Direct Torque Control of Brush less DC Motor drive with modified switching algorithm

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***Abstract*— Conventional direct torque control (DTC) of BLDC motor drive is quite cumbersome, because it operates on trapezoidal back EMF. The conventional DTC gives high torque ripple and switching frequency is variable due to bang-bang controllers. In this article, a new direct torque control scheme is proposed to a BLDC motor. This paper focuses to provide better direct torque control mechanism without using co-ordinate transformation and a new modified switching table is proposed with decoupled stator flux linkages. The Proposed DTC is developed based on error produced from torque hysteresis controller and sector information of flux space vector. The sector of flux space vector is obtained by estimating the rotor position of BLDC motor using hall sensors. In this paper, operation of BLDC motor drive in forward and reverse motoring conditions was exhibited. The proposed method is simulated in MATLAB software, Simulation results are provided for forward and reverse motoring and it provides less torque ripple in steady state.

Keywords— Direct Torque Control (DTC), BLDC Motor, Modified Switching Table and Torque Ripple.

I. Introduction

The developments in permanent magnets lead to implementation PMBLAC (PMSM) and PMBLDC drives. PMSM and BLDC motor drives became popular for high performance applications, varies from position control to high power traction drive applications, due to its immense advantages such as high Torque density, more Pull out torque, high efficiency and large torque to inertia ratio [2]-[4]. The PMSM and BLDC differ only in their current and back EMF waveforms. BLDC motors are less expensive compared to PMSMs due to its concentrated stator windings.

In most of the position control applications low frequency ripple free torque is required for BLDC motors. A vast study has been done for current and torque control of BLDC, due to trapezoidal back EMF the coordinate transformation is not easy as compared to PMSM [4], [5].

In automotive industries and position control for robots and aeronautical drives are equipped with BLDC motors [4]. Most of control strategies for BLDC motors are based on current control and torque control. The most popular method for minimizing torque ripple is generalized harmonic injection scheme [7]-[12]. In these methods torque is not controlled directly, due to its fast dynamic variations depending on load. The dynamic torque control is developed by using position sensors. Hysteresis controllers are used to control the torque [6] but it is complex.

To overcome aforementioned difficulties DTC technique was developed for BLDC motor. The DTC technique was first proposed for induction motors [1] due to its fast dynamic characteristics and its simplicity DTC is extensively implemented for BLDC motors. Various distinct DTC schemes have been proposed for BLDC motors using different inverter topologies [13-16]. One of the recent methods is controlling torque directly and indirect flux control [17] of BLDC motor drive with non sinusoidal back EMF. In [17], a novel approach to achieve low frequency torque ripple-free DTC with maximum efficiency by using dq-reference frame theory was implemented. In this algorithm line-line constants are taken to eliminate low frequency oscillations of BLDC motor drive. The selection of back EMF constants plays a key role to reduce low frequency oscillations. A high performance DTC was proposed by Zhu and Leong [18] that exhibits a vector selection table for inverter. In this article comparison of BLAC/DC drives was carried and it is implemented with abc-dq transformation. DTC of BLDC motor drives with improved reliability is proposed by balancing switching frequencies and significant reduction in mean quantity of common mode voltage (CMV), the proposed method compromises with torque ripple [19]. A comparative study was performed on application of DTC to BLAC and BLDC drive [13].

The conventional DTC of BLDC motor is difficult since it has trapezoidal back EMF and flux linkage. Due to trapezoidal back EMF it is very difficult to apply abc-dq transformation. The conventional DTC utilizes torque hysteresis and flux hysteresis controllers so it develops higher amount of torque and flux ripple. In this paper flux linkages are decoupled, by decoupling the stator flux linkages it gives simple control algorithm. This article, introduces a new switching control strategy to reduce most of the problems while implementing conventional DTC of BLDC drives. In the proposed method, it utilizes three-level torque hysteresis comparator and sector information of flux space vector. The aim of this proposed paper is to operate BLDC motor drive in forward and reverse motoring with a new voltage switching table. The voltage vectors are

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selected in such a way to reduce torque ripple. The proposed direct torque control scheme can be used for position control applications such as robots, industrial applications.

II. Proposed DTC Strategy Of BLDC Motor Drive

Direct torque control allows direct control of BLDC motor variables by the selection of inverter gating signals. The control signals are used to develop the required torque either to increase or to decrease.

The voltage vectors of the inverter are selected based on torque hysteresis controller and sector identification. The block diagram of proposed DTC strategy is shown in Fig. 1(a). In the proposed scheme BLDC motor is fed with two level six switch three phase inverter as shown in Fig. 1(b). The two level inverter has six active (non-zero) states and two zero states. The switching vectors of the inverter are formulated using $V_S = \frac{2}{3} V_{dc}\left(S_a + S_b e^{j2\pi/3} + S_c e^{j4\pi/3}\right)$.

The three-phase conducting mode of BLDC motor drive is characterized by two null vectors and six active voltage vectors. The proposed DTC of BLDC drive is operated with a three-level torque hysteresis comparator and a sector number of flux space vector is utilized to select switching states of inverter.

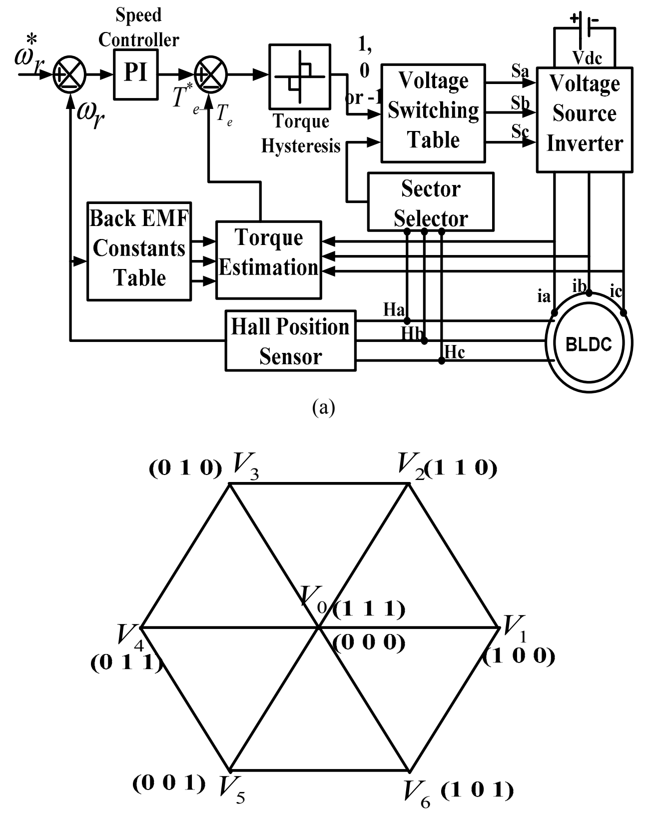

Fig.1: a) Block Diagram of Proposed DTC strategy and b) Switching States of two-level inverter and Division of sectors.

A. Identification of sector number:

The speed regulation of BLDC motor can be achieved by using Hall Effect signals, instead of using speed encoders. The hall sensors enhance the performance. The sectors of BLDC motor drive mainly depends on signals obtained from hall sensors. Table I Depicts sector identification based on signals generated from hall sensors. In this method a three-level torque hysteresis comparator is used instead of two level torque comparator used in the past decades. By using the three level torque controller forward and reverse motoring operation of BLDC drive can be obtained. The three-level hysteresis controller takes care on sector to sector commutations.

B. Algorithm for reduction of torque and flux ripple:

To reduce the torque ripple, it is important to reduce voltage ripple. The voltage ripple directly affects the performance of BLDC motor drive. Hence to maintain lower torque ripple, it is required to control voltage ripple. The output voltage of inverter is given by (1)

$$V_S = R_S i_S + L_S\left(\frac{di_S}{dt}\right) + e_0 \tag{1}$$

Where V_S is output voltage of inverter and it has six active switching states shown in Fig. 1(b). e_0 is developed EMF of motor and it depends on rotor speed, L_s is stator inductance of motor and i_s is stator current. On neglecting stator voltage, the variation of stator current is given by (2)

$$\left(\frac{di_S}{dt}\right) = \left(\frac{1}{L_S}\right) * \left(V_S - e_0\right) \tag{2}$$

From (2), the derivative of current can be maintained as minimum by using appropriate voltage space vectors, because the change of current depends on voltage space vector and back EMF and it is independent of flux linkages. The selection of active voltage vectors to maintain lower torque ripple are as shown in Table II.

Table I.
Identification of Sector Number

Ha	Hb	Hc	Sector
1	1	0	1
0	1	0	2
0	1	1	3
0	0	1	4
1	0	1	5
1	0	0	6

Table II.
Depicts the switching table used in proposed DTC

Torque Error	Sector					
	1	2	3	4	5	6
1	V_2	V_3	V_4	V_5	V_6	V_1
0	V_7	V_0	V_7	V_0	V_7	V_0
-1	V_6	V_1	V_2	V_3	V_4	V_5

III. Simulation Results

The proposed DTC algorithm is applied to two-level VSI based BLDC motor drive and it is simulated at different load conditions by using SIMULINK. The steady-state and transient results of proposed DTC are shown from Fig. 2 to Fig. 10. The simulations are carried out at different load conditions for convenience the results are exhibited for 60% of rated torque as a sample. The results are shown for both forward and reverse motoring of motor drive.

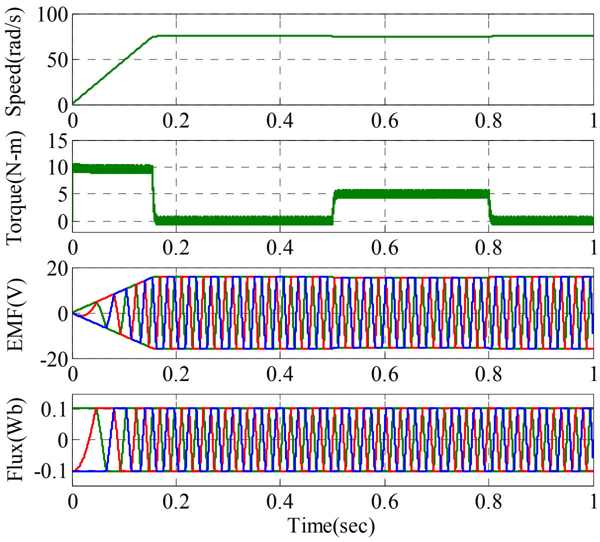

Fig. 2: Simulation response of proposed DTC: (a) variation of motor speed from 0 to 75 rad/s; (b) load torque of 5 N-m is applied at 0.5 s and unloaded at 0.8 s; (c) Induced EMF (V); and (d) Stator Flux (Wb).

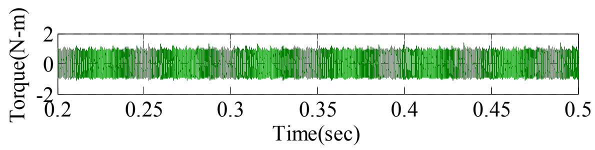

Fig. 3: Torque ripple of conventional DTC at 75 rad/s under steady-state.

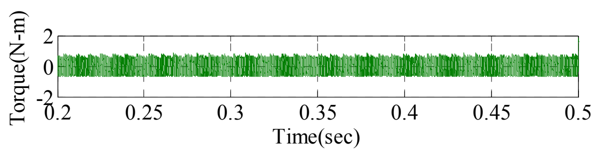

Fig. 4: Torque ripple of proposed DTC at 75 rad/s under steady-state.

The simulation response of forward motoring mode of BLDC motor drive with proposed DTC for a speed of 75 rad/s is shown in Fig. 2, and it represents the motor speed variation from 0 to 75rad/s, corresponding variation in load torque (N-m), induced EMF (V) and Stator flux (Wb). Fig. 3 represents steady state torque ripple of conventional DTC at a motor speed of 75 rad/s. Fig. 4 represents steady-state torque ripple of proposed DTC at 75 rad/s.

Fig. 5 represents the motor speed variation from 0 to 50 rad/s, corresponding variation of load torque (N-m) and motor is loaded with 5 N-m at 0.5 sec and unloaded at 0.8 s, induced EMF at motor terminals (V) and stator Flux (Wb). Same load torque is applied for 50 rad/s and 75 rad/s.

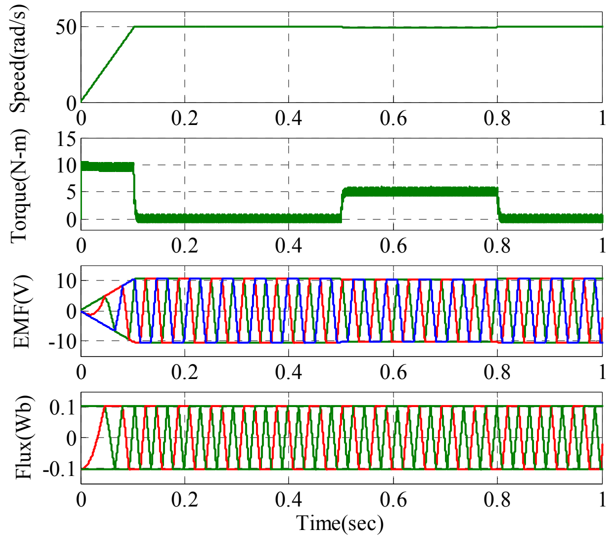

Fig. 5: Simulation response of proposed DTC: (a) variation of motor speed from 0 to 50 rad/s; (b) load torque of 5 N-m is applied at 0.5 s and unloaded at 0.8 s; (c) Induced EMF (V); and (d) Stator Flux (Wb).

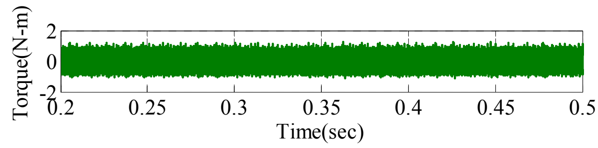

Fig. 6: Torque ripple of proposed DTC at 50 rad/s under steady-state.

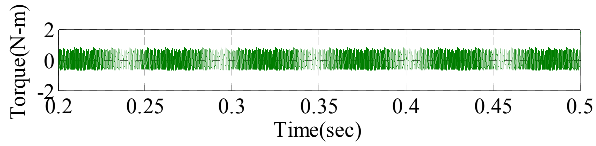

Fig. 7: Torque ripple of proposed DTC at 50 rad/s under steady-state.

Fig. 6 represents torque ripple of conventional DTC at a speed of 50 rad/s under steady-state. Fig. 7. represents torque ripple of proposed DTC at 50 rad/s under steady-state. Fig. 8 represents simulation results of BLDC motor in forward motoring and reverse motoring mode. Fig. 8 represents simulation results of BLDC motor in forward and reverse motoring modes. To realize two quadrant operation (quadrant 1 and 3) of BLDC motor drive initially motor is driven from 0 to 75 rad/s at 0.5 sec the speed of motor is varied from 75 rad/s to -75 rad/s. the corresponding variation of speed, torque, EMF and flux are represented in Fig. 8. Fig. 9 is to compare steady- state torque ripple of conventional and proposed DTC for speeds 75 rad/s and 50 rad/s. Fig. 10. represents forward motoring and reverse motoring operation of motor drive and speed varied from 0 to 50 rad/s at 0.5 s the speed changed from 50 rad/s to -50 rad/s. Fig. 4 and Fig. 7 represents steady state torque ripple of BLDC motor drive. From Fig. 4 and Fig. 7 the torque ripple of proposed DTC is less by comparing with conventional DTC. The proposed DTC strategy utilized a three-level torque hysteresis comparator, by using three-level torque comparator and modified voltage switching table the proposed DTC can produce less torque ripple at various speeds of operation of BLDC motor drive. Fig. 8 and Fig. 9 represent forward and reverse motoring operations of BLDC motor drive and also it shows the motor drive is capable to operate under high speed transients. From Fig. 10 it is identified that the proposed DTC has less torque ripple.

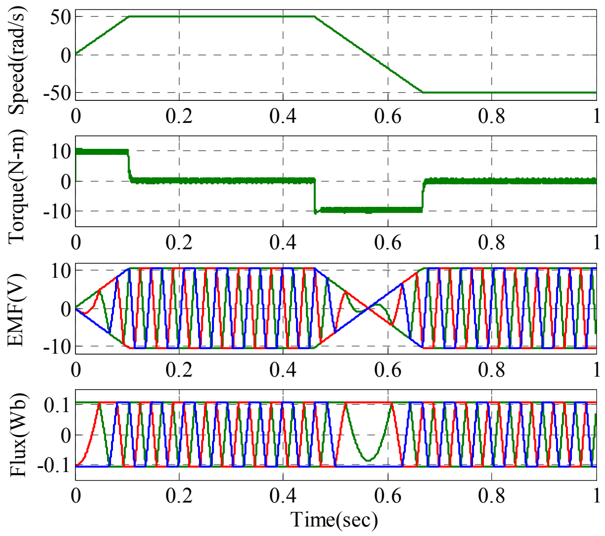

Fig. 8: Simulation results of proposed DTC: (a) variation of rotor speed from 0 to 50 rad/s and change of speed applied at 0.5 s from 50 rad/s to -50 rad/s; (b) load torque (N-m); (c) Induced EMF (V); and (d) Stator Flux (Wb).

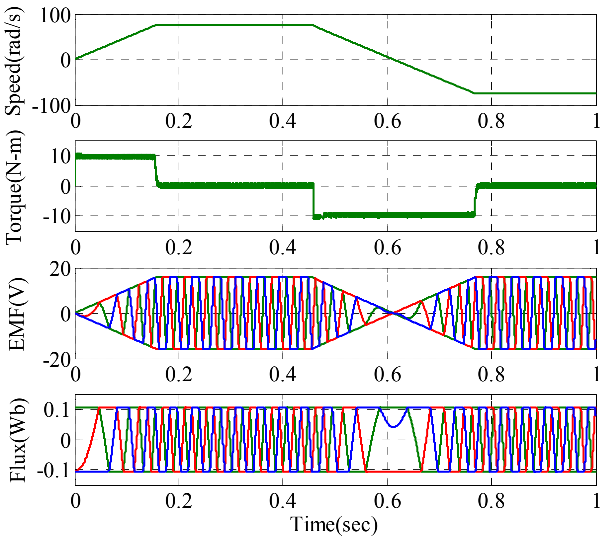

Fig. 9: Simulation results of proposed DTC: (a) variation of rotor speed from 0 to 75 rad/s and speed change applied at 0.5 s from 75 rad/s to -75 rad/s; (b) load torque (N-m); (c) Induced EMF (V); and (d) Stator Flux (Wb).

The simulation results of proposed DTC of BLDC motor drive is shown from Fig 2 to Fig 10. From the simulation results, it is clear that the proposed DTC reduces torque ripple when compared with conventional DTC and it is observed from Fig 3,4 and Fig 6,7. The numerical values of torque ripple is shown in Fig 10 for comparison.

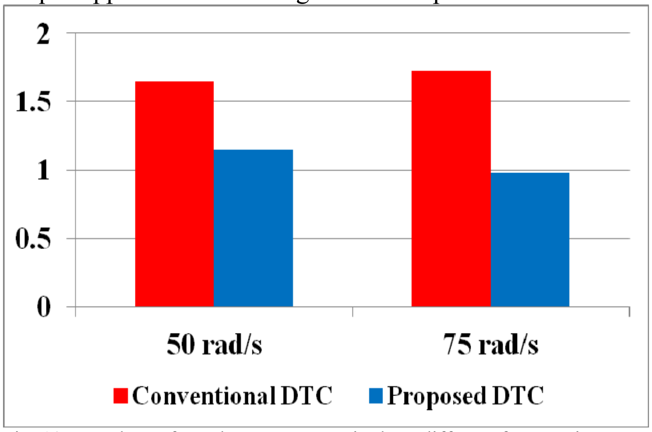

Fig. 10: Bar chart of steady state torque ripple at different frequencies.

IV. Conclusion

In this article, a new direct torque control of BLDC motor drive for forward and reverse motoring is developed with the help of an optimized switching table. The voltage vectors are selected in such a way that, it reduces voltage ripple and torque ripple. The implemented Switching table based DTC strategy is simple in structure, easily implementable, absence of co-ordinate transformation and uses simple hall sensors. It has excellent steady-state and transient performance during speed reversal and sudden changes of load demands so it has high reliability.

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