TWO-LEVEL AND FIVE-LEVEL INVERTER FED BLDC MOTOR DRIVES

P. DEVI KIRAN¹ & M. RAMACHANDRA RAO²

¹Scholar, Power Electronics & Drives, Department of Electrical & Electronics Engineering, K L University, Guntur, Andhra Pradesh, India

²Professor, Power Electronics & Drives, Department of Electrical & Electronics Engineering, K L University, Guntur, Andhra Pradesh, India

ABSTRACT

In high power high voltage application BLDC motor are widely used because of higher efficiency, simple in construction, lower cost, less in maintenance and higher torque or high output power per unit volume. For driving the BLDC motor an electrical commutator (inverter) is required. PWM inverter gives good performance. In two level inverter there are problems of harmonics distortions, low electromagnetic interference, higher DC link voltage required, higher dV/dt, heating of rotor (rotor shaft) etc. The increase in the number of steps in voltage is one of the solutions for the above problems. This can be possible by using multilevel inverters. In this paper PWM control, Variable DC link control, Hysteresis control techniques are discussed and finally five level cascade H bridge inverter fed BLDC motor drive is proposed. The phase shift PWM, design of the inverter topology and other methods are presented in this paper. Simulation is carried out using matlab / Simulink, validating the steady state and dynamic performance of the drive.

KEYWORDS: Brushless DC (BLDC) Motor, Single Current Strategy, High Performance Drives

INTRODUCTION

Multi-Level Inverter (MLI) topologies have been widely used in the motor drive industry to run induction machines for high power and high voltage configurations. Traditional multi-level converter topologies such as Neutral Point Clamped (NPC) MLI, Flying Capacitor (FC) MLI, and Cascaded H-Bridge (CHB) MLI have catered to a wide variety of applications. The CHB MLI might be the only kind of multi-level inverter where the energy sources (capacitors, batteries etc.) can completely be the isolated DC sources. Induction Motors (IMs) have been traditionally used for mostly all types of commercial, industrial and vehicular applications. However last decade’s active researches has shown that vehicular applications demand high performances which are delivered by certain special machines. These include Brush Less DC machines, Switched Reluctance machines, Permanent Magnet Synchronous Machines etc.

The obvious reasons for traditionally using Induction Motor is that the motor technology and control methodologies are well understood both by the academia and the industry. The paradigm shift towards the use of Permanent Magnet Synchronous Machines and Brushless DC Machines has been due to the increased demand in high performance, faster torque response and enhanced speed and efficiency from vehicles.

BLDC motor offers many advantages including high efficiency, low maintenance, greater longevity, reduced weight and more compact construction. The BLDC motors have been widely used for various industrial application based on inherent advantages. They are the most suitable motors in application field with requiring fast dynamic response of speed, because they have high efficiency and can be easily controlled in a wide speed range.

Most BLDC drives include a current control loop, which maintains the load current at some required level by switching the constant dc-link voltage across the motor windings. Conventional control of the current loop requires that the
feedback current be provided by direct measurement of the winding currents, which implies that each motor phase must have a separate current sensor. However, the current sensors and the associated accessories increase the complexity, the cost and size of the motor drives and reduce the reliability of the system. Therefore, reduction of the number of sensors is desirable in motor drives. The conventional method of current control in a three phase inverter is to compare current demand with actual winding current, where the winding current is obtained by direct measurements on the motor windings. This current measurement method relies upon the uniformity of current sensors, to achieve a balanced output currents and electromagnetic torque. Thus, the problem of current sensor imbalance can lead to unappreciable torque ripple at low speeds. By using a single current sensor located on the dc-link, there is an inherent balance. Therefore most current sampling method for BLDC motor is use single current sensor technique.

POWER CONVERTERS CLASSIFICATIONS

Figure 1: Classification of High Power Converters

Figure 1 shows the classification of power converters. Out of all power converters, Cascaded bridge configuration is more effective and popular. Cascaded bridge configuration is again classified into two types: Cascaded Half Bridge & Cascaded Full Bridge or Cascaded H-Bridge. In this paper, a novel cascaded H-Bridge topology is proposed for multi-source applications like PV applications.

Half H-Bridge

Figure 2: Half Bridge
Figure 2 shows the cascaded Half H-Bridge Configuration. By using a single Half H-Bridge we can get 2 voltage levels. The switching operation is as shown in Table 1

<table>
<thead>
<tr>
<th>Switches Turn On</th>
<th>Voltage Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>$V_{dc}/2$</td>
</tr>
<tr>
<td>S2</td>
<td>$-V_{dc}/2$</td>
</tr>
</tbody>
</table>

**Table 1: Switching Table for Half Bridge**

Figure 3 shows the Full H-Bridge Configuration. By using single H-Bridge configuration three voltage levels can be obtained. The number of output voltage levels of a cascaded Full H-Bridge is given by $2n+1$ and the voltage step for each level is given by $V_{dc}/n$. Where n is number of H-Bridges in cascaded connection. The switching sequence is as given in Table 2.

<table>
<thead>
<tr>
<th>Switches Turn On</th>
<th>Voltage Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1,S2</td>
<td>$V_{dc}$</td>
</tr>
<tr>
<td>S3,S4</td>
<td>$-V_{dc}$</td>
</tr>
<tr>
<td>S4,D2</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 2: Switching Table for Full H-Bridge**

Figure 4 shows the cascaded five level H-Bridge Configuration. By using single cascaded H-Bridge configuration we can get five voltage levels. For this CHB MLI IGBTs are used and control strategy used is based on the pwm pulses generated by the trapezoidal PWM where modulating trapezoidal signal is obtained by the back-emf generated by the BLDC machine. The switching table of five level cascaded H-Bridge is given in Table 3.

<table>
<thead>
<tr>
<th>Switches Turn On</th>
<th>Voltage Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1,S2,S3,S4</td>
<td>$V_{dc}$</td>
</tr>
<tr>
<td>S3,S4,S5,S6</td>
<td>$-V_{dc}$</td>
</tr>
<tr>
<td>S5,S6,S7,S8</td>
<td>$V_{dc}$</td>
</tr>
<tr>
<td>S7,S8,S9,S10</td>
<td>$-V_{dc}$</td>
</tr>
</tbody>
</table>

**Table 3: Switching Table for Five Level Cascaded H-Bridge**
### Table 3: Switching Table for Cascaded H-Bridge

<table>
<thead>
<tr>
<th>Switches Turn On</th>
<th>Voltage Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1, S2</td>
<td>$V_{dc}$</td>
</tr>
<tr>
<td>S1,S2,S5,S6</td>
<td>$2V_{dc}$</td>
</tr>
<tr>
<td>S4,D2,S8,D6</td>
<td>0</td>
</tr>
<tr>
<td>S3,S4</td>
<td>$-V_{dc}$</td>
</tr>
<tr>
<td>S3,S4,S7,S8</td>
<td>$-2V_{dc}$</td>
</tr>
</tbody>
</table>

**BLDC MOTOR OPERATION PRINCIPLE**

DC motors and PMDC motors normally use mechanical commutator and brushes to achieve the commutation. However, BLDC motors are provided with Hall Effect sensors in order to sense the rotor position and the mechanical commutator and brushes are replaced by electronic commutator which is an inverter. The stator of BLDC motor is made of concentrated wound coils, and the rotor is made of permanent magnet(s). The stator develops the magnetic field to make the rotor attain motion. Hall Effect sensors detect the position and commutates through signals to the control circuit. BLDC motors on using the permanent magnets instead of coils can rotate at higher speeds and high torque values than other machines. Three-phase and two-pole BLDC motor and its mathematical model is described. The back-EMF and phase current waveforms with 120° conduction mode are shown in Figure: 5.

![Configuration of BLDC Motor Drive System, Back-EMF and Reference Current Generation Patterns](image)

The mathematical analysis of a BLDC motor is represented by the following equations:
Two-Level and Five-Level Inverter Fed BLDC Motor Drives

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} = \begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R
\end{bmatrix}
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix} \\
+ \begin{bmatrix}
L - M & 0 & 0 \\
0 & L - M & 0 \\
0 & 0 & L - M
\end{bmatrix}
\frac{d}{dt}
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix} + \begin{bmatrix}
\end{bmatrix}
\tag{1}
\]

Where \(V_a, V_b, V_c\) are the phase voltages \(E_a, E_b, E_c\) are the phase back-EMFs, \(I_a, I_b, I_c\) are the phase currents, \(R\) is the resistance/phase, \(L\) is the self inductance/phase and \(M\) is the mutual inductance between any two phases. So the electromagnetic torque can be derived as:

\[
T_e = [E_a I_a + E_b I_b] + \tag{2}
\]

where \(\omega_r\) is the mechanical speed of the rotor and \(T_e\) is the electromagnetic torque. The equation of motion is given as:

\[
\frac{d}{dt} \omega_r = T_e - B \tag{3}
\]

\(B\) is the damping constant, \(J\) is the moment of inertia of the drive and \(T_l\) is the load torque. The electrical frequency related to the mechanical speed for a motor with \(P\) numbers of poles is:

**PWM Technique**

PWM controllers are used in wide range of applications. The switching frequency in this technique is usually kept constant. This control is based on the principle of comparing a triangular carrier signal of desire switching frequency and is compared to the error of the controlled signal. The error signal thus comes from the sum of the reference signal generated in the controller and the negative of the actual motor current value. The comparison of these will result in a control voltage signal that goes to the gates of the voltage source inverter (VSI) to generate the desire output. Its control will thus respond according to the error. If the error signal is greater than the triangle waveform, the inverter legs upper switch will be held on. When the error command is less than the triangle waveform, the inverter legs lower switch will be held on. Thus the PWM signals are generated. The inverter leg is forced to switch at the frequency of the triangle wave and produces an output voltage proportional to the current error command. The controlled output current consists of a regeneration of the reference currents with a high-frequency PWM ripple superimposed on it.

**Variable DC-Link Voltage Control**

Using a variable DC voltage source to control the applied voltage consequently to control the motor phase currents, can have some advantages over the PWM control scheme. This technique is cheaper than a Pulse Width Modulation control but the losses can be high at low voltage and high current conditions. However, at high speed, a linear power stage can be the best alternative when switching losses and commutation delay of a pulsed power stage significant. The variable dc-link voltage control technique is the only technique that does not cause high frequency disturbances, if assumed that the variable voltage source is ideal. Its performance was similar to the PWM method but it produced much smoother torque due to the absence of high frequency switching. In the frequency domain, the variable dc-link voltage control technique contains only harmonics caused by the current commutation.
Its performance was similar to the PWM method but it produced much smoother torque due to the absence of high frequency switching. In the frequency domain, the variable dc link voltage control technique contains only harmonics caused by the current commutation.

**Hysteresis Current Control**

Hysteresis current controller is also one of the best implemented techniques to control the inverter currents. The controller generates the reference currents for the inverter to be within a range which is a fixed band gap. In this technique the desired current of a given three phases is added with the negative of the measured current. The error signal is fed to a comparator having a hysteresis band. When this error signal crosses the lower limit of the hysteresis band, the inverter legs upper switch is turned on to make the error signal lie between the band limits. But when the current become less than the upper reference band, the bottom switch is turned on. This controller does not have a specific switching frequency and changes continuously but it is related with the band width.

**SIMULATION RESULTS**

**Case 1**

![Image of Simulink Model of the BLDC Motor which is Controlled by the PWM Controller](image)

**Figure 6: Simulink Model of the BLDC Motor which is Controlled by the PWM Controller**

![Image of Speed Curve of the BLDC Motor Controlled by PWM Controller](image)

**Figure 7: Speed Curve of the BLDC Motor Controlled by PWM Controller**

![Image of Electromagnetic Torque of the BLDC Motor Controlled by PWM Controller](image)

**Figure 8: Electromagnetic Torque of the BLDC Motor Controlled by PWM Controller**
Figure 9: Stator Current and Back EMF of the BLDC Motor

Case 2

Figure 10: Simulink Model of the BLDC Motor Controlled by Variable DC Link Voltage Controller

Figure 11: Speed Curve of the BLDC Motor Controlled by Variable DC Link Voltage Controller

Figure 12: Electromagnetic Torque of the BLDC Motor Controlled by Variable DC Link Voltage Controller
Figure 13: Stator Currents of the BLDC Motor Controlled by Variable DC Link Voltage Controller

Case 3

Figure 14: Simulation Circuit of the BLDC with Hysteresis Controller

Figure 15: Speed Curve of the BLDC Motor with Hysteresis Controller

Figure 16: Stator Currents of the BLDC Motor with Hysteresis Controller
Two-Level and Five-Level Inverter Fed BLDC Motor Drives

Case 4

Figure 17: Electromagnetic Torque of the BLDC Motor with Hysteresis Controller

Figure 18: Simulation Circuit of the BLDC Motor with Multilevel Inverter

Figure 19: Speed Curve of the BLDC Motor with MLI

Figure 20: Electromagnetic Torque of the BLDC Motor with MLI
CONCLUSIONS

In this paper various control methods of the BLDC motor are considered such as PWM, Variable DC link controller, Hysteresis controller are discussed. There are some limitations in these methods. These can be overcome by using the multilevel inverter.

REFERENCES


**AUTHOR’S DETAILS**

P. DEVIKIRAN was born in Secunderabad, Andhra Pradesh, India on August 21st, 1989. He received B.Tech degree in Electrical and Electronics Engineering from Tirumala Engineering College, Bogaram, affiliated to JNTU
University Hyderabad, Andhra Pradesh, India in June 2011. He is currently Pursuing M.Tech in Power Electronics and Drives at K L University, Vaddeswaram, Guntur Dist., AP, India.

M. RAMACHANDRA RAO was born in Vetapalem (Cheerala), Andhra Pradesh, India on October 23rd 1941. He received B.E (Hones...) from JNTU University Kakinada, Andhra Pradesh, India in 1962. He received Msc (Engg...) from Dindi (Anna University) College of Engineering and Technology, Chennai, India in 1963. He received M.S Degree from Oklahoma State University Stillwater, USA in 1970 .He also received Ph.D Degree from Oklahoma State University Stillwater,USA in 1972. He worked in H.M.T (R&D) Bangalore, Metal Cutting Centre. He worked as professor in REC Warangal. He was expert in Electro Magnetic Fields and totally 30+ years experience in teaching. He is currently working as professor in Electrical and Electronics Engineering Department in K L University, Vaddeswaram, Guntur district, AP, India.