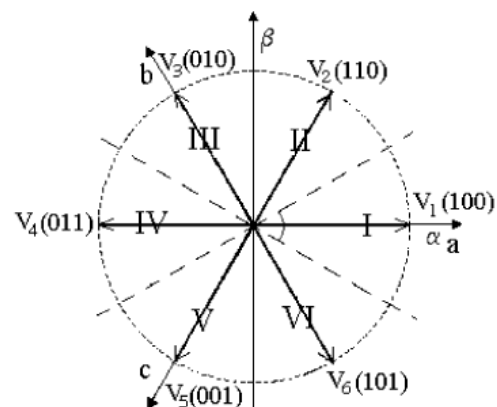
Fig.4(a). Sinusoidal model of the back-EMF  
 The trapezoidal back-EMF is given as:

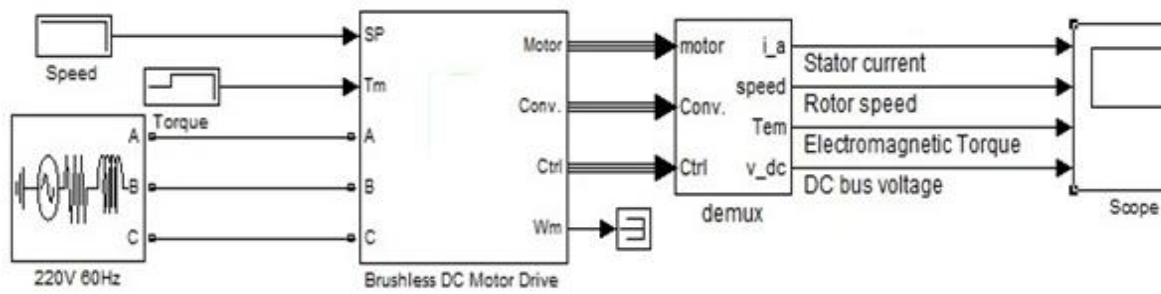


In SVM treats the sinusoidal voltage as a constant amplitude vector rotating at constant frequency. A three-phase voltage vector is transformed into a vector in the stationary d-q coordinate frame which represents the spatial vector sum of the three-phase voltage is the basic principle of SVM.

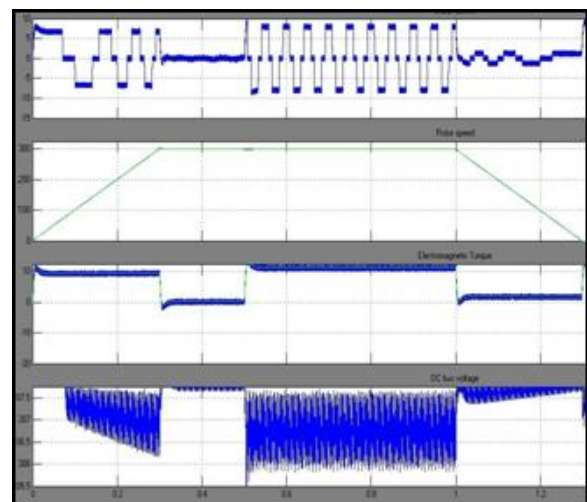
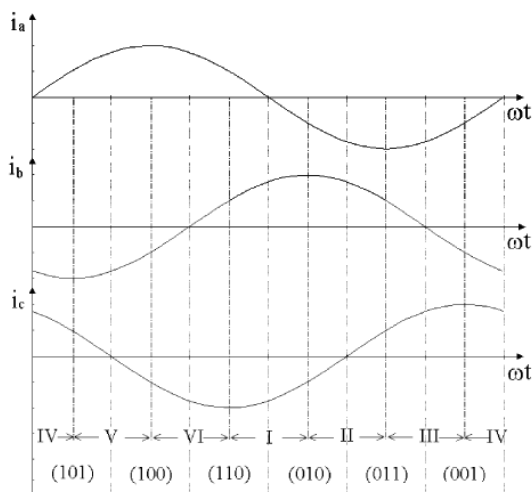
The 120 conduction mode is generally used in BLDC drives. In it only two phases are conducting in normal period while in commutation another phase also conducting through a freewheeling diode [12]. The inverter switching pulses are represent in six binary digits and each digit represents ON i.e. 1 and OFF i.e. 0 which are voltage space vectors. In this mode both the upper arm and lower arm switching of at the same time, so there is only one zero vector is present and the switching states are shown in Fig. 3. The region of three phase stator axes of the motor is divided into six sectors by non-zero voltage space vector and each sector can be composed of two non-zero voltage space vectors and the zero vectors.

Torque $\tau$	Flux $\phi$	Sector					
		I	II	III	IV	V	VI
1	1	$V_1$ (10001)	$V_2$ (001001)	$V_3$ (011000)	$V_4$ (010010)	$V_5$ (000110)	$V_6$ (100100)
	0	$V_2$ (001001)	$V_3$ (011000)	$V_4$ (010010)	$V_5$ (000110)	$V_6$ (100100)	$V_1$ (100001)
	-1	$V_3$ (011000)	$V_4$ (010010)	$V_5$ (000110)	$V_6$ (100100)	$V_1$ (100001)	$V_2$ (001001)
0	1	$V_1$ (100001)	$V_2$ (001001)	$V_3$ (011000)	$V_4$ (010010)	$V_5$ (000110)	$V_6$ (100100)
	0	$V_0$ (000000)	$V_0$ (000000)	$V_0$ (000000)	$V_0$ (000000)	$V_0$ (000000)	$V_0$ (000000)
	-1	$V_3$ (011000)	$V_4$ (010010)	$V_5$ (000110)	$V_6$ (100100)	$V_1$ (100001)	$V_2$ (001001)





Brushless DC Motor Drive



## V. SIMULATION RESULTS

simulation of motor using equations which have been given above parameters. Which have been belong to motor used simulation are as below

$R=0.2, L=8.5 \times 10^{-3}, J=0.089, \text{friction}=0.05, P=4, T_{ss}=20 \times 10^{-6}, f_{sm} = 20 \times 10^3, T_r = 0.076, \omega_n = 179.5069, \text{flux} = 0.17 \text{wb}, \text{Mutual inductance} = 0.002$

Input rotor= 220V,60Hz ,base voltage = $25 \times 10^3, T_L = (0.5 \text{ to } 1.5), \text{speed} = (0 \text{ to } 1) \text{sec}, \text{amplitude} = (300 \text{ } 0), \text{DC bus voltage} = 310 \text{V}, \text{torque limitation} = 17.8 \text{ Nm}, K_p = 3.312, \text{torque controller} = 300.13171, \text{speed cut of frequency} = 285.6936 \text{ Hz}$

## VI. CONCLUSION

In this study, DTC has been applied to a BLDCM, and its utility has been validated by simulations and measurements on BLDCM. Which have very different back-EMF waveforms. The implantation of BLDCM is the estimation of torque and representation of inverter voltage space vector. It has been shown that DTC is capable of improve speed torque control and characteristics , thereby reducing torque ripples.

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