DIRECT TORQUE CONTROL FOR REDUCTION OF TORQUE RIPPLE DURING COMMUTATIONS USING B4-INVERTER

S.Anishraj¹, B.Thamizhkani²

¹PG Scholar, Department of Electrical and Electronics Engineering, Dhanalakshmi Srinivasan College of Engineering and Technology, Chennai.

²Assistant Professor, Department of Electrical and Electronics Engineering, Dhanalakshmi Srinivasan College of Engineering & Technology, Chennai.

Abstract- This paper deals with the Direct Torque Control (DTC) of Brushless DC (BLDC) motor drives fed by four-switch inverters (also known as B4- inverters) rather than six-switch inverters (also known as B6 inverters) in conventional drives. The principle of operation of the BLDC motor is firstly recalled considering both cases of B6- and B4-inverters in the armature, with emphasis on the two- and three-phase conduction modes The B4-inverter could be regarded as a reconfigured topology of the B6-inverter in case of a switch/leg failure which represents a crucial reliability benefit for many applications especially in electric and hybrid propulsion systems.

Keywords-Direst Torque control, Brushless DC, Conventional drives, Three phase conduction.

I. INTRODUCTION

The control strategies that exhibit a high torque dynamic, one can distinguish the Direct Torque Control (DTC). DTC strategies have been widely implemented in squirrel cage induction machine drives. They allow a direct control of the electromagnetic torque and the stator flux through the application of suitable combinations of the control signals of the inverter switches. Brushless DC (BLDC) motor control strategies, it is quite commonly believed that they are based on the current and torque control approaches. One of the most popular is a generalized harmonic injection to find out optimal current waveforms minimizing the torque ripple.

The DTC strategies consider a vector selection table simply reduced to the torque control with a two-phase conduction mode during sectors and a three-phase conduction mode during sector-to-sector commutations. It deals with the DTC of BLDC motors with a B4-inverter in the armature. It has been reported in that the two-phase conduction mode is penalized by high torque ripple during sector-to-sector commutations.

The present study develops this approach in the case of B4-inverter-fed BLDC motor drives under DTC. This section deals with the description and the operation basis of the B4-inverter-fed BLDC motor drive. The connections of the drive with two phases (phase-a and phase-b) of the BLDC motor supplied through the B4-inverter legs, while the third one (phase-c) is linked to the middle point of the dc-bus voltage.
II. DTC STRATEGY

The present study introduces a new DTC strategy which exhibits a capability of reducing the torque ripple during sector-to-sector commutations. These have been focused by Zhu and Leong, considering the case where the BLDC motor is fed by a B6-inverter. They proposed an approach consisting in 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.

![Fig.1 DTC Control platform](image)

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. The application of the previously described approach has been limited to the high-speed operation with the dc-link voltage Vdc being lower than four times the peak value E of the back EMF waveform (Vdc < 4E). With this condition accounted for, the following limitations have been noticed:

1) The rising rates (|dia/dt|, |dib/dt|, and |dic/dt|) of the phase currents 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.

Therefore, the rising and the falling times Δt of the phase currents depend on their peak value I which is directly linked to the load torque Tl. It has been found that, although at high-speed operation (Vdc < 4E), an irregular phenomenon is associated with the falling of the electromagnetic torque during sector-to-sector commutations especially for low values of the peak current I and the self-inductance L. Furthermore, it has been noted that, during torque acceleration or deceleration, the rising and falling times Δt of the phase currents are variables which affect the electromagnetic torque by remarkable dips.

2) The previously described approach requires an instantaneous measurement of the dc-link voltage Vdc especially in electric and hybrid propulsion systems where the dc-bus is achieved by a battery pack. In what follows, an alternative is proposed to eradicate the previously described limitations.

It consists in the substitution of the two-level torque controller by a four-level one. In fact, the positive high level cτ = +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 (Tem > 0), whereas its negative high level cτ = −2 is systematically activated when the torque falls during sector-to-sector commutations in the case of a clockwise rotation (Tem < 0). The low levels cτ = 1 are applied during the whole cycle except for the torque dips taking place during sector-to-sector commutations.

A. Torque and Torque Ripple

Electrical motor torque is proportional to the product of magnetic flux and the armature current.

\[ T_g = K_a \Phi I_a \]  

(1)

Mechanical or load torque is proportional to the product of force and distance. Motor current varies in relation to the amount of load torque applied.

When a motor is running in steady state, the armature current is constant, and the electrical torque is equal and opposite of the mechanical torque. When a motor is decelerating, the motor torque is less than the load torque. Conversely, when a motor is accelerating, the motor torque is higher than the load torque.

Torque ripple is an effect seen in many electric motor designs, referring to a periodic increase or decrease in output torque as the output shaft rotates. It is measured as the difference in maximum and minimum torque over one complete revolution, generally expressed as a percentage.

The smoothness of variable speed drive operation is critical and a viable measure used in the design and development of motion control applications. The torque produced in a brushless DC (BLDC) motor with trapezoidal back electromotive force (BEMF) is constant under ideal conditions. However, in practice, torque ripple appears on the delivered output torque.

Some of these ripples result from the natural structure of the motor, while some are related to the motor design parameters. Nevertheless, this torques could be minimized throughout the machine design process. Another source of ripples is associated with the control and drive side of the motor.

Torque pulsations are mainly minimized by two techniques: improved motor designs and improved control schemes. Improved motor design techniques for pulsating torque minimization include skewing, fractional slot winding, short pitch winding, increased number of phases, air-gap windings, adjusting stator slot opening and wedges, and rotor magnetic design through magnet pole arc, width, and positions.

For improved motor control schemes, digital control-based techniques, such as adaptive, preprogrammed current, harmonics injection techniques, estimators and observers, speed loop disturbance rejection, high speed current regulators, commutation torque minimizations and others, will be introduced in details in this paper. The digital control found in many applications in motor drive systems, is used in applications requiring high-speed and precision control.

B. Sources of Torque Ripples in PMBLDC Motor

a. Motor nature: Ripples associated with motor nature refer to the physical properties and parameters of the motor’s manufactured materials. Better selection of materials lead to better performance.
b. Motor structure: This is associated with the motor’s design parameters, such as shape and dimensions. Careful consideration of these parameters leads to good performance design.

c. Motor Control: Many techniques have been introduced to minimize torque ripples. This paper will highlight the minimization of torque ripples in BLDC motors from the motor control side.

C. Evolution of Direct Torque Control

The basic function of a variable speed drive (VSD) is to control the flow of energy from the mains to the process. Energy is supplied to the process through the motor shaft. Two physical quantities describe the state of the shaft: torque and speed. To control the flow of energy we must therefore, ultimately, control these quantities. In practice, either one of them is controlled and we speak of “torque control” or “speed control”.

When the VSD operates in torque control mode, the speed is determined by the load. Likewise, when operated in speed control, the torque is determined by the load. Initially, DC motors were used as VSDs because they could easily achieve the required speed and torque without the need for sophisticated electronics.

Fig 2 Control loop of DC Motor Drive

However, the evolution of AC variable speed drive technology has been driven partly by the desire to emulate the excellent performance of the DC motor, inexpensive and maintenance free AC motors.

III. BRUSHLESS DC MOTOR (BLDC)

Conventional dc motors are highly efficient and their characteristics make them suitable for use as servomotors. However, their only drawback is that they need a commutator and brushes which are subject to wear and require maintenance. When the functions of commutator and brushes were implemented by solid-state switches, maintenance-free motors were realised. These motors are now known as brushless dc motors.

A. Commutation (Sector to Sector)

Commutation provides the creation of a rotational field. For proper operation of a BLDC motor, it is necessary to keep the angle between the stator and rotor flux as close to 90° as possible. Total six possible stator flux vectors can be obtained with a six-step control.
The stator flux vector must be changed at specific rotor positions, which are usually sensed by the Hall sensors. The Hall sensors generate three signals that also consist of six states. Each of the Hall sensors states corresponds to a certain stator flux vector. All the Hall sensors states, with corresponding stator flux vectors, are illustrated in below Fig.3

The brushless DC (BLDC) motor could overcome this issue by replacing the mechanical switching components (commutator and brushes) using electronic semiconductor switches.

Fig.3 Stator flux Vector at six-step control

Fig.4 Situation right before commutation (counterclockwise motion)

Fig.5 Situation right after commutation

The last two figures depict the commutation process. The actual rotor position in Fig.4 corresponds to the Hall sensors state ABC [110]. Phase A is connected to the positive DC-bus voltage by transistor Q1; Phase B is connected to the ground by transistor Q6, and Phase C is unpowered.
As soon as the rotor reaches a certain position, the Hall sensors state changes its value from ABC \[110\] to ABC \[100\]. See Fig.5 A new voltage patterns is selected and applied to the BLDC motor.

As shown in Fig.4 and Fig.5, it is difficult to keep the angle between the rotor flux and the stator flux precisely at 90° in a six-step control technique, while using the six-step control technique. The actual angle varies from 60° to 120°.

The commutation process is repeated per each 60 electrical degrees and is critical to change the switching pattern as fast as possible after a Hall sensor edge is detected. Any deviation causes torque ripples, resulting in speed variation.

### TABLE I

**IDENTIFICATION OF SIX SECTOR IN THE \(\alpha-\beta\) PLANT BASED ON THE HALL EFFECT SIGNAL**

<table>
<thead>
<tr>
<th>((H_{abc}))</th>
<th>((1\ 0\ 0))</th>
<th>((0\ 1\ 0))</th>
<th>((0\ 1\ 1))</th>
<th>((0\ 0\ 1))</th>
<th>((1\ 0\ 1))</th>
<th>((1\ 0\ 0))</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>II</td>
<td>III</td>
<td>IV</td>
<td>V</td>
<td>VI</td>
<td>VII</td>
</tr>
</tbody>
</table>

### TABLE II

**VECTOR SELECTION SUB TABLE DURING SECTOR-TO-SECTOR COMMUTATIONS IN THE CASE OF AN ANTICLOCKWISE ROTATION**

<table>
<thead>
<tr>
<th>(C_T)</th>
<th>+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector VI (\rightarrow) Sector I</td>
<td>(U_2(1010))</td>
</tr>
<tr>
<td>Sector II (\rightarrow) Sector III</td>
<td>(U_3(0110))</td>
</tr>
<tr>
<td>Sector III (\rightarrow) Sector IV</td>
<td>(U_4(0101))</td>
</tr>
<tr>
<td>Sector IV (\rightarrow) Sector V</td>
<td>(U_1(1001))</td>
</tr>
</tbody>
</table>

### TABLE III

**VECTOR SELECTION TABLE DURING SCTOR-TO-SECTOR COMMUTATIONS IN THE CASE OF AN CLOCKWISE ROTATION**

<table>
<thead>
<tr>
<th>(C_T)</th>
<th>-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector II (\rightarrow) Sector I</td>
<td>(U_1(1001))</td>
</tr>
<tr>
<td>Sector I (\rightarrow) Sector VI</td>
<td>(U_4(0101))</td>
</tr>
<tr>
<td>Sector V (\rightarrow) Sector IV</td>
<td>(U_3(0110))</td>
</tr>
<tr>
<td>Sector IV (\rightarrow) Sector III</td>
<td>(U_2(1010))</td>
</tr>
</tbody>
</table>
B. BLDC Control Drive System

The BLDC control drive system is based on the feedback of rotor position, which is obtained at fixed points typically every 60 electrical degrees for six-step commutation of the phase current. The BLDC drive system consists of the BLDC motor, power electronics converter, sensor, and controller as shown in Fig.7

![BLDC Drive System Components](image)

Fig.6 BLDC Drive System Components

To switch the motor stator coils in the correct sequence and at the correct time, the position of the rotor field magnets must be known. The exact location of the rotor field magnets can be sensed by Hall Effect sensors or by using encoders.

The function of the controller is to switch the appropriate currents in the right stator coils at the right time and sequence by taking the information supplied by the sensor and processing it with preprogrammed commands to achieve the desired motor performance. For a BLDC motor drive with a 120 electrical degree conduction time, the current produces the torque spike every 60 degrees, causing the rotor to pulsate at a frequency six times the fundamental one.

C. B4-Inverter Fed BLDC Motor Drive

This section deals with the description and the operation basis of the B4-inverter-fed BLDC motor drive. The connections of the drive with two phases (phase-a and phase-b) of the BLDC motor supplied through the B4-inverter legs, while the third one (phase-c) is linked to the middle point of the dc-bus voltage.

![B4-Inverter-fed BLDC Motor Drive](image)

Fig.7 B4-Inverter-fed BLDC Motor Drive

Permanent magnet BLDC motors with trapezoidal back electromotive forces (EMFs) are suitably fed by 120°-rectangular shaped currents that should be synchronized with the back EMFs in order to
develop a constant electromagnetic torque with reduced ripple. This section deals with the description and the operation basis of the B4-inverter-fed BLDC motor drive.

The connections of the drive with two phases (phase-a and phase-b) of the BLDC motor supplied through the B4-inverter legs, while the third one (phase-c) is linked to the middle point of the dc-bus voltage. Taking into account 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.

One can notice that 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.

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.

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. Consequently, their currents turn to be temporarily distorted by undesirable surges in order to generate the required torque.

**Fig 8 Block Diagram of BLDC Motor**

The above diagram is block diagram of BLDC motor. They proposed an approach consisting in 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.

**IV. SIMULATION AND MODELLING**

To design the DTC for Reduction of Torque Ripple during Commutation, following are utilized.

**A. Stator Current**

Thus the Fig.9 shows the output of stator current waveform. This waveform indicates the sudden rise of current initially and then it gradually rises.
B. Rotor Speed

Thus the Fig.10 shows the output of rotor speed waveform. During starting rotor speed increases highly at 1400 rpm and then it maintains at constant level.

C. Electromagnetic Torque

Thus the Fig.11 shows the output of electromagnetic torque waveform. The input voltage waveform has high harmonics content by reducing the switches this will be rectified and produced the output with ripple free and high efficiency.

V. CONCLUSION

In this paper, the simple current ripple compensation method employing simple calculation and decision process for B4 inverter has been proposed. The voltage distortion phenomenon caused by the voltage difference between the dc-link capacitors was analyzed. In order to do simulation for Y
as well as J-connected motors analytic models based on differential equations were developed. The compensation method based on modification of switching time was applied to both connection types. The simulation and experimental results applied in an induction motor with Y and J-connection have verified the control performance and the validity of the proposed method.

REFERENCES


