Performance Analysis of CB-SVM Three-Phase Five-Level DCMLI Fed PMSM Drive

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Abstract: Multilevel inverter (MLI) topology is popular in recent years in automobiles of low and high capacity. Compared to conventional inverters, such technology provides quality performance. Permanent magnet synchronous (PMS) motors are more prevalent in the constant speed and torque control of the electric motor drive. The main features of PMSM involve high energy density, improved time to current ratios, increased effectiveness, and smooth control. Field-oriented field control (FOC) can be used to improve the drive performance of PMSM over conventional two-level VSI by using the three-phase multi-level diode inverter (DCMLI). A 3-phase 5-level DCMLI driven PMSM drive is simulated and evaluated by PSIM software. This article describes an approach of space vector modulation based on the inverter-driven PMSM drive at 2 and 3 levels (CB-SVM). Five-level DCMLI performance comparison of a 2-level PMSM drive is carried out and verified with simulated results utilizing CB-SVM. CB-SVM signals are provided for inverter operation. The comparison is based on PMSM drive features to inverter output current and voltage response. Better constant speed and fewer torque ripples were shown by the simulation analysis.

Keywords: Diode Clamped Multilevel inverter (DCMLI), Carrier-based Space Vector Modulation (CBSVM), Voltage Source Inverter (VSI)

1. Introduction

The multi-level inverter uses multiple batteries and a power switch to synthesize the desired voltage of the waveform. MLI ac drive delivers good automotive performance and is the best alternative to save energy [1]. In conventional inverters, harmonic contents may be reduced by increasing the frequency of switching, but losses may be increased. A low-frequency waveform that reduces shifting losses, increased efficiency, and low THD and near-sinusoidal power are created by MLI advantage over 2 levels. The voltage stress and low EMI of the power switches are reduced [2-4]. The term 'multilevel' begins at the inverter's output at three or more voltage levels [4]. Initially, 1975 introduced the cascaded inverter [6]. The classic MLVSI configurations are known as three popular advertisements. The Diode Clamping (DC-MLI)[5], FC-MLI[7], and Cascading H-Bridge[8] are all included. There've been briefings of some MLI topology today [9-10].
The drawbacks of modulation methods include modularity loss, frequency switching problems, and control method restrictions [11]. DC sources with unequal potential are often used in asymmetric topology, even when hybrid converter have been intended employing various switch combinations. In comparison with conventional configurations, the objective of recent configurations is to reduce the required number of components [11-14]. Multilevel modulation methods such as SPWM, SHE-PWM, and SVM are used in the literature [15-16]. This article consists of simulation analyses for a FOC-based conventional VSI drive, and a CB-SVM modulation technology for the 5- levels DCMLI has driven PMSM drive.Hybrid vehicles depend on motor and generator to work (HEVs). These same generators transform mechanical energy into electricity that then charges battery packets which then power the motors. The torque required to drive a roller is generated by the motor. Induction switched reluctance as well as a permanent magnet is the different types of HEV engines and generators [17-19]. The core of electric vehicles, consisting of electric motors, converters, and controls [20] also includes electric pulsing structures. Both would be commonly used in various applications

and development. This same FOC has been used in the RF frame and aspiration description on the position of the rotor to enforce the transformation coordinates [20-25].
This article presents a comparative analysis of the DCMLI-topology CB-SVM simulated PSIM models. The detailed mathematical modeling of PMSM has been described in Section II and various multi-level structures have been described in Section III. Section IV provided the PMSM drive control Strategy. The proposed methodology, with simulation analysis and conclusion, has been represented in Section V and Section VI.

1.1 .MATHEMATICAL MODELING OF PMSM

1.1.1 *PMSM Designing*

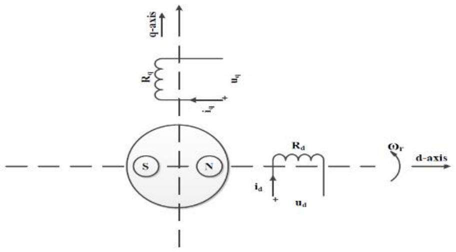


Figure 1. The PMSM model with rotor circuit

The field winding is absent in the rotor of PMSM [2]. There are two stator windings in the *d*-*q* frame. The direct-axis winding is along with the axis of the magnetic pole. If PMSM running in an anti-clockwise direction, at the speed of 'ω_r', as seen in Figure.1. The voltage Eqn. of four-pole 3-phase PMSM in the *d*-*q* domain is,

$$\overline{u_{dqos}} = R_s.\overline{i_{dqos}} + p\overline{\lambda_{dqos}} \tag{1}$$

The calculated value of linkage in the *d*-*q* frame is

$$\overline{\lambda_{dqos}} = L_{dqo}.\overline{i_{dqos}} + \overline{\lambda_{dqo,m}} \tag{2}$$

Where the inductance matrix is expressed as, (17)-(18)-(19)

$$L_{dqo} = \begin{bmatrix} L_d & 0 & 0 \\ 0 & L_q & 0 \\ 0 & 0 & L_o \end{bmatrix} = \begin{bmatrix} L_s & 0 & 0 \\ 0 & L_s & 0 \\ 0 & 0 & L_s \end{bmatrix} \tag{3}$$

In *d*-*q* axes, the voltages Eqn. are (14)-(15)

$$u_{ds} = R_s i_{ds} + L_s \frac{di_{ds}}{dt} - \omega_r L_s i_{qs} \tag{4}$$

$$u_{qs} = R_s i_{qs} + L_s \frac{di_{qs}}{dt} - \omega_r (L_s i_{ds} + \lambda_{pm}) \tag{5}$$

For machine, the electromagnetic torque is

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \tag{6}$$

For a cylindrical pole machine, with L_d=L_q, using better controls, only Electromechanical torque $T_{e\ gave}$ by,

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\lambda_{pm} i_{qs}\right) \tag{7}$$

From Eqn. (7) it is seen that the torque is produced due to quadrature-axis current. Park's transformation converts *d*-*q* variables to a, b, c variables in the following matrix.

$$\begin{bmatrix} Vq \\ Vd \\ Vo \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \tag{8}$$

The inverse transformation of the above is

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 2\pi/3) & \sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + 2\pi/3) & \sin(\theta + 2\pi/3) & 1 \end{bmatrix} . \begin{bmatrix} Vq \\ Vd \\ Vo \end{bmatrix} \quad (9)$$

***A.* Permanent Magnet Synchronous Motor's**

In Figure 2, PMSM single-phase equivalent circuit has been demonstrated [26].

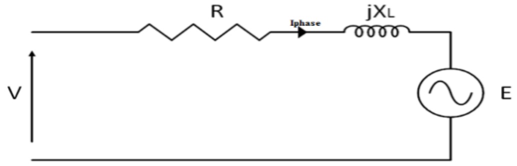


Figure2. PMSM equivalent circuit

The stator current (I) consists of the flux-producing component (I_f) and the torque-producing component (I_q) in the direction of the rotor PM flux.

***B.* PMSM phasor diagram without field-weakening**

In Figure.3 the phasor diagram of the PMSM [27] can be realized. For avoiding such a condition, it is necessary to reduce the back EMF along with the increasing speed which is performed by introducing field flux-weakening.

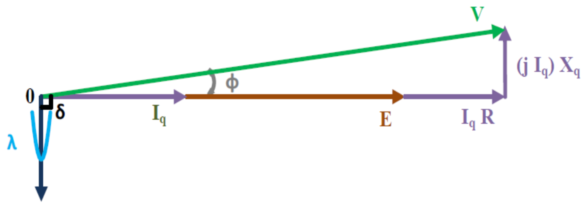


Figure.3. Single-Phase PMSM phasor Diagram before Field- Weakening

***C.* PMSM phasor diagram by introducing the field-weakening**

For the reduction of PM flux which is constant, flux producing current $I_d$in the opposite direction of the PM flux. It is injected which is called the flux-weakening component of current (I_d). In Figure.4.the voltage drop across the inductive reactance will be opposing to the direction of back EMF thereby reducing its effect.

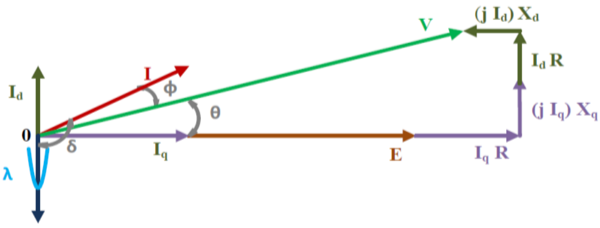


Figure.4. Single-Phase PMSM phasor diagram after Field- Weakening

From the phasor diagram in Figure 4,

$$V = \sqrt{(E + I_q R - I_d X_d)^2 + (I_d R + I_q X_q)^2} \quad (10)$$

For no field-weakening employed, $I_d = 0$ in Eqn. (10); and the phasor representation can be seen in Figure 3. The PF of the load '$\cos\varphi$' and the power factor angle 'φ' can be calculated as

$\Phi = \delta - \theta$

When field-weakening is absent, $\delta = \pi/2$

When field-weakening is present, $\delta > \pi/2$

$$\tan^{-1}(I_q/I_d) \quad (11)$$

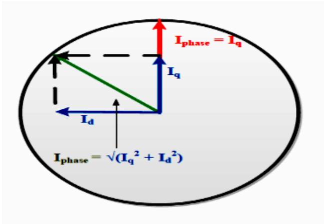


Figure.5. Quadrature axis and direct axis current Components of the Stator Phase Current

$$I_q < \sqrt{(I_{phase}^2 - I_d^2\ )} \tag{12}$$

$$N = \frac{120f}{p} \tag{13}$$

Also,

$$f = \frac{pN}{120} \tag{14}$$

Where, N = Machine speed (RPM), f = fundamental frequency (Hz) and p = number of poles

$$X_s = 2\pi f L_s \tag{15}$$

The maximum current rating of the machine can be determined from the maximum back EMF of the machine and the maximum power rating.

$$P_{max} = 3E_{LLmax}I_{max} \tag{16}$$

From Eqn. 16, the maximum current value, I_{max} can be obtained.

2. INVERTER TOPOLOGY (MULTILEVEL)

A. 2 Level Inverter

The input to three-phase VSI is output DC voltage and produced sinusoidal voltage and current for the three-phase motor. The conventional VSI is considered and switched over to a multilevel inverter due to the drawback of conventional VSI. The drawbacks of conventional VSI are as follow:

1. High-frequency switching causes high losses of switching.
2. Motor bearing failure and isolation failure caused by stator winding is caused by high *dv/dt*.
3. Due to large-frequency switching, EMI problems occur.

The circuit diagram of a conventional VSI as shown in Figure 6 is two per leg and the condenser is used as a filtration system. To simplify a 2-level inverter into the space vector representation

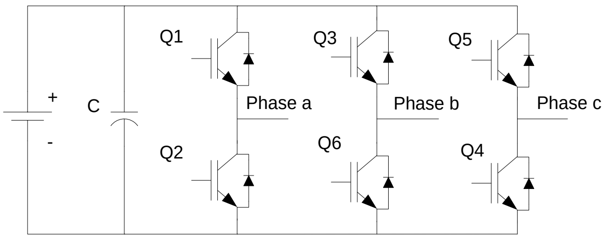


Figure 6. Three phases conventional voltage source inverter

B. Five Level Diode Clamped Inverter

In Figure 7, the 5-level inverter circuit model can be seen. The 3-level inverter's space vector diagram can combine six small hexagons of the conventional two-level inverter's space vector diagram. We have to take above that the two actions to simplify the 2-level inverter space vector diagram based on the carrier. The calculation of the voltage vector sequence and duration has been carried out using conventional 2-level CBSVM procedures [20].

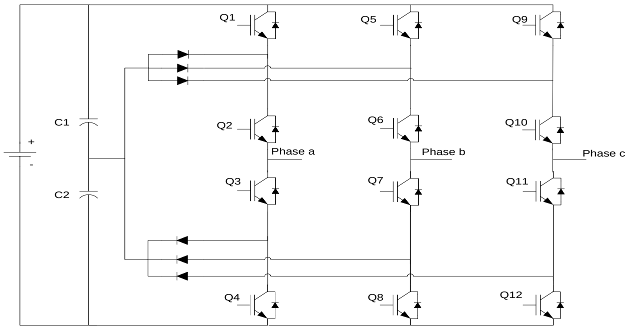


Figure 7. Three Phase Five-level diode clamped inverter

C. Carrier-Based Space Vector Modulation

The 5-level inverter has four switches per stage throughout the CBSVM, as well as 2 triangular carriers must be decided to switch on and off. Figure 9 shows the switching of the CB-SVM gate for DCMLI.
Modulation signal's standardized depiction seems to be equation.

$$u_i(t) = u_i^*(t) + e_i(t) \quad (17)$$

$$u_c^*(t)=m \sin(\omega t+4\pi/3) \quad (18)$$

$$UcN(t)=[E/2]\ [m \sin(\omega t+4\pi/3)+e_i(t)] \quad (19)$$

$$Uca(t) = [E/2]\ [\sqrt{3}m \sin(\omega t+3\pi/6) \quad (20)$$

It's indeed evident that the harmonic components injected don't really appear in line - to - line voltages.

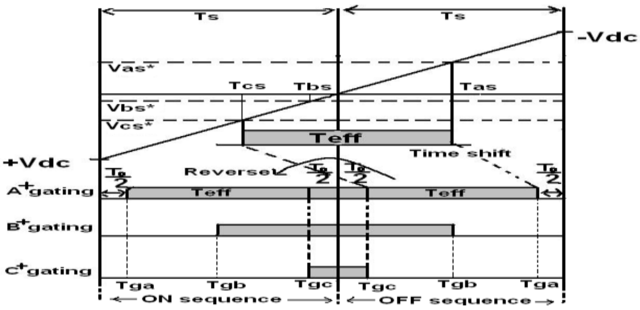


Figure.8. Actual gating time generation for CBSVPWM

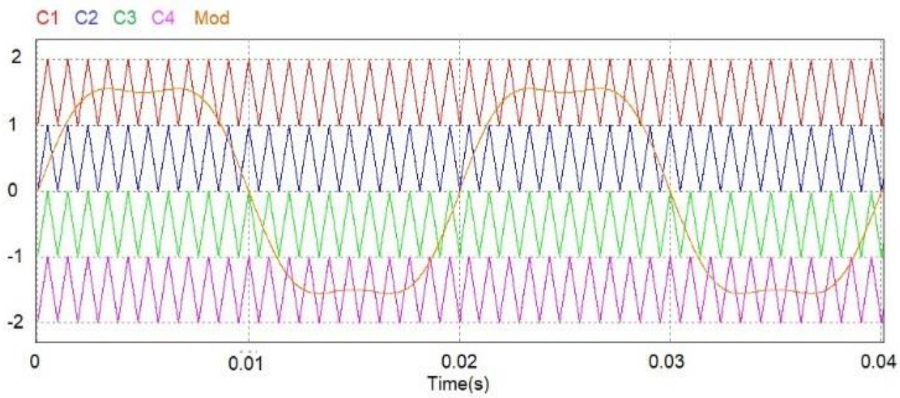


Figure.9.CB-SVM Gate switching for DCMLI

3. CONTROL STRATEGY OF PMSM DRIVE

The angle between the rotor and stator field is 90° in the FOC. Reference was made to the field control above 90°. The motor torque varies depending on the current of the stator that does have the id as well as i_q elements. The i_d&i_q can control the motor torque. The current id would have been for excitement. For the control strategy, i_d = 0 has been established. Suppose i_d = 0, authors obtain the highest torque in the vector control of PMSM via i_q control and i_d = 0. The FOC method was based on logic with the distinct d.c motor. The PMSM FOC would be an essential vector control variation. In FOC, the magnetic field, as well as the electromagnetic torque, has been governed by the elements of the stators directly and quadrature axes.

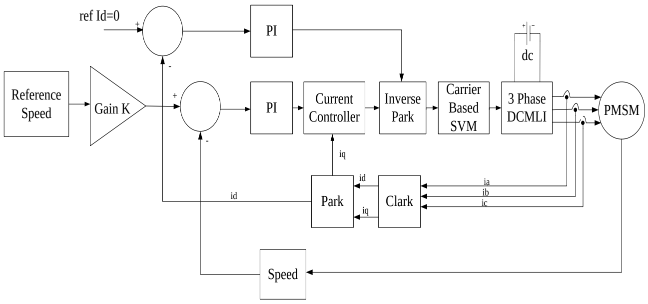


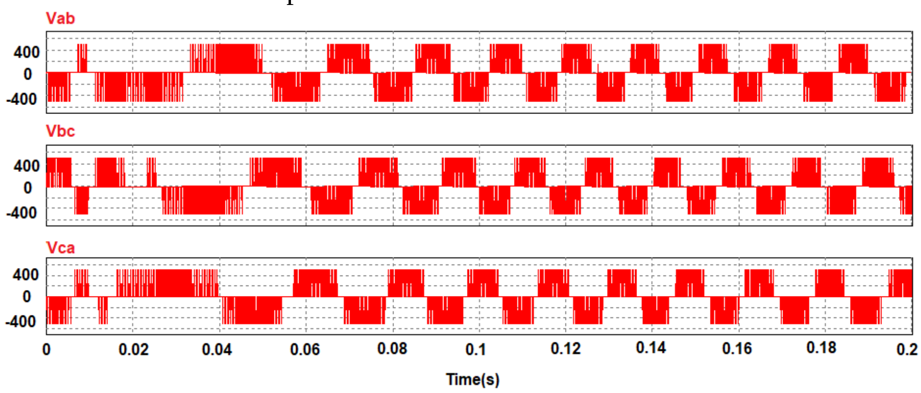
Figure.10. FOC-based three-phase DCMLI-fed PMSM drive control diagram

The whole technique could even regulate the motor torque as well as the flux flow, providing adequate information from the reference currents of both the stator and therefore the angle of the rotor. The control diagram of the FOC Mechanism has been seen in Figure.10. The prime purpose of the FOC has been to maintain the rotor flux link amplitude at that same fixed amount, with exception of the field weakening process, and only to adjust the torque-producing square element to regulate the torque of such motor. One such control technique has been based on estimates. The electromagnetic torque controls the current of the quadrature axis.

4. SIMULATION ANALYSIS

The simulation of the FOC based 2-level & 5-levels Diode clamped multilevel inverter drive is investigated respectively. For the 2-level & 5-levels diode clamped multilevel inverter, CBSVM modulation techniques are applied. The specifications/ variables of the simulation have been seen in Table I. This simulation was performed in the PSIM software with DC input voltage. Measurement of the motor current, speed, and torque of conventional VSI units and DCMLI PMSM 5-levels units can be seen in Figure.13, Figure 14 & Figure 15 respectively. The FFT analyses of 2-level & 5-levels DCMLI, V_{LL}&V_{Ph} waveform are discussed and as seen in Figure 12.

The fundamental component and THD are obtained when 2- levels DCMLI is operated with CBSVM. The THD obtained is high. The fundamental component and THD are obtained when a 5-levels NPC inverter is operated with CBSVM. The THD obtained is low as compared to the three levels of DCMLI. The torque response, phase current, and speed of PMSM fed on 2-levels inverter; Torque waveform contains a large number of ripples. The speed is of the motor is settled to low speed. The torque response, phase current, and speed of PMSM fed on 5-levels inverter. The ripple present in the torque waveform is reduced. The torque analyses of 2-level & 5-levels DCMLI are mentioned in Table II. In waveform obtained at the output of 5-levels inverter has more number of steps and THD obtained is less compared to 2-level DCMLI.



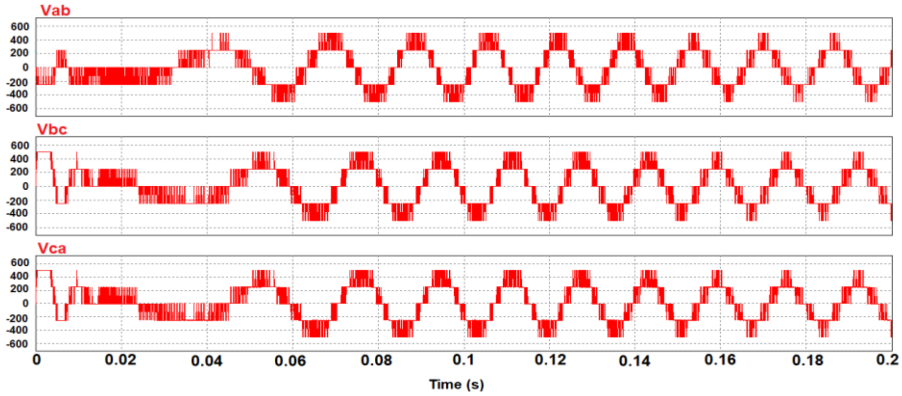


Figure. 11. Output Line voltage of conventional three phases VSI and 5-level DCMLI

Figure. 12.FFT analysis of conventional three-phase VSI and five-level DCMLI

The Multilevel inverters are connected to PMSM and the output waveforms are analyzed. It is inferred that the torque ripple present in the PMSM is very much reduced by using 5-levels DCMLI. The simulation results of the conventional three-phase VSI drive and 5-levels DCMLI drive has been presented using the PSIM environment. The findings demonstrate that torque ripple decreases throughout the drive with such a significant rise in the inverter level and thus an enhanced torque response has been achieved.

Even though better torque response is among the most favorable drive attributes, the same would be accomplished. This same current advancement in the waveform is quite evident from Figure 13. The speed response from 2 to 5-levels has also been continued to improve. Table II presents the graph between torque ripples for constant speed operation at TL=5 Nm. The modulation index of 0.8 has been used in the simulation process and the input voltage is maintained at 400 V. The Speed is found to be 1600 RPM at 0.25 sec. The reference torque is taken as 5 N-m. The torque ripple for 2-level and five-level inverter is found to be 7.57% 4.47% N-m respectively under steady-state operation. Due to this basic and prominent feature, a 5-level inverter drive is best suited to automotive applications.

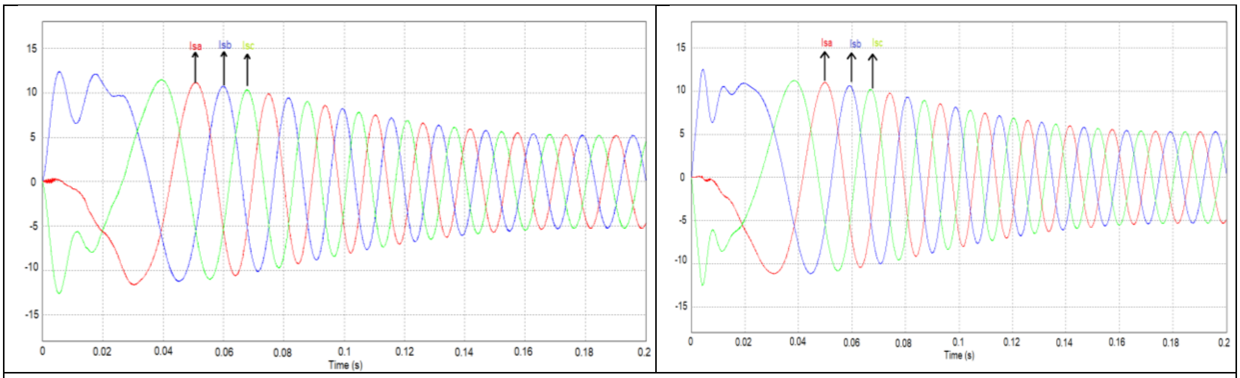


Figure. 13. Motor Current of Conventional Three-Phase VSI Drive and Five-Level DCMLI Drive

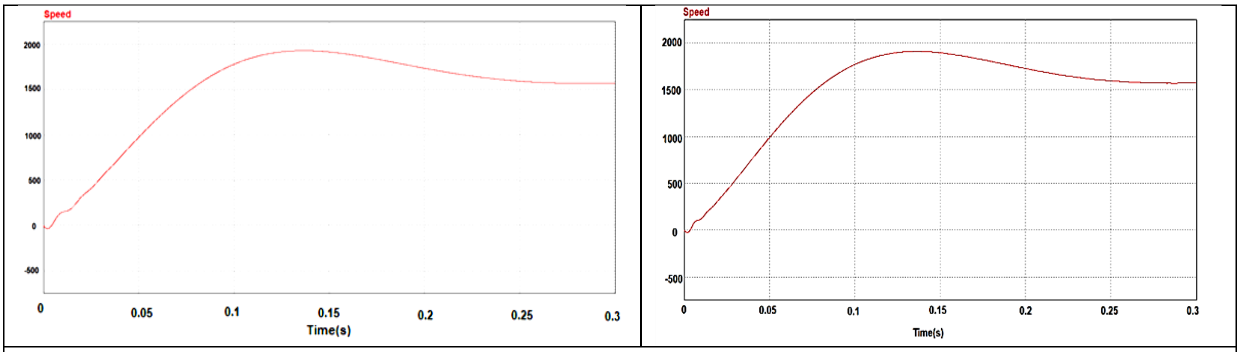


Figure 14. Speed Response of conventional 3-phase VSI drive and five-level DCMLI drive

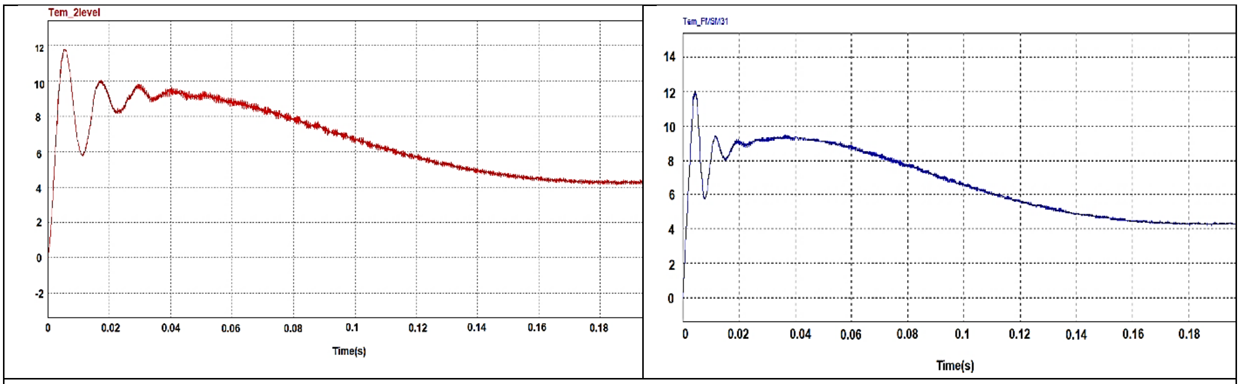


Figure. 15. Torque response of conventional 3-phase VSI drive and 3-level DCMLI drive

Table 1: Specification of PMSM

Sr. No.	**PMSM Parameter**	**Value**
1	Resistance of stator *(R_s)*	4.3 Ω
2	Inductance of d-axis (L_d)	0.00027H

3	Inductance of q-axis *(L_q)*	0.00067H
4	No of Pole pairs	2
5	Movement of Inertia(J)	0.000179 Kg/m^2
6	Mech time constant	10 Sec

Table 2: Torque ripple comparison for constant speed operation at TL=5 Nm

Type of Inverter	T_{max} (N-m)	T_{min} (N-m)	T_{avg} (N-m)	Torque ripple in %
Two-level inverter	4.45	4.129	4.28	7.57%
Five level inverter	4.45	4.26	4.338	4.47%

5. CONCLUSION

PSIM software has been used with CBSVM modulation techniques to analyze conventional three-phase VSI drives and five-level DCMLI PMSM drives. The CBSVM technique has been used for each leg of an inverter to continue driving the gate pulses. The output of the inverter such as voltage, current, speed, torque, and the PMSM motor currents was tracked. It was concluded that the drive of CB-DCMLI performs better when compared to the conventional three-phase VSI drive with less shrink content and better speed response. It can also efficiently use more dc-link voltage, generate the least harmonics than traditional VSI three-phase drives, and reduce the requirement for filters. The five-level DCMLI PMSM drive is perfect for automotive applications because of these prominent features. Many researchers have designed and implemented the conventional three-phase VSI-drive and five-level DCMLI as witnessed by the literature survey. There is, however, ample scope to decrease THD and torque on n-level inverters. The simulation work can be extended to n-level DCMLI PMSM drives, and artificial intelligence can be used to examine the optimized inverter levels for good performance.

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