DIRECT TORQUE CONTROL IN BLDC MOTOR USING FOUR SWITCH INVERTER

D.Suganyadevi[1], Dr. M. Sathiskumar[2]

Abstract—**Direct torque control (DTC) of three phase brushless DC Motor (BLDC Motor) using PI Controller. Speed performance is also improved when there is B4 inverter. Reconstruction of inverter design from six switches to four switch, which will reduce the torque ripples. Thus, Brushless DC motors also known as electronically commutated motors, where in torque ripples are minimized generally by using current control techniques but the present work has method of two level and four level torque controller for reduction of torque ripples in BLDC motor using the direct torque control. The whole drive system is simulated in MATLAB/SIMULINK based on the system devices, BLDC motor and inverter. The reference speed and actual speed is compared with the help of PI controller and that error signal is used for generating the reference torque and flux. The proposed method is implemented using MATLAB/SIMULINK version 2011a.**

***Index Terms*—DTC, BLDC Motro, B4, B6 switches, two level and four level controller.**

I. INTRODUCTION

A motor that retains the characteristics of a dc motor but eliminates the commutator and the brushes is called a Brushless DC motor. Brushless DC(BLDC) motors can in many cases replace conventional DC motors. They are driven by dc voltage but current commutation is done by solid state switches i.e., the commutation is done electronically. BLDC motors are available in many different power ratings, from very small motors as used in hard disk drives to large motors in electric vehicles. Three phase motors are most common but two phase motors are also found in many applications. The torque of the BLDC motor is mainly influenced by the waveform of back-EMF (the voltage induced into the stator winding due to rotor movement).The permanent magnet materials used for BLDC motors are ALINCO, Cobalt-samarium, Barium and strontium ferrites, Neodymium-Iron-Boron. A brushless dc motor is a dc motor turned inside out, so that the field is on the rotor and the armature is on the stator. The brushless dc motor is actually a permanent magnet ac motor whose torque-current characteristics mimic the dc motor. Instead of commutating the armature current using brushes, electronic commutation is used. This eliminates the problems associated with the brush and the commutator arrangement, for example, sparking and wearing out of the commutator-brush arrangement, thereby, making a BLDC more rugged as compared to a dc motor. Having the armature on the stator makes it easy to conduct heat away from the windings, and if desired, having cooling arrangement for the armature windings is much easier compared to a dc motor[1,2]. In effect, a BLDC is a modified PMSM motor with the modification being that the back-EMF is trapezoidal instead of being sinusoidal as in the case of PMSM. The” commutation region” of the back-EMF of a BLDC motor should be as small as possible, while at the same time it should not be so narrow as to make it difficult to commutate a phase of that motor when driven by a Current Source Inverter. The flat constant portion of the back-EMF should be 120° for a smooth torque production. The position of the rotor can be sensed by using an optical position sensors and its associated logic. Optical position sensors consist of phototransistors (sensitive to light), revolving shutters, and a light source. The output of an optical position sensor is usually a Logical signal[2,3].A BLDC motor is a permanent magnet synchronous that uses position detectors and an inverter to control the armature currents. The BLDC motor is sometimes referred to as an inside out dc motor because its armature is in the stator and the magnets are on the rotor and its operating characteristics resemble those of a dc motor shown in figure 1.Instead of using a mechanical commutator as in the conventional dc motor, the BLDC motor employs electronic commutation which makes it a virtually maintenance free motor. There are two main types of BLDC motors: trapezoidal type and sinusoidal type[4]. In the trapezoidal motor the back-EMF induced in the stator windings has a trapezoidal shape and its phases must be supplied with quasi-square currents for ripple free operation. The sinusoidal motor on the other hand has a sinusoidal shaped back EMF and requires sinusoidal phase currents for ripple free torque operation. The shape of the back EMF is determined by the shape of rotor magnets and the stator winding distribution[3,4]. The sinusoidal motor needs high resolution position sensors because the rotor position must be known at every time instant for optimal operation. It also requires more complex software and hardware. The trapezoidal motor is a more attractive alternative for most applications due to simplicity, lower price and higher efficiency.

BLDC motors exist in many different configurations but the three phase motor is most common type due to efficiency and low torque ripple. Based on the rotor position, the power devices are commutated sequentially every 60 degrees. Instead of commutating the armature current using brushes, electronic commutation is used for this reason it is an electronic motor[5]. This eliminates the problems associated with the brush and the commutator arrangement, for example, sparking and wearing out of the commutator brush arrangement, thereby, making a BLDC more rugged as

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ISSN: 2278 – 7798

compared to a dc motor. The brushless dc motor consist of four main parts power converter, permanent magnet-synchronous machine (PMSM) sensors, and control algorithm [5,6]. The power converter transforms power from the source to the PMSM which in turn converts electrical energy to mechanical energy. One of the salient features of the brush less dc motor is the rotor position sensors ,based on the rotor position and command signals which may be a torque command, voltage command speed command and so on the control algorithms determine the gate signal to each semiconductor in the power electronic converter.

II. CONCEPT OF DTC OPERATION

DTC strategies allow a direct control of the BLDC motor variables through an appropriate selection of the inverter control signals, in order to fulfil the requirements as whether the electromagnetic torque needs to be increased or decreased. Direct torque control (DTC) was originally developed for induction machine drives and directly controls the flux linkage and electromagnetic torque, considering the electrical machine, the power electronic inverter, and the control strategy at the system level. A relationship is established between the torque, the flux and the optimal inverter switching so as to achieve a fast torque response. It exhibits better dynamic performance than conventional control methods, such as vector control, is less sensitive to parameter variations, and is simpler to implement. DTC has been successfully applied to induction machines and more recently, to BLAC machines [10]. This paper considers the application of direct torque control, to a three-phase BLDC drive operating in the 120° conduction mode (i.e. two phases conducting) to achieve instantaneous torque control and reduced torque ripple. The essential differences between the DTC of BLDC and BLAC drives are in the torque calculation and the representation of the voltage space vectors.

The electromagnetic torque estimation is the key factor in the DTC of a BLDC motor drive in the constant torque region. For a surface–mounted BLDC motor the back-EMF waveform is trapezoidal irrelevant of conducting mode. BLDC operates in both constant torque region and constant power region. Back-EMF of motor is below the DC voltage source of inverter in constant torque region (below base speed) and is increased more than DC voltage value above nominal speed [10]. Therefore stator inductance avoids abrupt increase of phase current and deteriorates output torque of motor. Therefore in this paper operation of BLDC motor is considered only in the constant torque region. Torque error, stator flux error, and stator flux angles are regularly used to select proper voltage space vector for switching in DTC technique. In this paper flux linkage error is eliminated because of variations of stator flux magnitude regarding changes in resistance, current and voltage, and specifically sharp dips at every commutation. This is due to the presence of freewheeling diode. Therefore the control of stator flux linkage is very complex [4,8].

III.B4 INVERTER IN THE ARMATURE

The operation basis of the B4-inverter-fed BLDC motor drive. Fig.1shows the connections of the drive with two phases (phase-a and phase-c) of the BLDC motor supplied through the B4-inverter legs, while the third one (phase-b) is linked to the middle point of the dc-bus voltage [3,9]. The four switch three phase BLDC motor drive system is based on some assumptions. All the stator phase windings have equal resistance per phase and constant self and mutual Inductances. Power semiconductor devices are ideal Iron losses are negligible and the motor is unsaturated.

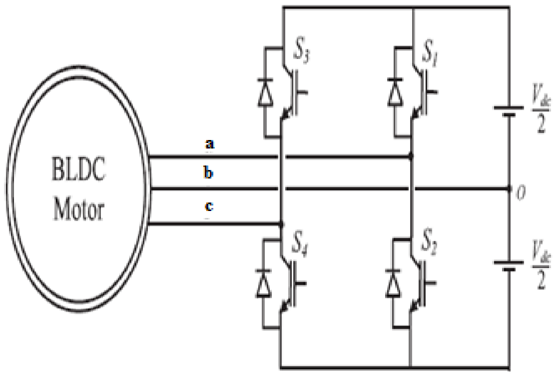

Fig .1 B4-inverter-fed BLDC motor drive connection

A. Operation Under Two-Phase Conduction Mode

The four active voltages vectors are V_1 , V_2 , V_3 , and V_4 generated by the B4-inverter under the two-phase conduction mode.The corresponding switching combinations ($S_1S_2S_3S_4$) are equal to (1000), (0010), (0100), and (0001), respectively, where, from left to right, the binary values denote the state of the upper and lower switching signals, corresponding to phase-*a* and phase-*c*, respectively. These combinations yield four operating sequences characterized by the conduction of phase-b. The two remaining sequences are characterized by the simultaneous conduction of phase-a and phase-c, and inevitably of phase-b, leading to a three-phase conduction mode [7,9].

Table 1: B4-Inverter under the Two-Phase Conduction Mode: Switching States, Average phase Voltages, their Clarke components and corresponding active voltage vectors

S_{1234}	v_a	v_b	v_c	V_α	V_β	V_i
(1000)	$\frac{V_{dc}}{4}$	0	$\frac{-V_{dc}}{4}$	$\frac{\sqrt{3}V_{dc}}{4\sqrt{2}}$	$\frac{V_{dc}}{4\sqrt{2}}$	V_1
(0010)	0	$\frac{V_{dc}}{4}$	$\frac{-V_{dc}}{4}$	0	$\frac{V_{dc}}{2\sqrt{2}}$	V_2
(0100)	$\frac{-V_{dc}}{4}$	$\frac{V_{dc}}{4}$	0	$\frac{-\sqrt{3}V_{dc}}{4\sqrt{2}}$	$-\frac{V_{dc}}{4\sqrt{2}}$	V_3
(0001)	0	$\frac{-V_{dc}}{4}$	$\frac{V_{dc}}{4}$	0	$\frac{-V_{dc}}{2\sqrt{2}}$	V_4

Following the application of the Clarke transform to the average phase voltages, a characterization of the B4-inverter-fed BLDC motor drive under the two-phase conduction mode is given in Table 1.The resulting active voltage vectors are illustrated in Figure 2.

ISSN: 2278 – 7798

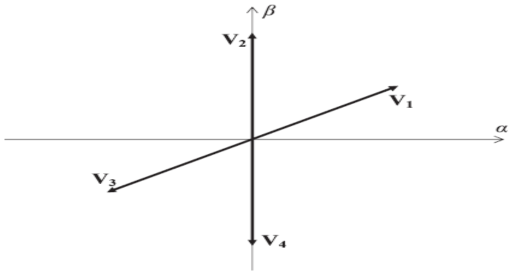

Fig. 2 Active voltage vectors generated by the B4-inverter in the two-phase conduction mode

B. DTC of B4 Inverter Fed BLDC Motor

The operation basis of BLDC motor drives treated in the preceding section, a DTC strategy dedicated to these drives in the case of a B4-inverter in the armature could be inspired from the one considering the case where the motor is fed by a B6-inverter[6,8]. The implementation scheme of such a DTC strategy is shown in Figure 3. The implementation scheme does not include a flux loop, and that the identification of the sectors in the *α–β* plane is achieved considering appropriate combinations of the Hall-effect signals, as given in Table 1. Moreover, these signals enable the speed estimation and hence a sensor less control. The speed estimation assumes that the velocity remains constant during a given sector with an opening of *π/*3 and is equal to the average one in the previous sector. The resulting algorithm is expressed as follows:

$$\Omega_k = \frac{\frac{\pi}{3}}{P\Delta t_{k-1}} \quad (3.4)$$

Where *P* is the pole pair number of the BLDC motor and Δt_{k-1} is the time interval spent to cross the preceding sector.

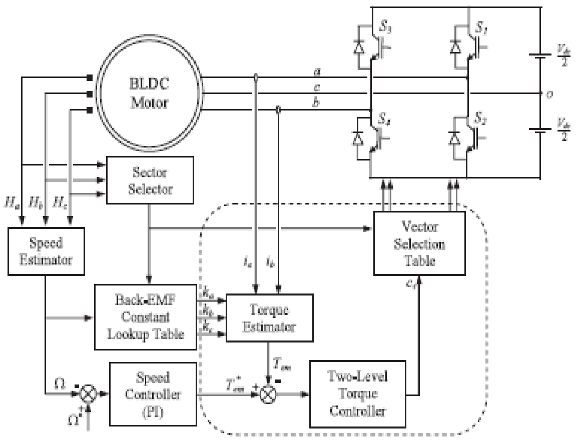

Fig.3 Implementation scheme of a DTC strategy of B4-inverter-fed BLDC motor drives inspired from the one considering the case where the BLDC motor is fed by a B6 inverter

The estimation of the electromagnetic torque is based as follows:

$$T_{em} = [K_a - K_c]i_a + [K_b - K_c]i_b \quad (3.5)$$

Where k_a k_b, and k_c are back-EMF normalized functions, obtained by interpolation and saved in a lookup table. Considering the subdivision of the α–β plane in six sectors, as illustrated in Fig.4, and accounting for the output c_τ of the two level hysteresis torque controller, the vector selection table can be synthesized considering both anticlockwise and clockwise rotations of the BLDC motor, as given in Table 2. From the Table 2 that in Sectors II and V, the BLDC motor operates under the three-phase conduction mode. Although these sectors are characterized by the conduction of phase-a and phase-b, there is always a current flowing through phase-c due to its back EMF and its continual connection to the dc-bus. Thus, phase-b behaves as a generator which produces a torque opposite to the ones of phase-a and phase-c. Consequently, their currents turn to be temporarily distorted by undesirable surges in order to generate the required torque.

It has been found that a reduction of the current distortion during Sectors II and V can be gained through an independent control of the torques T_{em_a} and $|T_{em_{ab}}$ developed by phase-*a* and phase-*b*, respectively, instead of the motor overall torque T_{em}.

Table.2 Vector selection table of a DTC strategy dedicated to B4-Inverter-Fed BLDC

C_T	+1	-1
Sector I	V2(0010)	V4(0001)
Sector II	U3(0110)	U1(1001)
Sector III	V3(0100)	V1(1000)
Sector IV	V4(0001)	V2(0010)
Sector V	U1(1001)	U3(0110)
Sector VI	V1(1000)	V3(0100)

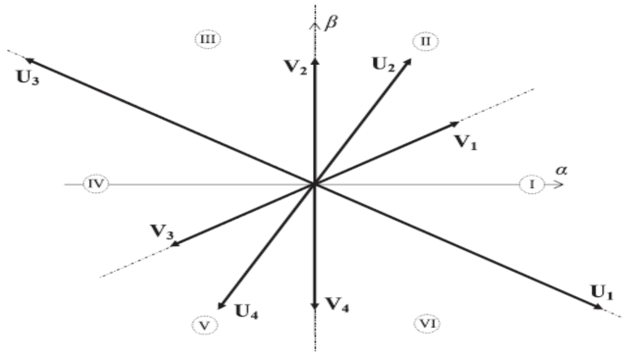

Fig.4 Subdivision of the *α–β* plane in six sectors limited by the four vectors yielded by the two-phase conduction mode and the two larger ones yielded by the three-phase conduction mode

Table.3 Vector selection subtable to reduce the distortion of the BLDC motor phase current in sectors II and V

C_{Ta}	+1		-1	
C_{Tb}	+1	-1	+1	-1
Sector II	U3(0110)	U4(0101)	U2(1010)	U1(1001)
Sector V	U1(1001)	U2(1010)	U4(0101)	U3(0110)

ISSN: 2278 – 7798

Sectors II and V of Table 3.6, by the vector selection sub table given in Table VII, where $c_{\tau a}$ and $c_{\tau b}$ are the outputs of the two-level hysteresis controllers of T_{em_a} and $|T_{em_{ab}}$, respectively. The application of active voltage vectors corresponding to the three-phase conduction mode, at the beginning of each sector in order to force the current in the turned-off phase to flow through a controllable IGBT instead of an uncontrollable freewheeling diode. Thus, the rising rate $|di/dt|$ of the current in the turned off phase is regulated in an attempt to make it similar to the one of the current in the turned-on phase. It consists in the substitution of the two-level torque controller by a four-level one.

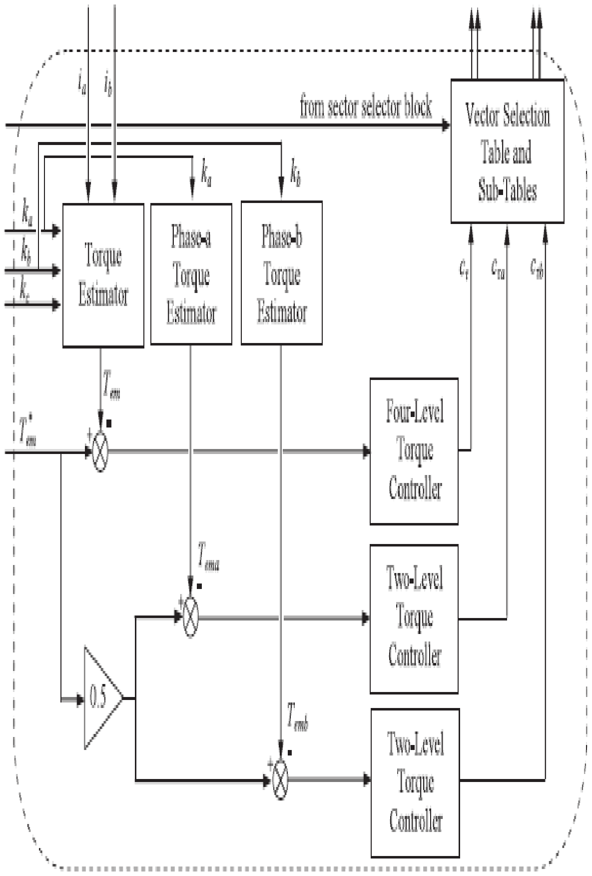

Fig 5 Changes in the implementation scheme corresponding to the proposed DTC strategy

The positive high level $c_\tau = +2$ of the torque hysteresis controller is systematically activated when the torque falls during sector-to-sector commutations in the case of an anticlockwise rotation ($T_{em} > 0$) whereas its negative high level $c_\tau = -2$ is systematically activated when the torque falls during sector to-sector commutations in the case of a clockwise rotation ($T_{em} < 0$). The low levels $c_\tau = \pm 1$ are applied during the whole cycle except for the torque dips taking place during sector-to sector commutations. The resulting changes in the implementation scheme concern just the blocks surrounded by the dashed line in Figure .5. These turn to be as illustrated in Figure 3. The proposed DTC strategy exhibits a capability of reducing the torque ripple during sector-to sector commutations without any dependence of V_{dc}, I, Δt, and L.

IV.SIMULATION RESULTS

A SIMULINK model is developed for the DTC with four switch PI controller.

A. Simulation For Dtc Of B4 Inverter

Simulation results are shown for

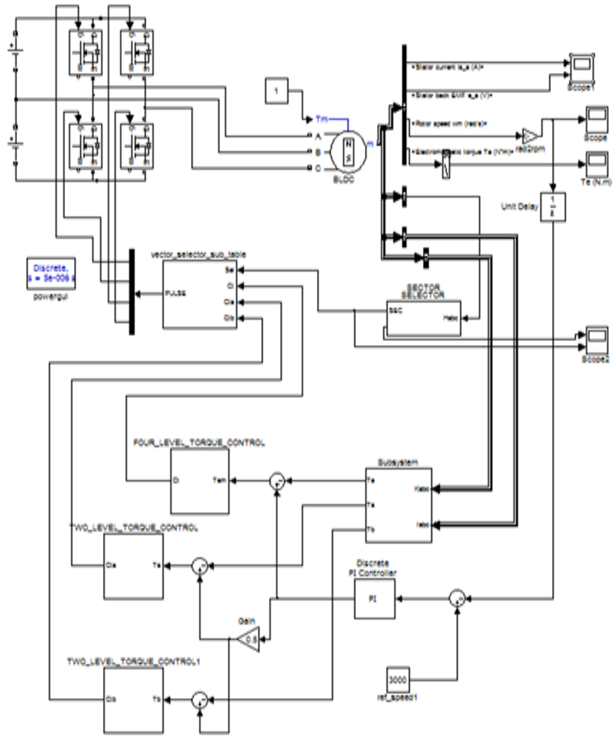

Fig.6 Simulation for DTC of B4 Inverter

The simulation for direct torque control of four switch inverter with BLDC motor was simulated. The pulses of four switches are applied based on the look up tables of Hall Effect sensor from the BLDC motor. The input DC supply is ((motor rating: 96 volts) 96*1.414*2). Here the two level controller and four level controller are used. The sector selector allows to the identification of the sector in which the stator flux vector lies in the α-β plane. It is based on the combination of the three Hall-effect signals as depicted in Table 3.6, the two-level hysteresis controller in the torque loop is substituted by a three-level hysteresis controller. Hence, high-speed operation and during sequence-to-sequence commutations, the proposed DTC strategy considers the application of the active voltage vectors corresponding to the three phase conduction mode Thus, the corresponding waveforms of speed, current, back EMF sector output results are analyzed.

ISSN: 2278 – 7798

B. Stator Current And Back EMF

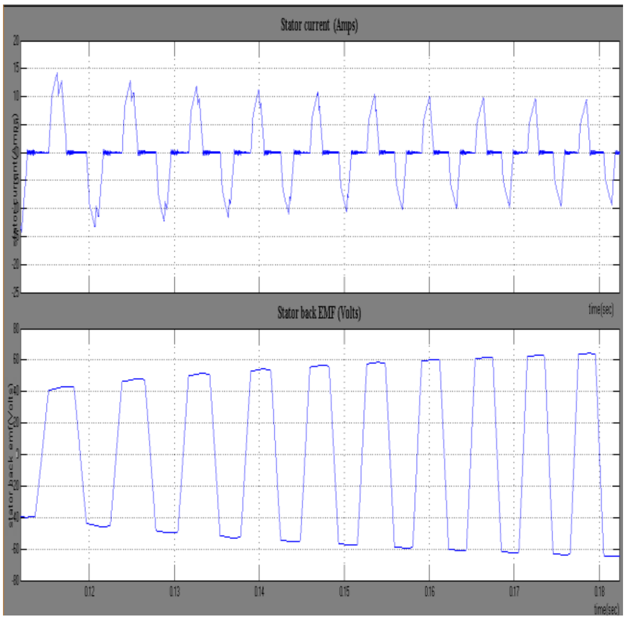

Fig.7 Waveform for stator current and Back EMF using DTC of B4 Inverter

The stator current and the back EMF using PI controller will give trapezoidal back EMF voltage. The two level and four level torque controller will give pulses to the switches.

4.8.2 ROTOR SPEED

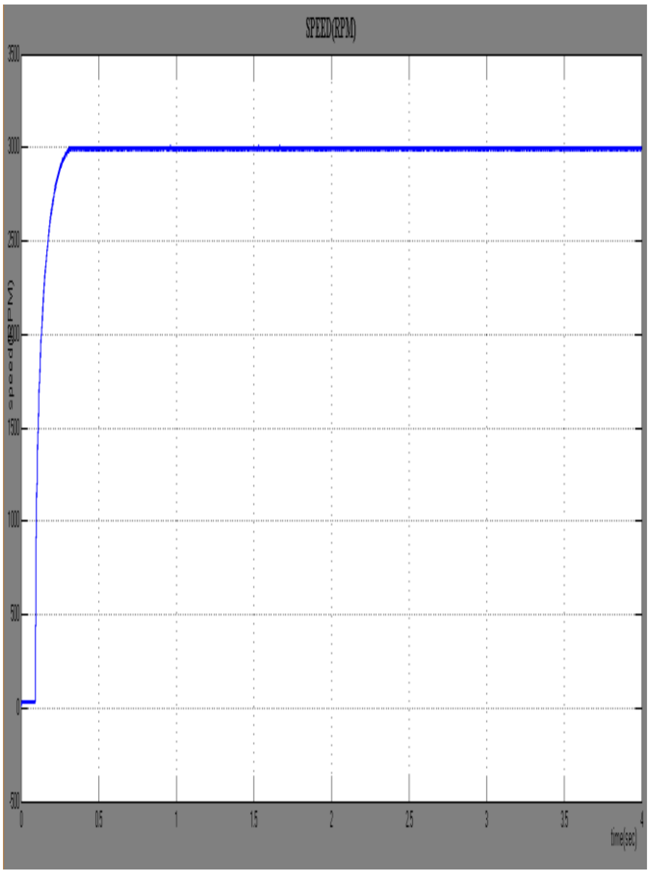

Fig.8 Waveform for speed using DTC of B4 Inverter

The rotor speed for BLDC motor using look up table of sector selection is shown in FigURE.8. The rotor speed is settled at 3000 rpm. From the proposed system, the simulated waveform for speed performance is improved compared to the existing six switch method. Hence, the reference speed is 3000 rpm. The closed loop DTC scheme will produce the corresponding set speed.

4.8.3 ELECTROMAGNETIC TORQUE

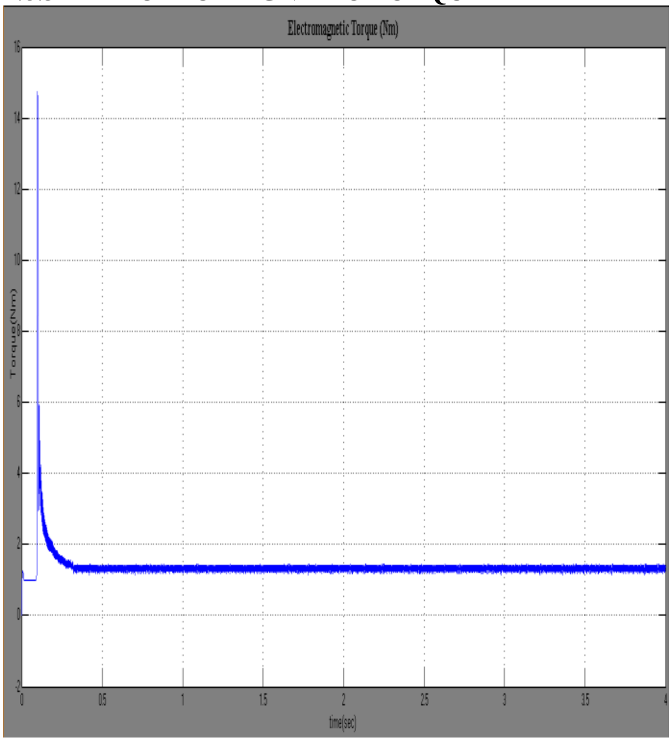

Fig.9 Waveform for Electromagnetic Torque using DTC of B4 Inverter

Output waveform of the Electromagnetic Torque for four Switch inverter fed BLDC Motor. The torque ripples are reduced to 1.8 Nm.

V.CONCLUSION

In this work, a new DTC scheme for BLDC motor drives is proposed. A PI controller is used by the outer loop to develop the performance of speed control. Simulink models were developed in Matlab 2011a with the PI controller and the speed control of BLDC motor. The main advantage is control the speed of the BLDC motor is to increase the dynamic performance and provide good stabilization. The results shows that, the proposed control technique gives better performance as the motor torque and the speed are better than that of the conventional type the feedback based modulation technique was replaced by carrier based space vector modulation at the expense of simplicity lost and partially of inferior quality dynamics. During commutation periods at high rotational speeds, it automatically combines two- and three-phase switching modes by minimizing the error between the commanded torque and the estimated torque. Hence, the proposed system PI based controller can be implemented for controlling the torque ripple reduction. Thus, the torque ripple is reduced to 1.8Nm.Further, to reduce the torque we can implement the soft computing technique of neural network, fuzzy logic system instead of PI controller. This technique can also be implemented for PMSM motor to analyze the torque ripple and the speed.

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ISSN: 2278 – 7798