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DIRECT TORQUE CONTROL STRATEGY OF BLDC MOTOR DRIVE FOR FAST DYNAMIC RESPONSE AND TORQUE RIPPLE MINIMIZATION

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ABSTRACT

Brushless DC (BLDC) motor drives are continually gaining popularity in motion control applications but torque ripple generated in the commutation interval is one of the main drawbacks of Brushless DC (BLDC) motors. Therefore,it is necessary to reduce torque ripple and improve effective dynamic response of BLDC motor. This paper presents an comprehensive analysis on the generated torque ripples due to phase commutation in the six switch, three-phase inverter brushless dc motor drives. This paper describes an improved implementation of Direct Torque Control (DTC) to a Brushless DC (BLDC) drive. It is based on the criterion of minimizing the error between the commanded torque and the estimated torque. It adaptively adjusts the phase-current waveform to maintain constant electromagnetic torque so that commutation torque ripple is minimized. The simulation results showed the torque pulsations are minimized with the proposed DTC control strategy and also showed that the dynamic response is fast.

Keywords: Direct torque control, Brushless DC motor drive, torque pulsations and PI controller.

I. INTRODUCTİON

The Brushless DC (BLDC) is a type of AC synchronous motor having characteristics similar to DC motor. This feature makes the BLDC motor superior to induction and other ac motor with respect to easy speed control. In recent times, BLDC drives are used extensively for many applications, like home appliances, automobiles, industries, transportation, and aerospace due to better torque-speed characteristics, dynamic response, high efficiency, long operating life, noiseless operation and higher speed ranges.

BLDC motor has high torque/current ratio compared to permanent magnet synchronous motor. To produce a constant torque, it is required to feed constant current (ideal portion of trapezoidal back EMF) [1], [2], [3]. The commutation occurs at every 600 and torque ripple may be generated during commutation period. These torque ripples due to commutation have made the BLDC motor less suitable for high performance position application. Detailed analysis and attenuating algorithms of the torque ripple due to commutation phenomena were presented in [2] and [3].Torque ripples can be minimized by injecting appropriate current harmonics to cancel the selected torque harmonics [4], [5].

Direct Torque Control (DTC) is another method of controlling the torque ripple and flux linkages. DTC has been developed, implemented and tested BLDC in the papers [6-8]. PI has been used with DTC to improve the dynamic performance of the induction motors [9-10].

This paper presents both conventional current control and Direct Torque Control to minimize torque ripple in a BLDC motor drive. Both the proposed methods are implemented using MATLAB/SimPowerSystems.

The paper is distributed in following sections: Second section describes the operation and modeling of BLDC. Third section describes the conventional current control method. Fourth section depicts the Direct Torque Control strategy for BLDC. Fifth section illustrates simulation results of the proposed method. Conclusions are described in sixth section.

II. MODELING OF BLDC MOTOR

BLDC motor can be analyzed mathematically in two ways: abc phase variable model and d-q axis model. d-q model is consider in this paper due to non-sinusoidal nature of back EMF.The motor is assumed to be star connected with isolated neutral in this model. Following assumptions are made in modeling the motor.

- The motor is not saturated.
- Stator resistances of all the windings are equal and self and mutual inductances are constant.
- Ideal power semiconductor devices.

The electrical and mechanical system is written as:

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

$$\frac{di_b}{dt} = \frac{1}{3L_r}\,[\,V_{ca} + 2V_{bc} - 3Ri_b + (e_a + e_c - 2e_b] \quad 2$$

$$\frac{di_c}{dt} = \frac{1}{3L_r}\,[\,V_{ca} - V_{bc} - 3Ri_c + (e_a + e_b - 2e_{cb}] \quad 3$$

$$E_k = \sum_k K_e\ \omega_m f_e(\theta_r) \quad 4$$

$$T_e = \sum_k K_t\ i_k f_k(\theta_r) \quad 5$$

$$T_e - T_L = J\frac{d\omega}{dt} + B\ \omega_m \quad 6$$

Where, k=a.b,c

ik is the phase current of Kth phase
ek is the back-EMF of Kth phase
Te is the electromagnetic torque
ωm is the mechanical speed of the motor
J is the rotor inertia
B is the damping constant
Rs is the resistance of each phase of the motor
Lr is the inductance of each phase of the motor
Kt is torque constant
Ke is back EMF constant
P is the number of poles
fk(θr) represents the back-EMF as a function of rotor position.

BLDC system is represented by the above equations which are sub divided into mechanical and electrical equations.

III. CONVENTIONAL CURRENT CONTROL

In conventional current control algorithms for BLDC drives, the sinusoidal reference currents are tracked by the stator current through the inner loop designed Hence it is more commonly referred to as current control rather than torque control. A typical current control scheme has the structure shown in Fig. 1. It consists of three independent hybrid current controllers for the three phase currents ia, ib and ic. From the position feedback signal and the torque command signal, phase current reference signals are generated. These reference signals are sinusoidal functions of position θ, and its amplitude is proportional to the desired torque.

ia = I sin(θ)

ib = $I \, \mathrm{Sin}\left(\theta - \frac{2\pi}{3}\right)$ 7

ic = $I \, \mathrm{Sin}\left(\theta + \frac{2\pi}{3}\right)$

The purpose of each of the three current controllers is to produce the switching signals to the inverter in order to force the stator phase currents to follow the reference signals. Sub-harmonic PWM method is used for this purpose. In the sub-harmonic PWM method Fig. 2, the error signal obtained from the difference between the reference and actual current is filtered by a PI controller. The filtered signal is then modulated by a triangular wave so as to produce the inverter switching signals. If the motor has a rotor flux distribution non-sinusoidal then a certain amount of torque ripples, the degree being dependent on the harmonics that are in the back EMF waveform. It is not possible to obtain smooth torque from such a motor using a conventional current control algorithm. If the rotor flux distribution is not sinusoidal, it can be represented as a Fourier series,

$$M_{af} i_f = E_1 \cos\theta + E_3 \cos 3\theta + E_5 \cos 5\theta + E_7 \cos 7\theta + \cdots$$

In case of non-sinusoidal rotor flux distribution,it is observe that after transformation, the Ed term and hence the instantaneous torque will now contain an average component plus harmonics of multiples of six

$$E_d = T_0 + T_6 \cos(6\theta) + T_{12} \cos(12\theta) + \cdots$$

$$T = \frac{3}{2} PI(T_0 + T_6 \cos(6\theta) + T_{12} \cos(12\theta) + \cdots)$$

Hence motor with non-sinusoidal back emf when used with conventional current controller torque ripples are arises.

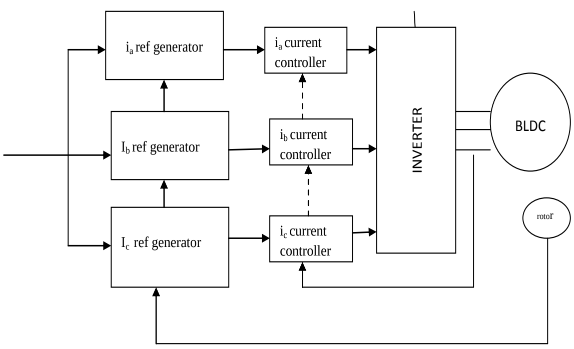

Figure 1. Conventional current control method

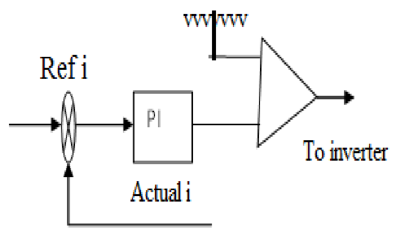

Figure 2. Sub Harmonic PWM converter

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IV. DIRECT TORQUE CONTROL

The electromagnetic torque of permanent magnet brushless machine in the synchronously rotating d-q reference frame can be expressed as [11],[12],[13], when the influence of mutual coupling between the direct axes is neglected.

$$T_e = \frac{3}{2}\frac{P}{2}\left[\left(\frac{dL_d}{d\theta_e}i_{sd} + \frac{d\psi_{rd}}{d\theta_e} - \psi_{sq}\right)i_{sd} + \left(\frac{dL_q}{d\theta_e}i_{sq} + \frac{d\psi_{rq}}{d\theta_e} + \psi_{sd}\right)i_{sq}\right] \quad 8$$

Where as $\psi_{sd} = L_d i_{sd} + \psi_{rd}$

$$\psi_{sq} = L_q i_{sq} + \psi_{rq} \quad 9$$

and θ_e is the rotor electrical angle, i_{sd} and i_{sq} are the d-axes and q axes currents, Ld and Lq are the d and q axes inductances and ψ_{rd} , ψ_{rq} , ψ_{sd} ,and ψ_{sq} are the d and q axes rotor and stator flux linkages, respectively.

A fundamental component of flux linkage is transformed into a dc component, after d-q transformation. while 5th and 7th harmonics transform into 6th harmonics, 11th and 13th harmonics transform into 12th harmonics, 17th and 19th harmonics transforms into 18th harmonics, and so on. Thus for a machine having non sinusoidal flux ψ_{rd} is composed of dc component and 6th, 12th, 18th harmonics etc., while ψ_{rq} consist of 6th, 12th, 18th harmonics etc.

These flux harmonics are causes for the torque pulsations and the influence of higher order harmonics in the stator winding inductance usually being negligible[14] therefore, for machines equipped with a surface mounted magnet rotor i.e. non salient, it can be assumed that Ld and Lqare constant i.e., $L_d = L_{d0}$, $L_q = L_{q0}$, and the electromagnetic torque can be expressed as

$$T_e = \frac{3}{2}\frac{P}{2}\left[\left(\frac{d\psi_{rd}}{d\theta_e} - \psi_{rq}\right)i_{sd} + \left(\frac{d\psi_{rq}}{d\theta_e} + \psi_{rd}\right)i_{sq} + (L_{d0} - L_{q0})i_{sq}i_{sd}\right] \quad 10$$

Hence $L_{q0} = L_{d0} = L_s$,For non-salient pole brushless machine with a non-sinusoidal stator flux linkage, the electromagnetic torque of BLDC can be simplified as

$$T_e = \frac{3}{2}\frac{P}{2}\left[\left(\frac{d\psi_{rd}}{d\theta_e} - \psi_{rq}\right)i_{sd} + \left(\frac{d\psi_{rq}}{d\theta_e} + \psi_{rd}\right)i_{sq}\right] \quad 11$$

Electromagnetic torque in the rotating d-q axes reference frame as,

$$T_e = \frac{3}{2}\frac{P}{2}\left[\left(\frac{d\psi_{rd}}{d\theta_e}\right)i_{sd} + \left(\frac{d\psi_{rq}}{d\theta_e}\right)i_{sq}\right] \quad 12$$

Where $\psi_{r\alpha}$ and $\psi_{r\beta}$ are the α and β axes rotor flux linkages. In stationary α-β reference frame.

$$\psi_{r\alpha} = \psi_{rd}\cos\theta_e - \psi_{rq}\sin\theta_e$$

$$\psi_{r\beta} = \psi_{rd}\sin\theta_e + \psi_{rq}\cos\theta_e \quad 13$$

The stator flux linkage vector can be found from the measured currents $i_{s\alpha}$ and $i_{s\beta}$ and stator voltages $U_{s\alpha}$ and $U_{s\beta}$ as

$$\psi_{s\alpha} = \int (U_{s\alpha} - R i_{s\alpha})dt$$

$$\psi_{s\beta} = \int (U_{s\beta} - Ri_{s\beta})dt \quad 14$$

Where R is the stator resistance. The magnitude and angular position of the stator flux linkage vector is found as

$$\psi = \sqrt{\psi_{s\alpha}^2 + \psi_{s\beta}^2} \quad 15$$

$$\theta = \arctan\frac{\psi_{s\alpha}}{\psi_{s\beta}} \quad 16$$

The rotor flux linkages can be obtained from the stator flux linkages.

$$\psi_{r\alpha} = \psi_{s\alpha} - L_s i_{s\alpha} \quad 17$$

$$\psi_{r\beta} = \psi_{s\beta} - L_s i_{s\beta} \quad 18$$

The torque can be calculated from (12). Here it is assuming that the rotor speed is proportional to the EMF and the differential term in (12) can be pre-determined from the back EMF waveform. Six nonzero voltage space vectors are defined for a BLDC drive and the sectors of the circular voltage vector which enable the voltage vector to be selected in terms of the stator flux linkage being shown in fig3.

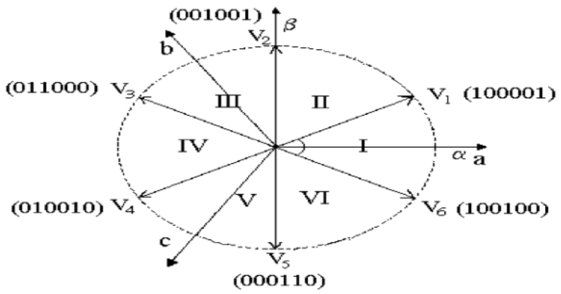

Figure 3. Nonzero-voltage space vectors for BLDC drive

However, in BLDC motor drive, only two phases are conducting in the 1200 conduction mode, except during commutation periods when all three phases conduct, the unexcited phase conducting via a freewheeling diode. Since upper and lower switches in the same phase leg may both be simultaneously off in BLDC drive, irrespective of the state of the associated freewheeling diode , six digits are required to represent the states of the inverter switches, one digit for each switch. Thus , the voltage space vector V1, V2, V3, V4, V5 and V6 are represented as switching signals, the logical values express the states of upper and lower switching signals for phase A, B and C respectively. The zero voltage space vector is defined as (000000).The voltage space vectors have a 300 phase difference in the α-β reference frames for a BLDC drive.

Fig 4 shows a block diagram of a DTC BLDC drive, stator phase currents and phase voltages are measured and then transformed into a stationary reference transformation.The stator flux linkage in the stationary reference frame can be found from stationery reference current and voltage. The rotor flux linkage in the stationary reference frame can be calculated from (17) and (18), while the magnitude of stator flux linkage and the electromagnetic torque can be obtained from (15) and (12), respectively. Torque command is obtained when the speed feedback derived from rotor position sensors is compared to the reference speed command and is fed to the proportional integral controller. The torque command and stator flux linkage are obtained from hysteresis controllers by comparing the estimated electromagnetic torque and stator flux linkage with their demanded values. The switching sequence of the inverter can be determined according to the torque status and stator flux linkage from the outputs of two regulators as shown in fig4 and table I, and the sector in which the stator flux linkage is located at that instant of time. In each sector, if the actual stator flux linkage is equal to the commanded stator flux linkage (Φ=0), only one non zero voltage space vector and a zero voltage vector are used to control the increase (T=1) or decrease (T=0) of the torque, since during any 600 electrical period only two phases are excited and controlled in a BLDC drive,as indicated in table I. in addition , when the actual flux linkage is smaller than the commanded value (Φ=1), the non-zero voltage space vector is used to increase the flux linkage, while when the actual flux linkage is greater than the commanded value (Φ=-1), the non-zero voltage space vector is used to decrease the stator flux linkage.

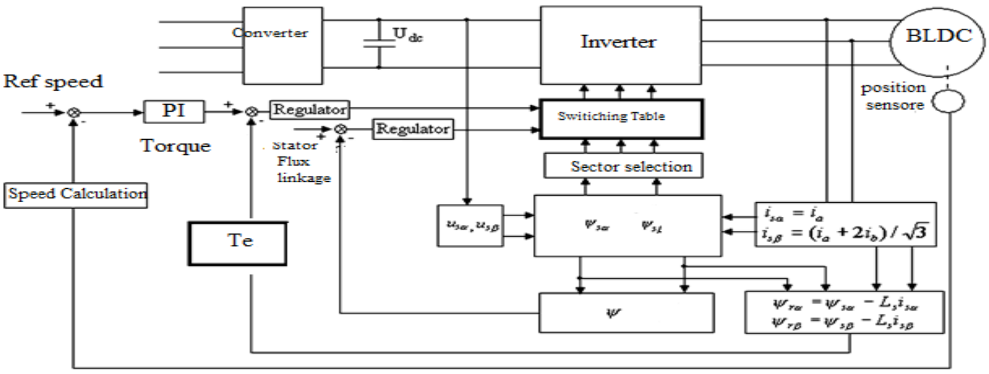

Figure 4. Block diagram of DTC BLDC

V. RESULTS

In order to show the effectiveness of the proposed DTC technique, simulation has been carried out on a 4-pole BLDC model whose parameters are given in appendix. The sampling period is chosen as 0.13 s for the DTC BLDC drive. Figures shows the steady state performances of torque voltage and current for the sampling period of Δt=0.13s. The reference value for torque is0.6 Nm and 1Wb for the stator flux. The rotor speed is set to 400 rpm. Fig. 6 shows phase to ground voltage in trapezoidal shape according to basic of BLDC, fig.7 shows the estimated torque with minimum ripples due to DTC BLDC technique, fig 9 shows the line voltage and fig.10show the locus of the stator flux linkage. An appreciable reduction of torque ripples has been obtained by using the DTC BLDC techniquehere presenting simulation results.

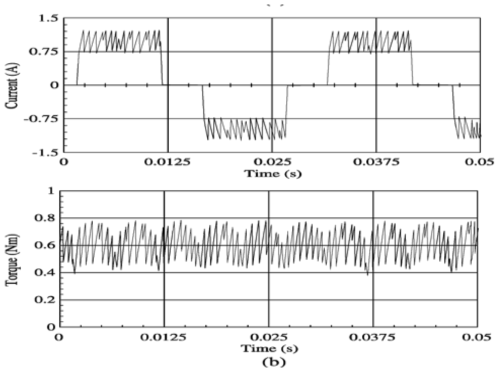

Figure 5. Current and torque waveforms with.

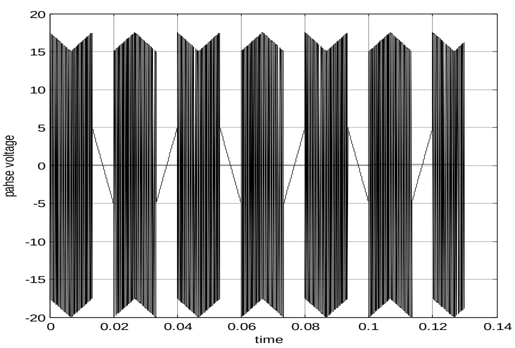

Figure 6. Phase to ground voltage

conventional PWM current control

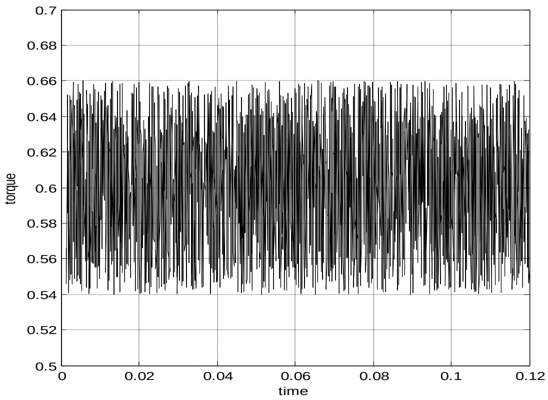

Figure 7. Estimated electromagnetic Torque

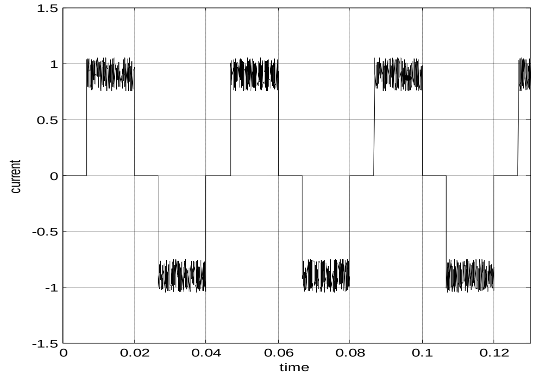

Figure 8. phase current

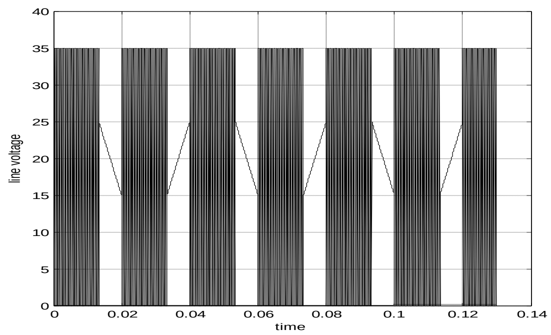

Figure 9. Line voltage

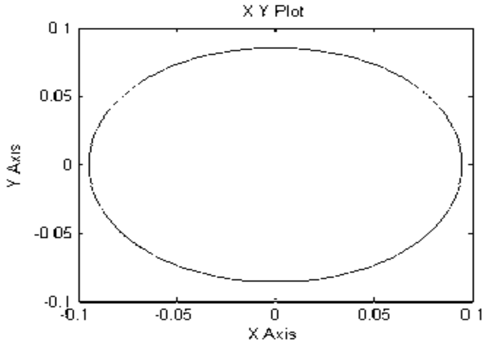

Figure 10. Locus of stator flux linkages

As shown in Fig. 5 and Fig. 7, the torque ripple in DTC BLDC scheme is smaller than that of conventional PWM current control method. Furthermore, the improvement of torque ripple is much more. In conventional PWM current control method, the torque error is ±0.2 Nm and it is reduced to ±0.06 Nm in case of proposed DTC BLDC motor drive. In Fig.7, the torque is more stable and there is lessharmonic current than that in Fig. 5.

V. CONCLUSIONS

In this paper, torque ripple which is generated during current commutation have been analyzed and improved DTC technique has been developed to BLDC motor drive to reduce torque ripple. The simulation results showed better dynamic performance of the BLDC motor and reduced torque ripple.

REFERENCES

[1] P. Pillay and R. Krishnan, “Application characteristics of permanent magnet synchronous and brushless DC motors for servo drives,” in Cont Rec. IEEHIAS Annu.Meeting, 1987, pp. 38C390.

[2] Carlson, M. Lajoie-Mazenc, and J. Fagundes, “Analysis of torque rippledue to phase commutation in brushless DC machines,” IEEE Trans. Ind.Applicaf..vol. 28, no. 3, pp. 632-638, 1992.

[3] C. Berendsen, G. Champenois, and A. Bolopion, “Commutation strategiesfor brushless DC motors: Influence on instant torque,” IEEE Trans.on Power Electron.. vol. 8, no. 2, pp. 231-236, Apr. 1993.

[4] D. Jouve and D. Bui, "Torque ripple compensation in DSP based brushless servo drive," in Proc. PCIM, Intelligent Motion, 1993, pp.28-37.

[5] F. Piriou, A. Razek, R. Perret, and H. Le-Huy, "Torque characteristics of brushless dc motors with imposed current waveform," in ContRec.IEEWIASAnnu. Meeting, 1986, pp. 176-181.

[6] Y. S. Lai and J. H. Chen, "A new approach to direct torque control of induction motor drives for constant inverter switching frequency and torque ripple reduction," IEEE Trans. Energy Converters., vol. 16, no. 3,pp. 220–227, 2001.

[7] T. S. Low, K. J. Tseng, K. S. Lock, and K.W. Lim, "Instantaneous torque control," in Proc. Fourth Int. Conf. Electrical Machines and Drives, Sep.13–15, 1989, pp. 100–105.

[8] C. French and P. Acarnley, "Direct torque control of permanent magnet drives," IEEE Trans. Ind. Appl., vol. 32, no. 5, pp. 1080–1088, Sep./Oct.1996.

[9] D. Ishak, Z. Q. Zhu, and D. Howe, "Permanent magnet brushless machines with unequal tooth widths and similar slot and pole numbers, "IEEE Trans. Ind. Appl., vol. 41, no. 2, pp. 584–590, Mar./Apr. 2005.

[10] Bimal K Bose, "Modern Power Electronics and AC Drives", Pearson Education Publications, New Delhi, 2002, Chapter 9, pp483 - 495.

[11] S. K. Chung, H. S. Kim, C. G. Kim, and M. J. Youn, "A new instantaneous torque control of PM synchronous motor for high-performance direct-drive applications," IEEE Trans. Power Electron., vol. 13, no. 3, pp. 388–400, May 1998.

[12] P. C. Krause, Analysis of Electric Machinery. New York: McGraw- Hill, 1987.

[13] V. Gourishankar, Electromechanical Energy Conversion. Scranton, PA: International Textbook, 1965.

[14] B. H. Ng, M. F. Rahman, and T. S. Low, "An investigation into the effects of machine parameters on torque pulsation in a brushless dc drive," in Proc. IEEE IECON'88, 1988, pp. 749–754.

Table1: Switching table for DTC of BLDC drive

Torque T	**Flux Φ**	**Sector**					
		I	**II**	**III**	**IV**	**V**	**VI**
0	**-1**	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_0	V_0	V_0	V_0	V_0
	1	V_1	V_2	V_3	V_4	V_5	V_6
1	**-1**	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_2	V_3	V_4	V_5	V_6	V_1
	1	V_1	V_2	V_3	V_4	V_5	V_6

V_1 = 100001 V_2 =001001

V_3 = 011000 V_4 =010010

V_5 = 000110 V_6 =100100

V_0 =000000