COMPARISON AND PERFORMANCE ANALYSIS OF DTC - DCMLI DRIVEN PMSM DRIVE USING SPACE VECTOR MODULATION

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Abstract
The paper focus on comparison and performance analysis of DTC - DCMLI driven PMSM drive using space vector modulation is designed, and implemented for automotive application. The simulation work is done using MATLAB software. A DTC based novel SVM was proposed to control of torque, torque angle and stator flux. From the detailed comparison, direct torque control (DTC) based three-level DCMLI driven PMSM drive has stood out as a feasible solution as compared to the conventional inverter in automotive application. Hence direct torque control (DTC) based PMSM drives can validated for hardware implementation. The proposed method three–level DTC - DCMLI driven PMSM drive is found acceptable because of its less distorted output, lower costs, better control performance and other advantageous features. Hence it is used in automotive applications.

Keywords: Direct Torque Control, Diode clamped Multilevel Inverter (DCMLI), Permanent Magnet Synchronous Motor (PMSM), Space Vector Modulation (SVM), Total harmonic distortion (THD).

1. Introduction
Electric motors (EMs) and generators are the primary workhorses in hybrid electric vehicles (HEVs). The generators convert mechanical power from the engine electrical power in order to charge the batteries and operate the motors. Motors produce the required torque to drive the wheels. There are many types of motors and generators used in HEVs: induction, switched reluctance, and permanent magnet. [1-5]. Electric propulsion systems are the main part of electric vehicle (EV).It consist of electric motors, power converters and electronic controllers [6-12].DTC method is proposed to maintain constant switching frequency also reduce torque and current ripple. [13-18]. This paper focus on DTC based DCMLI Using SVM techniques on a surface mounted PMSM used in electrical vehicle. A novel technology of space vector modulation for the DTC is proposed [19-26].

The DTC simulation of PMSM is developed using MATLAB Simulink. The DTC are the efficient control methods for AC machine. DTC method is robust, simple and also has excellent dynamic performance. The limitations of the DTC are its flux ripples and relatively high torque also variable switching frequency in case of Induction motor. The performance of the DTC of PMSM can be improved by reducing the high flux and torque ripples and maintaining a fix switching frequency using novel technology of space vector modulation. [27-35].
This paper presents a DTC based 2-level & 3-level DCML inverter using SVM techniques. In section 1, the introduction is explained. In section 2, the Mathematical Analysis of PMSM model is explained. In section 3, the control topology is explained. In section 4, simulation model & results analysis is presents. In Section 5 the conclusion are present.

2. Mathematical Analysis of PMSM Model
The field winding is absent in rotor of PMSM [2]. There are two stator windings in the dq reference frame. The direct-axis winding is along with the axis of magnetic pole.

The induced voltage in the direct-axis winding:
\[ u_d = R_d i_d + \frac{d\lambda_d}{dt} - \omega_r \lambda_q \]  
(1)

Where, ‘id’ and ‘Rd’ are called d-axis stator current and resistance respectively.

The induced voltage in the q-axis winding:
\[ u_q = R_q i_q + \frac{d\lambda_q}{dt} - \omega_r \lambda_d \]  
(2)

Where, ‘Rq’ and ‘iq’ are called the quadrature-axis resistance and current of stator.

\[ \lambda_d = L_d i_d + \lambda_m \]  
(3)

\[ \lambda_m \] is the PM rotor flux and,

\[ \lambda_q = L_q i_q \]  
(4)

\[ \lambda_q \] = flux-linkage in the quadrature-axis stator (Wb).

In this case of quadrature-axis, there are no magnets so \( \lambda_m \) is absent.

Considering round rotor PMSM, we have

\[ L_d = L_q \]  
(5)

3. Control Topology

Direct torque control
In DTC, it is to calculate the torque and flux errors from hysteresis comparators and select voltage vectors directly based on the differences between reference and actual value of flux linkage & torque. Low complexity, low computational power, and good dynamic performance are the advantages of Direct Torque Control. The basic concept of Direct Torque Control is to controlled the amplitude and angular position of the stator flux vector. \( \lambda_r \) be the rotor flux linkage vector in d-q coordinate and \( \lambda_s \) be the stator flux linkage vector.

In d-q coordinate system, PMSM stator flux linkage and torque equations are

\[ D = L_d i_d + R \]  
(6)

\[ Q = L_q i_q \]  
(7)

\[ \lambda_v = \sqrt{(\lambda_d^2 + \lambda_q^2)} \]  
(8)

\[ \tau_{sd} = \frac{3}{2} \frac{d}{dt}(\lambda_d i_q - \lambda_q i_d) \]  
(9)

The d-q current equations are

\[ i_d = \frac{\lambda_d - \lambda_s}{L_d} \]  
(10)

\[ i_q = \frac{\lambda_q - \lambda_s}{L_q} \]  
(11)

The flux linkage equations are

\[ \lambda_d = \lambda_{s0} \cos \delta \]  
(12)

\[ \lambda_q = \lambda_{s0} \sin \delta \]  
(13)

put in the torque expression

\[ \tau_{sd} = \frac{3}{2} \frac{d}{dt}(\lambda_d i_q - \lambda_q i_d) \]  
(14)
Inverter topology
i) Two level Inverter
In Figure 1, the number of switches is two per leg and the capacitor is used as a filter. Problems associated with conventional adjustable speed drive inverter are High frequency switching is responsible for large switching losses, Motor bearing failure and stator winding insulation breakdown problems occurs due to high dv/dt and Electromagnetic interference problems occur due to high frequency switching.

![Figure 1: Conventional, two-level inverter](image)

Table 1 switching vectors and line voltages

<table>
<thead>
<tr>
<th>Voltage Vectors</th>
<th>Switching Vectors</th>
<th>Line to line voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>V₀</td>
<td>0 0 0</td>
<td>0 0 0</td>
</tr>
<tr>
<td>V₁</td>
<td>1 0 0</td>
<td>1 0 -1</td>
</tr>
<tr>
<td>V₂</td>
<td>1 1 0</td>
<td>0 1 -1</td>
</tr>
<tr>
<td>V₃</td>
<td>0 1 1</td>
<td>-1 1 0</td>
</tr>
<tr>
<td>V₄</td>
<td>0 1 1</td>
<td>-1 1 0</td>
</tr>
<tr>
<td>V₅</td>
<td>0 0 1</td>
<td>0 -1 1</td>
</tr>
<tr>
<td>V₆</td>
<td>0 1 1</td>
<td>1 -1 1</td>
</tr>
<tr>
<td>V₇</td>
<td>1 1 1</td>
<td>0 0 0</td>
</tr>
</tbody>
</table>

ii) Diode Clamped Multilevel Inverter
The DCMLI comprises of two series-connected capacitors, C₁ and C₂, the DC-link capacitors which divide the DC bus voltage into three levels; +Vdc/2, 0 & -Vdc/2. ‘n’ is the neutral point between two capacitors C₁ and C₂. (Sₐ₁, Sₐ₃) and (Sₐ₂, Sₐ₄) are two complementary switch pairs and (D₁, D₁₀) are the two clamping diodes per phase.
If Sₐ₁ and Sₐ₂ is ON, so Van = +Vdc/2.
If Sₐ₂ and Sₐ₃ is ON, so Van = 0.
If Sₐ₃ and Sₐ₄ is ON, so Van = -Vdc/2.
The investigations on DTC based conventional inverter and DCMLI-PMSM drive has been done in MATLAB software. The SVM techniques have been applied to the conventional inverter and DCMLI fed PMSM drive system under steady state only. The load torque is applied in steps. The Simulink model of DTC based conventional inverter and DCMLI-PMSM drive shown in the Fig.3 & Fig.4. The output voltage & current waveforms of conventional inverter and DCMLI using SVM are in fig.2 and fig.3. The speed, electromagnetic torque, and Stator rotor flux response respectively are in fig.7, fig.8 and fig.9. The frequency spectrum of line voltage and phase current are in fig.10 and fig.11. Table I and Table II shows the THD analysis and torque ripple analysis of DTC based conventional inverter and DCMLI-PMSM drive. The specification of Permanent Magnet Synchronous Motor as in the Table III.

**Figure 2:** Three-level Diode-Clamped Inverter

**Simulation model & Results analysis**

**Figure 3:** Simulink model of DTC based conventional inverter PMSM drive

**Figure 4:** Simulation Model of DTC based DCMLI PMSM drive
Figure 5: Voltage response of (a) Two-level (b) Three-level inverter

Figure 6: Stator current response of (a) Two-level (b) Three-level inverter
Figure 7: Torque response of (a) Two-level (b) Three-level inverter

Figure 8: Speed response of (a) Two-level (b) Three-level inverter
Figure 9: motor flux response (a) Two-level (b) Three-level inverter

Figure 10: FFT response of stator voltage (a) Two-level (b) Three-level inverter
(a) Two-level

(b) Three-level inverter

Figure 11: FFT response of stator current (a) Two-level (b) Three-level inverter

<table>
<thead>
<tr>
<th>Controller Speed</th>
<th>Two-Level with DTC-SVM</th>
<th>Three-Level with DTC-SVM</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 rpm</td>
<td>21.58%</td>
<td>18.5449%</td>
</tr>
<tr>
<td>1000 rpm</td>
<td>20.54%</td>
<td>17.26%</td>
</tr>
<tr>
<td>1500 rpm</td>
<td>18.27%</td>
<td>15.86%</td>
</tr>
</tbody>
</table>

Table 3. Specification of PMSM

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>PMSM Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stator Resistance</td>
<td>2.885Ω</td>
</tr>
<tr>
<td>2</td>
<td>Permanent Magnet Flux</td>
<td>0.185 Wb</td>
</tr>
<tr>
<td>3</td>
<td>No of Pole pairs</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>d-axis Inductance</td>
<td>8.5x10^-3 H</td>
</tr>
<tr>
<td>5</td>
<td>q-axis Inductance</td>
<td>8.5x10^-3 H</td>
</tr>
<tr>
<td>6</td>
<td>Torque</td>
<td>0.031 Nm</td>
</tr>
<tr>
<td>7</td>
<td>Movement of Inertia</td>
<td>2.26x10^-2 Kg·m²</td>
</tr>
<tr>
<td>8</td>
<td>Viscous coefficient</td>
<td>1.349x10^-5 N·m·s</td>
</tr>
</tbody>
</table>
5. Conclusion

The comparison and performance analysis of DTC - DCMLI driven PMSM drive using space vector modulation is designed, and implemented for automotive application has been done in this paper using MATLAB software. Modelling and simulation investigations of SVM -DTC based conventional inverter and SVM -DCMLI PMSM drive SVM method provides better steady state response of DCMLI driven PMSM drive as compared to conventional inverter. As seen from its response, the SVM is easy and the fastest method. The methods demonstrated the reduction in torque ripple, THD in inverter output and improved driving performance. Due to these characteristics, investigations on DCMLI driven PMSM drive system is found better suited for EV application.

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