Performance analysis of FOC space vector modulation DCMLI driven PMSM drive

Rakesh Shriwastava1, Mohan P. Thakre2, Jagdish Choudhari3, Sunil Somnath Kadlag4, Rahul Mapari5, Deepak Prakash Kadam6, Shridhar Khule1

1Department of Electrical Engineering, Matoshri College of Engineering and Research Center, Nashik, India
2Department of Electrical Engineering, SVERI’s College of Engineering, Solapur, India
3Department of Electrical Engineering, Nagpur Institute of Technology, Nagpur, India
4Department of Electrical Engineering, Amrutvahini College of Engineering, Sangamner, India
5Department of Electrical Engineering, Pimpri Chinchwad College of Engineering and Research, Ravet Pune, India
6Department of Electrical Engineering, MET Institute of Engineering, Nashik, India

ABSTRACT

The effectiveness of a permanent magnet synchronous motor (PMSM) drive managed by an automatic voltage regulator (AVR) microcontroller using field oriented control (FOC) with space vector modulation (SVM) and a diode clamped multilevel inverter (DCMLI) is investigated. Due to its efficacy, FOC would be widely implemented for PMSM speed regulation. The primary drawbacks of a 3-phase classic bridge inverter appear to be reduced dv/dt stresses, lesser electromagnetic interference, and a relatively small rating, especially when compared to inverters. PMSMs have a better chance of being adopted in the automotive industry because of their compact size, high efficiency, and durability. The SVM idea states that an inverter's three driving signals are created simultaneously. Using MATLAB simulations, researchers looked into incorporating a DCMLI with a resistive load on an AVR microcontroller. Torque, current, and harmonic analysis were evaluated between the SVM and the inverter-driven PMSM drive in this research. In comparison to the prior art, the proposed PMSM drive has better speed and torque management, less output distortion, and less harmonic distortion.

Keywords:
Automatic voltage regulator
Field oriented control
Permanent magnet synchronous motor
Space vector modulation
Total harmonic distortion

This is an open access article under the CC BY-SA license.

Corresponding Author:
Rakesh Shriwastava
Department of Electrical Engineering, Matoshri College of Engineering and Research Center
Nashik, India
Email: rakesh_shriwastava@rediffmail.com

1. INTRODUCTION

The characteristics of permanent magnet synchronous motor (PMSM) are the low value of cogging torque, ruggedness, high efficiency, high power to weight ratio, and additional reluctance torque. In an electric vehicle application, the motor, run to different load and speed profiles; hence it is used application. In PMSM, due to the magnet in the rotor and constant air gap, it is not needed to supply magnetizing currents through the stator flux. When at high speed, it gives high current and fewer switching losses. If put into practice, it would allow for a range of speeds by rapidly switching between low switching frequencies for slow speeds and high switching frequencies for fast speeds [1], [2]. Vector control is the most useful method for field oriented control (FOC). The FOC approach has replaced the direct torque control (DTC) method in AC drives [3], [4] because of its superior performance. The good-current regulation, high torque response, and simple construction have the advantages of FOC. Some of the advantages of multilayer inverters include increased efficiency, lower voltage
distortion, lower harmonic content, and lower dv/dt at each switch. A pulse width modulation (PWM) controller multilayer inverter can switch to a lower frequency [5], [6]. The FOC is a vector control method based on the working principle of a separately excited d.c motor. This method can effectively control the motor torque and flux by controlling the stator reference currents, rotor angle, and torque of the alternating machine. In this paper, a novel space vector modulation (SVM) technique is designed for the FOC based diode clamped multilevel inverter (DCMLI) PMSM drive to drive for torque, speed, and stator current of PMSM [6].

The inverter switching vectors have been automatically constructed from the instantaneously sampled reference phase voltages [7], [8] without the need for lookup tables or difficult logical choices. In this study, we analyze DCMLI using a simulated SVM and then feed the results into a three-phase resistive load. It reduces switching losses and total harmonic distortion (THD). In this case, the automatic voltage regulator (AVR) microcontroller simulation results have been confirmed for use in actual projects. Pulses are generated by the atmega 8 and fed into the inverter.

FOC provides high-quality control capability in FOC SVM over the full range of torque and speed fluctuations [9]–[11]. There are d & q current modes in FOC. The q torque mode is run the desired torque from the PMSM. The d current mode is run with a zero to minimize the unwanted direct torque component [12]–[14]. To overcome this drawback in PWM, an SVM modulation technique is used. SVM selects vectors in a d-q stationary frame. Space vectors are based on induction machines magnetism. Three-phase amounts become two-phase [15], [16]. Space vectors can represent active and "0" switching [17]. V1-V6 forms a symmetric hexagon to diversify sectors (1 to 6). Each sector is 60° apart. SPWM compares sine waves to triangular waves [18]–[20]. Switching points result from the triangular carrier wave of frequency fc and the reference modulatory sine wave of frequency fm.

This research presents MATLAB simulation and hardware validation of three-level DCMLI-fed FOC-PMSM drives using SVM and AVR microcontroller [21]–[25]. This paper follows this format. Section 1 covers the overview, section 2 the analytical approach, section 3 the virtual world assessment and outcomes, and section 4 the hardware configuration. section 5 is the experimental outcome and the conclusion of this paper is in section 6.

2. METHODOLOGY

Mathematical model analysis of PMSM is a concern, the d-axis-induced voltage is:

\[ u_d = R_d i_d + \frac{d\lambda_d}{dt} - \omega_r \lambda_q \]  

The q-axis induced voltage is:

\[ u_q = R_q i_q + \frac{d\lambda_q}{dt} - \omega_r \lambda_d \]  

\[ \lambda_d = L_d i_d + \lambda_m \]  

\[ \lambda_q = L_q i_q \]  

\[ L_d = L_q \]

The torque equation is:

\[ T_e = \frac{3}{2} p \lambda_m i_q \]

Put in (7):

\[ T_e = \frac{3}{2} p \left( \lambda_d i_q + \lambda_m i_q - L_q i_q i_d \right) \]

\[ T_e = \frac{3}{2} p \left( L_d - L_q \right) i_d i_q + \lambda_m i_q \]

\[ Reluctance torque = \frac{3}{2} p \left( L_d - L_q \right) i_d i_q \]

\[ Field torque = \frac{3}{2} p \lambda_m i_q \]

\[ T_e = \frac{3}{2} p \lambda_m i_q \]
Therefore, electromagnetic torque is:
\[ T_e = T_l + B \omega_m + J \frac{d\omega_m}{dt} \] (14)

The primary goal of FOC is the control of torque and currents along the stator axis (d and q). By regulating the motor’s torque and flux based on information from the stator currents and the rotor angle, FOC can accomplish desirable results such as high output and reduced torque ripple. The system consists of a current regulator, a direct-axis component, a q-axis component, and a speed regulator. The FOC method is depicted in block format in Figure 1.

Design of converter:
- Design of diode bridge rectifier
  Voltage (input)=290 V, frequency=50 Hz, filter output voltage (rectifier)=380 Vdc
- Design of three-level diode clamp inverter, while selecting MOSFET, \( V_{dc}>0.707 \times m_a \) Vdc [let \( m_a=1 \) (max)]\( \times 0.707 \times 380>268.66 \) volts, \( V_{gs}>12 \) volts, \( I_d>I_{Lmax}>2 \) ams
  Transition times should be minimized. IRFP460 is the MOSFET of choice, output voltage (inverter)=280 V, switching frequency=2.5 KHz, inverter rating (KVA)=1.5 KVA
- Isolator drive and AVR microcontroller details
  To regulate the output, there are twelve 7,812 ICs and twelve 4N35 optical couplers. The transformers have a rating of 230 volts to 12 volts and 500 milliamperes (12 No). The ATmega8 (28 Pin) is responsible for creating pulses, while the ATmega16 (40 Pin) is in charge of the control and monitoring circuit (40 Pin).

3. SIMULATION ANALYSIS AND DISCUSSION

The simulation diagram of FOC is shown in Figure 2. Design, simulation, and implementation of FOC SVM DCMLI-driven PMSM drive using an AVR microcontroller are investigated for the different speeds. It is shown in Figures 3-7. The frequency analysis of the inverter output and THD analysis are shown in Figures 8 and 9. The parameters of the motor and inverter have been listed in Tables 1 and 2. THD, torque, and current ripples of DCMLI are listed in Tables 3 and 4. Figures 3 and 4 shows inverter voltage and current respectively with less THD. Figures 5-7 show the performance of the PMSM drive using SVM.

The reference speed changed from 0 to 1,000 rpm for time \( t=0.05 \) s and speed are constant for the time of \( t=0.05 \) s to 0.3 s. Motor speed was 1,700 rpm for time \( t=0.3 \) s to 0.35 s. Speed reached the reference value for time \( t=0.6 \) s as shown in Figure 6. The value of load torque is 0.2 N.m for time \( t=0 \) s to 0.4 s. It is decreased for time \( t=0.3 \) s to 0.4 s shown in Figure 6. The initial current of the motor was 1.4 amp and it reduces up to 1.3 amp for time \( t=0 \) s to 0.1 s as shown in Figure 7.
Performance analysis of FOC-SVM DCMLI driven PMSM drive (Rakesh Shriwastava)
Figure 5. Output speed response of FOC-DCMLI

Figure 6. Output torque response of FOC-DCMLI

Figure 7. Output phase current FOC-DCMLI
Performance analysis of FOC-SVM DCMLI driven PMSM drive (Rakesh Shriwastava)

Table 1. PMSM specification

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor stator resistance ($R_s$)</td>
<td>4.865 Ω</td>
</tr>
<tr>
<td>Motor stator inductance ($L_a$)</td>
<td>0.0174 H</td>
</tr>
<tr>
<td>Motor torque ($T_e$)</td>
<td>0.544 N-m</td>
</tr>
<tr>
<td>Movement of inertia ($J$)</td>
<td>0.000114 Kg/m2</td>
</tr>
<tr>
<td>Viscous coefficient ($f$)</td>
<td>0.0000447 Nms</td>
</tr>
<tr>
<td>Number of pole(P) pair</td>
<td>2</td>
</tr>
<tr>
<td>Inductive load</td>
<td>PMSM</td>
</tr>
</tbody>
</table>

Table 2. Inverter parameter

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>280 V (rms)</td>
</tr>
<tr>
<td>Output filter voltage</td>
<td>380 Vdc</td>
</tr>
<tr>
<td>Supply frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Inverter voltage</td>
<td>270V</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>2.5 kHz</td>
</tr>
<tr>
<td>Inverter rating</td>
<td>1.5 KVA</td>
</tr>
<tr>
<td>Resistive load</td>
<td>200 Watts</td>
</tr>
</tbody>
</table>

Table 3. THD analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>10.89</td>
</tr>
<tr>
<td>Current</td>
<td>2.33</td>
</tr>
</tbody>
</table>

Table 4. Torque and current ripples

<table>
<thead>
<tr>
<th></th>
<th>1100 rpm</th>
<th>1300 rpm</th>
<th>1600 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque ripples</td>
<td>0.52 Nm</td>
<td>0.49 Nm</td>
<td>0.46 Nm</td>
</tr>
<tr>
<td>Current ripples</td>
<td>8.4 mA</td>
<td>7.8 mA</td>
<td>7.5 mA</td>
</tr>
</tbody>
</table>

4. HARDWARE ANALYSIS

The block diagram of the proposed AVR microcontroller-based three-level DCMLI with three-phase resistive load and real image for the experiment is shown in Figures 10 and 11 respectively. The three-level DCMLI is used to convert DC to three phases of AC. The generation of pulses using the SVM
A proposed method has been established by using AVR microcontroller. An empirical investigation has been carried out with a view to the validity of the presented AVR microcontroller premised SVM. Methods of regulation have been presented, and their efficacy with a 3 Nm load has been demonstrated. It has been experimentally looked into how fast each approach can respond. Load-related variations in the motor speed at constant modulating frequencies of 40 Hz, 45 Hz, and 50 Hz. Figures 12(a)-(c) display DCMLI phase voltages at 40 Hz, 45 Hz, and 50 Hz, respectively.

To verify the reliability of the suggested SVM approach, a three-tiered DCMLI was devised and implemented. DC-modulated multi-level interleaved-switched voltage modulation is superior to PWM. Figures 13(a)-(c) display the DCMLI line voltages at 40 Hz, 45 Hz, and 50 Hz, respectively.

Observational data shows low levels of THD, ripple current (IR), and ripple torque (Tr). The evidence is in Tables 3 and 4. Tables 5 and 6 illustrate the load readings for 33 Hz and 59 Hz, respectively, at various motor speeds. Figure 14 shows waveforms of DCMLI current, speed-torque variation at 33 Hz and 59 Hz is seen in Figure 15.

There is no change in frequency or speed due to changes in load. Changing the inverter's frequency will also vary the motor's output. Power output vs torque is depicted in Figure 15(a) and load versus speed is depicted in Figure 15(b).
Performance analysis of FOC-SVM DCMLI driven PMSM drive (Rakesh Shriwastava)

Figure 12. DCMLI phase voltages: (a) at 40 Hz, (b) at 45 Hz, and (c) at 50 Hz

Figure 13. DCMLI line voltages: (a) at 40 Hz, (b) at 45 Hz, and (c) at 50 Hz

Table 5. Motor speed-load reading at 33 Hz

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Weight (gm)</th>
<th>Actual speed (rpm)</th>
<th>Calculated speed (rpm)</th>
<th>Voltage (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>600</td>
<td>998</td>
<td>1011</td>
<td>272</td>
</tr>
<tr>
<td>2.</td>
<td>1100</td>
<td>998</td>
<td>1011</td>
<td>272</td>
</tr>
<tr>
<td>3.</td>
<td>1600</td>
<td>998</td>
<td>1011</td>
<td>272</td>
</tr>
<tr>
<td>4.</td>
<td>2100</td>
<td>998</td>
<td>1011</td>
<td>272</td>
</tr>
<tr>
<td>5.</td>
<td>2600</td>
<td>998</td>
<td>1011</td>
<td>272</td>
</tr>
<tr>
<td>6.</td>
<td>3200</td>
<td>998</td>
<td>1011</td>
<td>272</td>
</tr>
</tbody>
</table>

Table 6. Motor speed-load reading at 59 Hz

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Weight (gm)</th>
<th>Actual speed (rpm)</th>
<th>Calculated speed (rpm)</th>
<th>Voltage (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>600</td>
<td>1770</td>
<td>1792</td>
<td>268</td>
</tr>
<tr>
<td>2.</td>
<td>1100</td>
<td>1770</td>
<td>1792</td>
<td>268</td>
</tr>
<tr>
<td>3.</td>
<td>1600</td>
<td>1770</td>
<td>1792</td>
<td>268</td>
</tr>
<tr>
<td>4.</td>
<td>2100</td>
<td>1770</td>
<td>1792</td>
<td>268</td>
</tr>
<tr>
<td>5.</td>
<td>2600</td>
<td>1770</td>
<td>1792</td>
<td>268</td>
</tr>
<tr>
<td>6.</td>
<td>3200</td>
<td>1770</td>
<td>1792</td>
<td>268</td>
</tr>
</tbody>
</table>

Figure 14. Waveforms of DCMLI current
6. CONCLUSION

In this study, we analyze the efficiency of a PMSM drive controlled by a FOC SVM DCMLI and driven by an AVR microcontroller. This evaluation is predicated on an AVR microcontroller-driven PMSM motor and is controlled by a DCMLI. The inverter-driven PMSM drive with SVM was compared in terms of torque, current, and harmonic analysis. Less harmonic distortion is achieved as a result of using DCMLI. Improved steering efficiency in terms of speed and torque response, in addition to better dynamic characteristics, less contorted output, and reduced costs are provided by the proposed AVR microcontroller-based DCMLI-driven PMSM drive. Since it can adapt to changes in speed quickly and has a lower load ripple than conventional inverters, it is well suited for use in the automotive industry.

REFERENCES


Dr. Rakesh Shriwastava obtained Ph.D. Degree in Electrical Engineering specializing in Power Electronics and Drives from RTM Nagpur University, India in 2017. He occupied various positions to serve the Engineering Institutes for about 24 years. He is currently working as Professor at Department of Electrical Engineering, Matoshri College of Engineering and Research Center, Nashik. His research interests include the analysis and control of electrical drives, particularly in hybrid and electric vehicle applications. He has several publications in national and international journals. He attended International and National conferences and also worked as a jury member. He is a member of professional bodies such as ISTE and IAENG. He can be contacted at email: rakesh_shriwastava@rediffmail.com.

Dr. Mohan P. Thakre received the B.Tech. and M. Tech degrees in Electrical Power Engineering from Dr. Babasaheb Ambedkar Technological University (Dr. BATU), Maharashtra, India, in 2009 and 2011 respectively, and the Ph.D. degree in Electrical Engineering from Visvesvaraya National Institute of Technology, (VNIT), Nagpur, Maharashtra, India in 2017. Currently, he is an Associate Professor at the Department of Electrical Engineering, SVERI’s College of Engineering, Pandharpur, Maharashtra, India. His research interests include FACTS and power system protection. He can be contacted at email: mohanthakre@gmail.com.

Jagdish Choudhari completed his Bachelor of Electrical Engineering and Master of Engineering in Electrical Power System from Government College of Engineering in 1999 and 2002 respectively. He has completed his Ph.D. in the area of Electrical Drives and Control in 2019 from Rashtrasant Tukadoji Maharaj Nagpur University. He has published 60 plus papers in National and International Journal and Conferences and granted 01 International and 01 National Patent. He is a member of LMISTE, MIE, QCFI and IAENG. He is working as Associate Professor and Head, Department of Electrical Engineering from June 2018 and Dean Academics from September 2022 at Nagpur Institute of Technology, Nagpur, Maharashtra (India). He can be contacted at email: jagdishchoudhari260878@gmail.com.
Dr. Sunil Somnath Kadlag received B.E in Electrical Engineering from Dr. Babasaheb, Ambedkar, Marathawada University, Aurangabad (Dr B.A.M.U) in 1997 and M.E in Electrical Engineering (Control System) from Government College of Engineering Pune (Pune University) in 2005 and Ph.D. in Electrical Engineering from Suresh Gyan Vihar University Jaipur (Rajasthan) in 2021. His research area is electric vehicles. He is presently working as an Associate Professor and Head of the Department of Electrical Engineering, Amrutvahini College of Engineering, Sangamner, Savitribai Phule Pune University, Pune, Maharashtra, India. He can be contacted at email: sunilkadlag5675@gmail.com.

Dr. Rahul Mapari received a bachelor’s degree and master’s degree in Electronics Engineering from Savitribai Phule Pune University, India, in 2004 and 2007 respectively, and a Ph.D. degree in Electronics and Telecommunication Engineering from Amravati University, India in 2016. He has a total of 17 years of experience in various reputed Technical Institutes. He is working as a Professor in the Department of Electronics and Telecommunication Engineering of Pimpri Chinchwad College of Engineering and Research, Pune since 2017. His research interests include power converters and power electronics. He can be contacted at email: rahul.mapari@pccoer.in.

Dr. Deepak Prakash Kadam received a B.E from the Government College of Engineering, Amravati, and M.E degrees in Electrical Power Systems from Walchand College of Engineering, Sangli, Maharashtra, India, in 1997 and 2005 respectively, and the Ph.D. degree in Electrical Engineering from Savitribai Phule Pune University, Pune Maharashtra, India in 2015. Currently, he is an Associate Professor at the Department of Electrical Engineering, Bhujbal Knowledge City, MET Institute of Engineering, Nashik, India. His research interests include renewable energy technology, power quality, and power system. His total teaching experience is around 23 years. He can be contacted at email: dpkadam@gmail.com.

Dr. Shridhar Khule obtained Ph.D. Degree in Electrical Engineering specializing in power systems from Sant Gadge Baba Amravati University, Amravati, Maharashtra, India in 2021. He occupied various positions to serve engineering institutes for about 20 years. He is currently working as Professor in the Electrical Engineering Department of Matoshri College of Engineering and Research Center, Nashik. His research interests power system. He attended International and National conferences. He is a member of professional bodies such as ISTE and IET. He can be contacted at email: shridhar.khule@matoshri.edu.in.