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Torque Control of BLDC Motor Fed by Z-Source B4 Inverter Using Fuzzy Logic Controller

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Abstract—this paper mainly deals with the Direct Torque Control (DTC) of Brushless DC (BLDC) motor drives operated by four-switch inverters (otherwise called B4-inverters). The guideline of operation of the BLDC motor is firstly viewed as both instances of B6-and B4-inverters in the armature, with highlighting on the two and three stage conduction modes. Sector to sector commutation is achieved using vector selection table and control is achieved using the fuzzy logic controller. The B4-inverter could be viewed as a reconfigured topology of the B6-inverter which speaks to an essential dependability in reducing the switches or legs and also helps in reducing the torque ripples.
Keywords-Direct Torque control, Brushless DC conventional drives, Three phase conduction,sector to sector commutation,B4 Inverter.

I. INTRODUCTION

The control procedures that show a high torque powerful one can recognize the Direct Torque Control (DTC). DTC techniques have been generally executed in squirrel confine instigation machine drives. They permit an immediate control of the electromagnetic torque and the stator flux through the utilization of suitable mixes of the control signs of the inverter switches. Brushless DC (BLDC) motor control techniques, it is regularly trusted that they depend on the current and torque control approaches. A standout amongst the most well known is a summed up symphonious infusion to figure out ideal current waveforms minimizing the torque ripple. The DTC systems consider a vector determination table basically decreased to the torque control with a two-stage conduction mode amid divisions and a three-stage conduction mode amid area to-part substitutions. It manages the DTC of BLDC motors with a B4-inverter in the armature. It has been accounted for in that the two-stage conduction mode is punished by high torque ripple in the area to part substitutions. The present study builds up this methodology on account of B4-inverter-helps in BLDC motor drives under DTC. This segment manages the depiction and the operation premise of the B4-inverter-nourished BLDC motor drive. The drive's associations with two stages (stage A and stage B) of the BLDC motor supplied through the B4-inverter legs, while the third one (stage C) is connected to the center purpose of the dc-transport voltage. Managing Brushless DC (BLDC) motor control techniques. It is usually trusted that they depend on the current and torque control approaches. A standout amongst the most prevalent is a summed up symphonious infusion to discover ideal current waveforms minimizing the torque ripple.

II. CONSTRUCTION AND OPERATING PRINCIPLE

The BLDC motor is additionally alluded to as an electronically commutated motor. There are no brushes on the rotor and the recompense is performed electronically at certain rotor positions. The stator stage windings are embedded in the spaces (a circulated winding) or can be twisted as one curl on the attractive post. The changeless polarization magnets and their relocation on the rotor are picked in a manner that the Back-EMF shape is trapezoidal. This permits the three-stage voltage framework with a rectangular shape to be utilized to make a rotational field with low torque swells. In this regard, the BLDC motor is proportional to a transformed DC commutator motor in that the magnets pivots while the conductors stay stationary is turned around by the commutator and the brushes yet in the brushless DC motor, the extremity inversion is performed by semiconductor changes which are to be exchanged in synchronization with the rotor position.. The commutator is likewise a constraining component in the maximal velocity of the DC motor. Consequently the BLDC motor can be utilized in applications obliging rapid. Substitution of a DC motor by a BLDC motor place higher requests on control calculation and control circuit. Firstly, the BLDC motor is generally considered as a three-stage framework. In this way it must be controlled by a three-stage power supply. Next the rotor position must be known at specific edges, so as to adjust the connected voltage to the back-EMF. The arrangement between the back-EMF and replacement occasions is critical. In this condition the motor acts as a DC motor and keeps running at the best living up to expectations point. In any case, the downsides of the BLDC motor brought on by necessity of force converter and rotor position estimation are adjusted by magnificent execution and unwavering quality, furthermore by the continually falling costs of force segments and control circuits

III. MATHEMATICAL MODEL OF THE BLDC MOTOR

Modeling of a BLDC motor can be created in the comparative way as a three-stage synchronous machine. Since there is a continuous magnet mount on the rotor, some dynamic qualities are different. Flux linkage from the rotor relies on the magnet material. In this way, immersion of attractive flux is average for this sort of motors. As any run of the mill three-stage motors, one structure of the BLDC motor is sustained by a three stage voltage source. The source is not so much to be sinusoidal. Square wave or other wave-shape can be connected the length of the top voltage not exceed the most extreme voltage point of confinement of the motor. Also, the armature's model twisting for the BLDC motor is communicated as takes after:

$$Va= Ria+ L\ dia/dt \qquad (1)$$

$$Vb= Rib + L\ dib/dt \qquad (2)$$

$$Vc= Ric+ L\ dic/dt \qquad (3)$$

Where,

L is armature self-inductance [H],

R-armature resistance [Ω],

Va, Vb, Vc– terminal phase voltage [V],

ia, ib, ic– motor input current [A],

ea, eb, ec– motor back-EMF [V].

In the 3-phase BLDC motor, the back-EMF is related toa function of rotor position and the rotor position and the back-EMF of each phase has 120 degree phase angle difference so equation of each phase should be as follows:

$$ea= Kwf(\theta e)\omega \qquad (4)$$

$$eb= Kwf(\theta e2/3)\omega \qquad (5)$$

$$ec= Kwf(\theta e+ 2/3)\omega \qquad (6)$$

Where,

Kw is back EMF constant of one phase [V/rad.s-1],

θe-electrical rotor angle [degree.],

ω- Rotor speed [rad.s-1].

The electrical rotor angle is equal to the mechanical rotor angle multiplied by the number of pole pairs p:

$$\theta e= p/2\ \theta m \qquad (7)$$

Where,

θmis mechanical rotor angle [rad].

Total torque output can be represented as summation of that of each phase. Next equation represents the total torque output:

$$Te= eaia+ebib+ecic/\omega \qquad (8)$$

Where,

Te is total torque output [Nm],

The equation of mechanical part is represented as follows:

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$$Te\text{-}Tl = Jd\omega/dt + B\,\omega \qquad (9)$$

Where,

Tl is load torque[Nm],

J – inertia of rotor and coupled shaft [kgm2],

B – friction constant [Nms.rad-1].

IV. DTC OF BLDC MOTOR

DTC methodology considers a vector determination suitable that empowers the free control of the electromagnetic torques created by the stages associated with the inverter legs are in synchronous Conduction. On the other hand, it has been accounted for in that the two-stage conduction mode is punished by high torque swell during sector-to-area compensations. To defeat this disadvantage, the three-stage conduction mode has been incidentally thought to be amid part to-division recompenses. The present study adds to this methodology on account of B4-inverter-nourished BLDC motor drives under DTC.

V. DTC OF B4-INVERTERFED BLDC MOTOR DRIVES

A. Study Statement

Taking into account the operation basis of BLDC motor drives treated in the preceding section, a DTC strategy dedicated to these drives in the B4-inverter in the armature could be inspired from the one considering the case where the motor is fed by a B6-inverter. The implementation scheme of such a DTC strategy is shown in one can notice that the achievement scheme does not include a flux loop, and that the identification of the sectors in the α–β plane is achieved considering appropriate combination of the *Hall*-effect signals, as given in Table II. Moreover, these signals

TABLE I
CASE OF THE B4-INVERTER UNDER THE TWO-PHASE CONDUCTION MODE: SWITCHING STATES, AVERAGE PHASE VOLTAGES, THEIR CLARKE COMPONENTS AND CORRESPONDING ACTIVE VOLTAGE VECTORS

(S1234)	va	Vb	Vc	Vα	Vβ	Vi
(1000)	Vdc/4	0	-Vdc/4	√3Vdc/4√2	Vdc/4√2	V1
(0010)	0	Vdc/4	-Vdc/4	0	Vdc/2√2	V2
(0100)	-Vdc/4	0	Vdc/4	-√3Vdc/4√2	-Vdc/4√2	V3
(0001)	0	-Vdc/4	Vdc/4	0	-Vdc/2√2	V4

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 π3and is equal to the average one in the previous sector. The resulting algorithm is expressed as follows:

$$\Omega k=\pi/3/P\Delta tk-1 \qquad (10)$$

Where,
P is the pole pair number of the BLDC motor and $\Delta tk-1$
is the time interval spent to cross the preceding sector.

B. Case Of A B4-Inverter In The Armature

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This section deals with the description and the operation basis of the B4-inverter-fed BLDC motor drive. Fig. 5 shows the connections of the drive with two phase (phase-*a* and phase-*b*) of the BLDC motor supplied through the B4-inverter legs, while the third one (phase-*c*) is connected to the middle point of the dc-busvoltage.

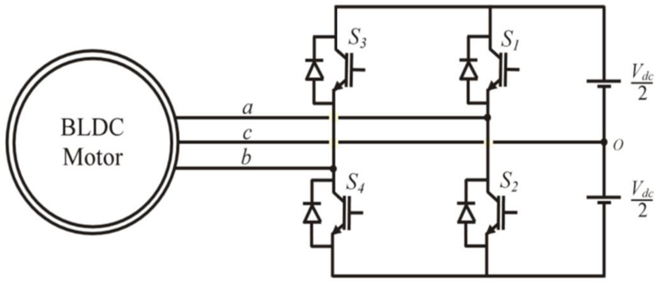

Fig.1 Brush Less DC motor Fed B4- Inverter

1) Operation Under Two-Phase Conduction Mode: Let us call **V1** ,**V2** , **V3** , and **V4** the four active voltage vectors generated by the B4-inverter under the two-phase conduction mode. The equivalent switching combinations (*S*1*S*2*S*3*S*4)are equal to (1000), (0010), (0100), and (0001), respectively, where, from left to right where both the binary standards denote the state of the upper and lower switching signals, corresponding to phase-*a* and phase-*b*, respectively. These combinations yield four operating sequences characterized by the conduction of phase-*c*.The two remaining sequences are characterized by the simultaneous conduction of phase-*a* and phase-*b*, and inevitably of phase-*c*, leading to a three-phase conduction mode. Following the application of the *Clarke* transform to the average phase voltages, a description of the B4-inverter-fed BLDC motor drive under the two-phase conduction mode is given in Table II. The resulting active voltage vectors are illustrated in Fig. 1

2) Operation Under Three-Phase Conduction Mode: The three-phase conduction mode is characterized by the combinations during which each leg of the B4-inverter has an IGBT in the on-state, such that: (1001), (1010), (0110), and (0101), with the respective active voltage vectors, noted U1,U2,U3, andU4. Following the application of the *Clarke* transform, with the previous combinations accounted for, has led to a characterization of the BLDC motor drive operation under the three-phase conduction mode as given in Table IV. The resulting active voltage vectors are located in the *α*–*β* plane as illustrated.

TABLE II
CASE OF THE B4-INVERTER UNDER THE THREE-PHASE CONDUCTIONMODE: SWITCHING STATES, AVERAGE PHASE VOLTAGES, THEIR CLARKE COMPONENTS AND CORRESPONDING ACTIVE VOLTAGE VECTORS

(S1234)	Va	Vb	Vc	Vα	Vβ	Ui
(1000)	Vdc/2	-Vdc/2	0	√3Vdc/2√2	Vdc/2√2	U1
(0010)	Vdc/6	Vdc/6	-Vdc/3	√3Vdc/2√6	Vdc/2√2	U2
(0100)	-Vdc/2	-Vdc/2	0	-√3Vdc/2√2	-Vdc/2√2	U3
(0001)	-Vdc/6	-Vdc/6	Vdc/3	-√3Vdc/2√2	-Vdc/2√2	U4

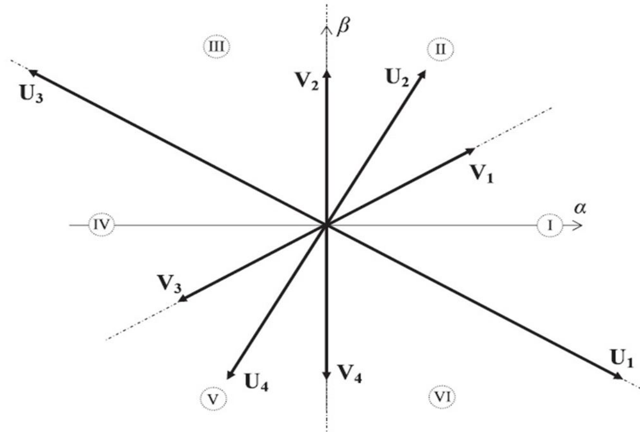

Fig.2 Subdivision of the *α–β* plane in six sectors limited by the four vectors Yielded by the two-phase conduction mode and the two larger ones yielded by the three-phase conduction mode

C. Proposed DTC Strategy

The proposed system introduces a new DTC strategy which exhibits a capability of reducing the torque ripple during sector- to-sector commutations, considering the case where the BLDC motor is operated by a B6-inverter. They proposed an approach consisting in the application of active voltage vectors equivalent to the three-phase conduction mode, at the initial condition 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 increasing rate|di/dt|of the current in the turned- off phase is synchronized in an attempt to make it similar to the one of the current in the turned-on phase. In [7], the application of the previously described approach has been limited to the high-speed process with the dc-link voltage Vdc being minor than four times the peak value E of the back EMF waveform (Vdc <4E). With this stateof ac- counted for, the following boundaries have been noticed: 1) The rising rates (|dia/dt|, |dib/dt|, and |dic/dt|) of the phase currents mainly depend on three variables, such that: i) the dc-link voltage Vdc, ii) the back-EMF peak value E, and iii) the self-inductance L..It has been found that, even though at high-speed operation (Vdc < 4E), an unequal phenomenon is associated with the falling of the electromagnetic torque during sector-to- sector commutations particularly for low values of the peak current I and the self-inductance L

VI. SECTOR TO SECTOR COMMUTATION

In sector to Sector commutation mainly deals with the positive high level $c\tau = +2$of the torque hysteresis controller is analytically activated when the torque ripples reduced during sector-to-sector commutations in the case of an anticlockwise rotary motion (Tem > 0), whereas its negative high level $c\tau = -2$ is This section is devoted to an experimentally based comparison between the three DTC strategies treated in Section III, such that:

DTC-1: strategy inspired from the case where the BLDC motor is fed by a B6-inverter.

DTC-2: strategy developed in [9].

DTC-3: proposed strategy. The study firstly considers the investigation of the steady- state features of the B4-inverter-fed BLDC motor drive under DTC-1.Thesearecomparedtothesteady-state features obtained under DTC-3 taking into account of the same operating speed. Then, the investigation of the features of the B4-inverter-fed BLDC motor drive under DTC-3 is extended to low-speed operation as well as to the transient behavior. Finally a comparison between DTC-2 and DTC-3 is carried out taking into account of the sector-to-sector commutations.

A. Comparison between DTC-1 and DTC-3

Steady-state electrical features of the B4-inverter-fed BLDC motor drive under DTC-1 and DTC-3 for a speed Ω=+120 rad/s,the phase-a to phase by voltage uab in Sectors I, II III,IV,andVI is almost the same under DTC-1 and DTC-3, with uab = ±Vdc 4 −eb when the current flows through phase- a and phase-c, uab = ±Vdc 4 + ea when the current flows through phase-b and phase-c. However in Sectors II and V, uab commutates between ±Vdc underDTC-1 and between−Vdc, 0 and+Vdc under DTC-3. 2) The

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phase-c current ic measured under DTC-1 is totally out of control during Sectors II and V, During Sectors II and V greatly affects ia during the first half of these sectors, and ib during their second half. 1) the average value of Temc turns to be null during Sectors II and V, as illustrated in the distortion of ia and ib and the resulting ripple penalizing Tema + Temb have been almost eradicated.3) the high dips affecting the overall torque Tem during Sectors II and V. The investigation of the performance of the B4-inverter-fed BLDC motor drive under the DTC-3strategy has been expended to:

The low speed steady-state operation. One can notice that the distortion of ic turns to be high during Sectors II and V, but remains lower than the one under DTC-1.

The transient behavior considering both load and no-load operations as illustrated, considering the following steps: a) starting from a steady-state no-load operation at a reference speed of +50 rad/s; b) a ramp-shaped increase of the speed to reach Ω=+100 rad/s; c) the application of a load torque Tl proportional to the speed at almost 10 s; d) a ramp-shaped decrease of the speed to reach Ω=+30 rad/s, with the load torque maintained. Once more, one can notice that the distortion of ic during Sectors II and V is higher at low speed especially at load operation.

B. Comparison between DTC-2 And DTC-3

As far as the improvement gained by the proposed DTC strategy concerns the sector-to-sector commutations, except those involving Sectors II and V, the comparison between DTC-2 and DTC-3isbasedonzoomedviews of the currents ia and ib as well as the overall torque Tem, during the commutation from Sector III to Sector IV,one can clearly notice that the rising rates |dia/dt| and |dib/dt| under DTC-2 are totally different during the sector-to-sector commutations, while they are almost similar under DTC-3.Moreover, comparing the results of and it is to be noted that the torque dip penalizing DTC-2 during the sector-to-sector commutation has been damped following the implementation of DTC-3

TABLE III
VECTOR SELECTION SUBTABLE DURING SECTOR-TO-SECTOR COMMUTATIONS IN THE CASE OF AN ANTICLOCKWISE ROTATION

Cτ	+2
Sector VI->Sector->I	U2(1001)
Sector II->Sector->III	U3(0101)
Sector III->Sector->IV	U4(0110)
Sector V->Sector ->VI	U1(1010)

TABLE IV
VECTOR SELECTION SUBTABLE DURING SECTOR-TO-SECTOR COMMUTATIONS IN THE CASE OF A CLOCKWISE ROTATION

Cτ	-2
Sector II->Sector->I	U1(1001)
Sector I->Sector ->VI	U4(0101)
Sector V->Sector-> IV	U3(0110)
Sector IV->Sector ->III	U2(1010)

VII. DESIGN OF FUZZY LOGIC CONTROLLER (FLC)

The block diagram of FLC with two inputs 1 2 (*e1, e2*) and one output (*u*) is shown in Figure 3. The error is calculated by subtracting the reference speed from the actual
rotor speed as follows:

$$e1[n] = \omega ref[n] - \omega r[n] \qquad (11)$$

where,

e1[n] is the error, ωref[*n*] is the reference speed, and ωr[n] is the actual motor speed. The change in error is calculated by Equation (12), where e1[*n*−1] is the previous error value.

$$e1[n] = e1[n] - e1[n-1] \qquad (12)$$

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In the fuzzy logic control system, two normalization (Ne1,Ne2)parameters for input and one denormalization parameter (Nu)for output are defined.

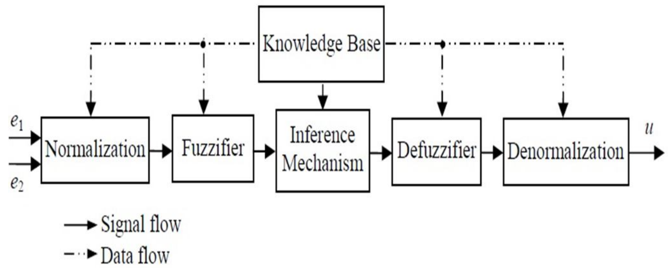

Fig.3 Simulation for Direct Torque controller with Fuzzy logic controller

Infuzzy logic controller system two normalization parameters normalization process, the input values are scaled between (-1, +1) and in the denormalization process, the output values of fuzzy controller are converted to a value depending on the terminal control element.

VIII. BLOCK DIAGRAM FOR THE FOR THE PROPOSED SYSTEM

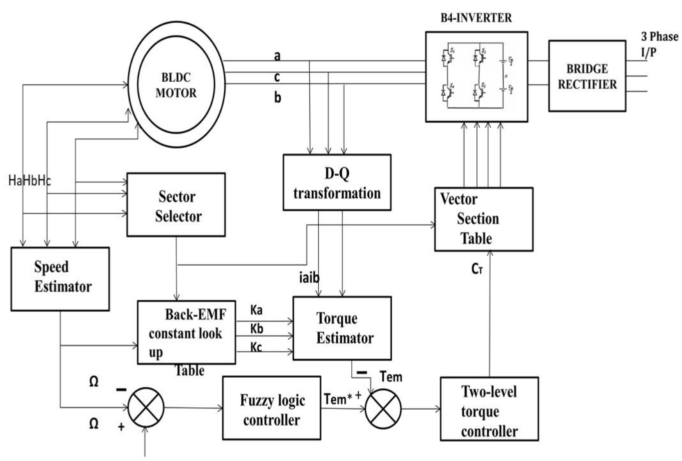

Fig.4. Block diagram of a DTC strategy of B4-inverter-fed BLDC Motor drives.

IX. SIMULATION

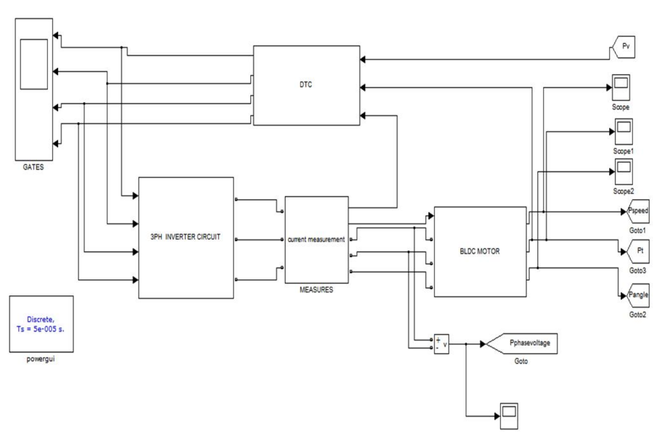

Fig.5 Simulation for Direct Torque control of BLDC Fed B4- Inverter With Fuzzy logic controller

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X. SIMULATION RESULTS

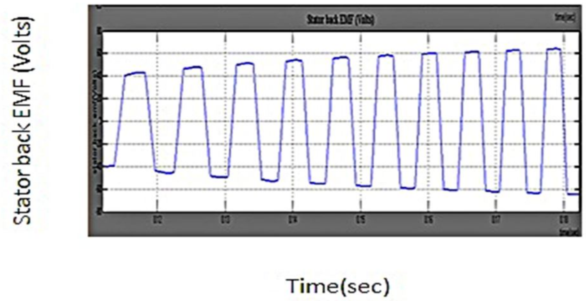

Fig.6. Simulation results of a DTC strategy of B4-inverter-fed BLDC Motor drive stator back EMF.

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

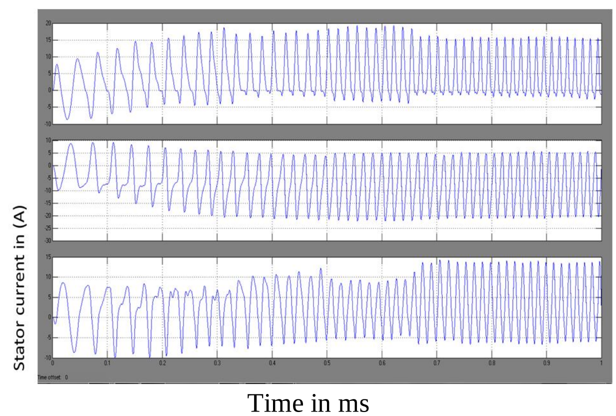

Fig.7 Simulation results of a DTC strategy of B4-inverter fed BLDC Motor drive 3 phase stator current

This waveform shows the output of rotor speed waveform.

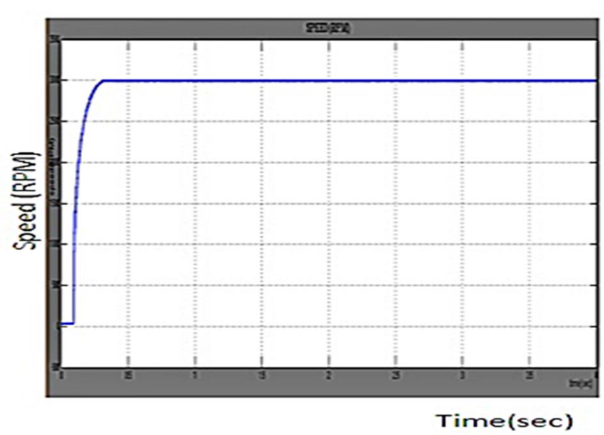

Fig.8 Simulation results of a DTC strategy of B4-inverter-fed BLDC Motor drive rotor speed in RPM

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During starting rotor speed increases highly at 3000 rpm and then it maintains at constant level

XI. CONCLUSION

In this proposed project, the straight forward current ripple compensation technique utilizing basic figuring and choice procedure for B4 inverter has been proposed. BLDC motor achieves superior with diminished torque swells. Torque control of the BLDC Motor below the sector to sector compensation the relentless state operation is accomplished. The voltage twisting marvel brought on by the voltage contrast between the dc-join capacitors was analyzed.The study has been achieved by an experimentally based comparison considering, in the first step, the BLDC motor steady- state operation under DTC-1 and DTC-3. Then, a special attention has been compensated to the comparison of the BLDC motor performance below DTC-2 and DTC-3, during sector-to-sector commutations. It has been clearly shown that B4-inverter-fed BLDC motor drives exhibit, under DTC-3, high performance with reduced torque ripple. Further comparison criteria shall be considered in the future. Of particular interest are acoustic noise and vibration which are of great importance in many applications such as electric and hybrid propulsion systems in so far as the passenger comfort.

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