

Comparative Analysis of DTC-FOC CBSVM for Twelve-Switch NPC Inverter-Fed PMSM Drives in EVs

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ABSTRACT:

The increasing adoption of electric vehicles (EVs) demands high-performance, efficient, and reliable electric drive systems with improved torque control and reduced power losses. This paper presents a comparative evaluation of Direct Torque Control with Carrier-Based Space Vector Modulation (DTC-CBSVM) and Field-Oriented Control with Carrier-Based Space Vector Modulation (FOC-CBSVM) for a twelve-switch Neutral Point Clamped (NPC) multilevel inverter-fed Permanent Magnet Synchronous Motor (PMSM) drive intended for EV applications. The study aims to evaluate both control strategies in terms of speed tracking, torque response, torque ripple, stator current quality, flux regulation, inverter performance, and overall drive efficiency. A simulation model of the twelve-switch NPC inverter-fed PMSM drive is developed in MATLAB/Simulink, and both DTC-CBSVM and FOC-CBSVM strategies are implemented under identical operating conditions for a fair comparison. The results demonstrate that DTC-CBSVM provides faster torque response and improved dynamic performance, while FOC-CBSVM offers precise flux and torque control with smoother steady-state operation. The comparative analysis highlights the advantages and limitations of both strategies under different speed and load conditions. The study confirms that the integration of CBSVM with a twelve-switch NPC inverter can improve voltage utilization, reduce harmonic distortion, and enhance the overall performance of PMSM drives. The findings provide useful

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guidance for selecting suitable control strategies for high-performance and energy-efficient EV propulsion systems.

Keywords: PMSM Drive, DTC-CBSVM, FOC-CBSVM, Twelve-Switch NPC Inverter, Electric Vehicles.

1. Introduction

The rapid growth of electric vehicles (EVs) has created a strong demand for high-performance electric propulsion systems with high efficiency, high power density, fast dynamic response, low torque ripple, and reduced harmonic distortion. Among the various electric machines used for EV propulsion, the Permanent Magnet Synchronous Motor (PMSM) is particularly attractive because of its high efficiency, high torque-to-weight ratio, compact size, and excellent power-density characteristics. However, the performance of a PMSM traction system depends not only on the motor but also on the inverter topology, modulation technique, and control strategy employed for torque and speed regulation. PMSM drives are nonlinear and multivariable systems, making appropriate control selection important for achieving satisfactory dynamic and steady-state performance [1], [2].

Conventional two-level voltage-source inverters are commonly used for PMSM drives; however, their operation at higher voltage and power levels can result in increased semiconductor voltage stress, higher dv/dt , electromagnetic interference, and output-voltage harmonics[3]. Multilevel inverters (MLIs) provide an effective alternative because they synthesize staircase voltage waveforms with smaller voltage steps, thereby improving output-voltage quality and reducing harmonic distortion. Among different MLI configurations, the Neutral Point Clamped (NPC) inverter is widely investigated for high-performance motor drives. In particular, the Twelve-Switch Neutral Point Clamped (TSNPC) inverter provides an attractive topology for PMSM propulsion systems because of its multilevel voltage generation capability and potential for improved drive performance. A comparative study of two-level and twelve-switch NPC inverter-fed PMSM drives reported improved speed and torque response, reduced harmonic distortion, and lower torque ripple with the TSNPC configuration[4],[5].

The control strategy is another critical factor affecting PMSM-drive performance. Field-Oriented Control (FOC) achieves decoupled control of the torque- and flux-producing

components of stator current, providing accurate speed and torque regulation. FOC combined with space-vector modulation has been successfully applied to multilevel-inverter-fed PMSM drives. Jacob and Chitra demonstrated FOC of a space-vector-modulated multilevel inverter-fed PMSM drive and validated the complete system using MATLAB/Simulink. Their work established the suitability of FOC and SVM for controlling PMSM drives supplied by multilevel inverter structures. In contrast, Direct Torque Control (DTC) directly regulates the electromagnetic torque and stator flux and is known for its rapid dynamic response. Conventional DTC, however, can exhibit considerable torque and flux ripple because of hysteresis-based voltage-vector selection. The incorporation of Space Vector Modulation (SVM) into DTC provides more controlled voltage-vector generation and can significantly improve steady-state performance. Mesloub *et al.* experimentally and theoretically compared conventional DTC with DTC-SVM for PMSM drives and reported that the DTC-SVM approach reduced torque and flux ripples while improving dynamic and steady-state performance[6],[7].

For multilevel inverter applications, Carrier-Based Space Vector Modulation (CBSVM) provides an attractive modulation approach because it can generate appropriate switching pulses for multilevel voltage synthesis while retaining the advantages of space-vector-based modulation. Recent investigations have combined CBSVM with NPC inverter-fed PMSM drives[8],[9]. Shriwastava *et al.* investigated a multilevel NPC inverter-fed PMSM drive using CBSVM and FOC and reported satisfactory speed and torque response, reduced torque ripple, and reduced total harmonic distortion[10]. Hardware and simulation results showed good agreement, supporting the suitability of the approach for high-performance electric drives[11],[12].

The objectives of the proposed study are

- To develop a twelve-switch NPC multilevel inverter-fed PMSM drive model for EV applications.

- To implement DTC-CBSVM and FOC-CBSVM control strategies.
- To evaluate both strategies under identical speed and load conditions.
- To compare their performance in terms of speed response, torque response, torque ripple, flux regulation, current waveform, and THD.
- To investigate the dynamic and steady-state characteristics of both control strategies.
- To identify the more appropriate control strategy for high-performance and energy-efficient EV propulsion systems.

This paper presents, in section 1, Introduction. In section 2 Literature review In section 3 the PMSM Load modelling. Section 4 explain PMSM Proposed methodology. In section 5 the Simulation results analysis and In section 6 The Developed hardware model In Section 7, Conclusion is present.

2. Literature Review

- Jacob, J., and Chitra, A. (2017) investigated a FOC-controlled PMSM supplied by a space-vector-modulated multilevel inverter. A reduced-switch seven-level inverter was considered, and a low-computational-complexity space-vector algorithm was used for modulation. The PMSM was controlled using FOC with a PI-based speed controller, and the complete system was simulated in MATLAB/Simulink. The study demonstrated that the combination of FOC and SVM can provide effective PMSM control with a multilevel inverter. The study considered a reduced-switch asymmetrical MLI rather than the twelve-switch NPC topology, and it did not provide a DTC-CBSVM versus FOC-CBSVM comparison[13].
- Mesloub, H., Boumaaraf, R., Benchouia, M. T., Goléa, A., Goléa, N., and Srairi, K. (2020) compared conventional DTC with DTC-SVM for a PMSM using both simulation and experimental validation through a dSPACE-1104 platform. The authors identified the high torque and flux ripple associated with conventional hysteresis-based DTC and introduced SVM to improve the steady-state behavior. Their results demonstrated that DTC-SVM provided lower torque and flux ripple and improved dynamic and steady-state performance compared with conventional DTC. The investigation was conducted using a conventional inverter arrangement rather than a twelve-switch NPC multilevel inverter, and CBSVM was not specifically investigated[14].

- Pothuraju, R., Tejavathu, R., and Panda, A. K. (2022) authors proposed a multilevel inverter-fed direct torque and flux control with space-vector modulation for a speed-sensorless PMSM drive. The primary objective was to improve both steady-state and dynamic characteristics while reducing torque and flux ripples. The research demonstrated the applicability of DTC-SVM to multilevel inverter-fed PMSM drives and showed the potential of combining direct torque/flux control with space-vector modulation. The work focused on a general multilevel inverter configuration and did not compare the proposed DTC-SVM approach directly with FOC-CBSVM using a twelve-switch NPC inverter[15].

- Shriwastava, R. G., Chaudhari, J. G., and Thakre, M. P. (2023) presented a hardware-based comparative analysis of two-level and twelve-switch NPC inverter-fed PMSM drives for automotive applications. The authors used an AVR microcontroller and investigated SVM-based operation of the PMSM drive. The TSNPCI configuration demonstrated improved speed and torque response, reduced output distortion, lower harmonic distortion, and lower torque ripple compared with the conventional arrangement. The study mainly compared inverter topologies rather than comparing two different advanced control strategies such as DTC-CBSVM and FOC-CBSVM[16].

- This paper authors Shriwastava, R. G., Kadlag, S. S., Pawase, R., Dhote, N., Rewatkar, R., Mapari, R., Dhunde, R., and Bhagat Patil, H. R. (2024) investigated a 12-switch NPC inverter-fed PMSM drive for EV applications using carrier-based space-vector modulation and FOC. The study examined inverter and motor parameters including stator and rotor currents, speed, torque, and output characteristics. The reported results showed improved speed and torque response, good dynamic performance, reduced harmonic distortion, and reduced torque ripple. Simulation and hardware results were also reported to be in good agreement. The study primarily investigated the FOC-CBSVM configuration and did not provide a direct comparison with a DTC-CBSVM controller under identical operating conditions[17].

3. PMSM Load Modeling

The four quadrant operation of PMSM with EV application is implemented under both clockwise and anticlockwise direction with acceleration and retardation mode of operation[18],[19].

The non salient type three phase PMSM modeling can be obtained by using rotating d-q frame coordinates theory and their detailed modeling are given below

$$\overline{u_{dqos}} = R_s \overline{i_{dqos}} + p \overline{\lambda_{dqos}} \quad (1)$$

$$\overline{\lambda_{dqos}} = L_{dqo} \overline{i_{dqos}} + \overline{\lambda_{dqo,m}} \quad (2)$$

$$u_{ds} = R_s i_{ds} + L_s \frac{di_{ds}}{dt} - \omega_r L_s i_{qs} \quad (3)$$

$$u_{qs} = R_s i_{qs} + L_s \frac{di_{qs}}{dt} - \omega_r (L_s i_{ds} + \lambda_{pm}) \quad (4)$$

The d-q reference frame torque is

$$T_e = \left(\frac{3}{2} \right) \left(\frac{P}{2} \right) (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (5)$$

$$T_e = \left(\frac{3}{2} \right) \left(\frac{P}{2} \right) (\lambda_{pm} i_{qs}) \quad (6)$$

Modeling and simulation operation of PMSM with EV is obtained by using MATLAB-Simulink with EV drive operation system is obtained by individual block of MATLAB.

Following are the equation for stator flux linkage and torque equations of PMSM in d-q coordinate[35]

$$\lambda_D = L_D I_D + \lambda_R \quad (15)$$

$$\lambda_Q = L_Q I_Q \quad (16)$$

$$\lambda_s = \sqrt{(\lambda_D^2 + \lambda_Q^2)} \quad (17)$$

$$T_{EM} = \left(\frac{3}{2} \right) P (\lambda_D I_Q - \lambda_Q I_D) \quad (18)$$

The current equation for d-q axis is

$$I_D = \frac{\lambda_D - \lambda_Q}{L_D} \quad (19)$$

$$I_Q = \frac{\lambda_Q}{L_Q} \quad (20)$$

$$\lambda_D = \lambda_s \cos \delta \quad (21)$$

$$\lambda_Q = \lambda_s \sin \delta \quad (22)$$

Put in equation (18)

$$T_{EM} = \left(\frac{3}{2} \right) P \frac{|\lambda_s|}{2L_D L_Q} (2\lambda_R L_Q \sin \delta - |\lambda_s| (L_Q - L_D) \sin 2\delta) \quad (23)$$

The stator flux is calculated

$$\phi_{\alpha\beta} = \int (V_{\alpha\beta} - R_s I_{\alpha\beta}) dt \quad (24)$$

The torque is calculated as,

$$T_E = \left(\frac{3}{2} \right) \left(\frac{P}{2} \right) (\lambda_{s\alpha} I_{s\beta} - \lambda_{s\beta} I_{s\alpha}) \quad (25)$$

4. PMSM Proposed Methodology

4.1. Direct torque control (DTC)

Fig.1 shows the schematic diagram of the DCMLI -DTC PMSM drive. In DTC, select stator voltage vectors directly by hysteresis stator flux and torque control. Stator flux Ψ_s^* and torque T_e^* are compared by the hysteresis comparators for selection of voltage vector in inverter by switching table.[20],[21]

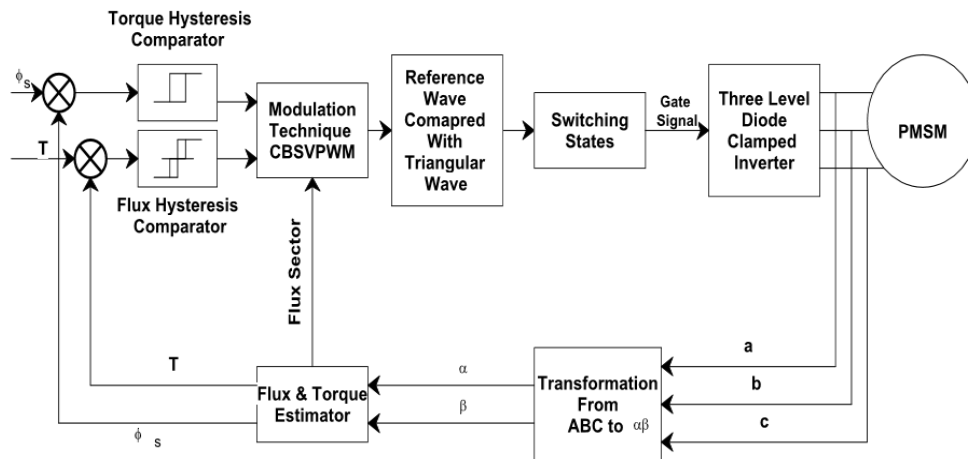


Figure 1. Schematic of DCMLI -DTC PMSM drive

For selecting an appropriate voltage vector, hysteresis, and comparators are replaced by an estimator for

torque and flux errors measurements. It gives less torque and flux ripple for getting a good dynamic performance and also gives simplicity, introduces more complexity, and loses DTC. A novel CBSVM is introduced. It has the advantages require effective time and the inverter output voltage is directly calculated fewer times for voltage modulation task simplification. The less time algorithm can be used to deduce actual gating signals for each inverter arm in a simple form. Using Clark transformation, the measured motor currents are transformed to α - β . The voltage is calculated from the inverter switching state into α - β reference frame for the DC-link voltage. Inverter output voltage is directly calculated and converted in a simple form in less time by the time relocation algorithm in the proposed DTC-CBSVM PMSM drive.[22],[23],[24]

4.2 Field Oriented Control (FOC)

Research methodology to implement the objective of the research work is obtained using Park's transformation.

In parks transformation, the measured currents and the voltages are converted into stationary reference frame and this stationary reference frame is converted into d-q frame. During this conversion process, the error signal generates the error in reference to speed fed to the PI controller. The two outputs of the PI controller are obtained such as q- axis current & reference $i_d = 0$ are fed to current controller. The pulses are generated for twelve IGBT's switches NPC inverter after comparing reference waves with the triangular waves. The detailed operation is described in Figure2.[25].[26],[27]

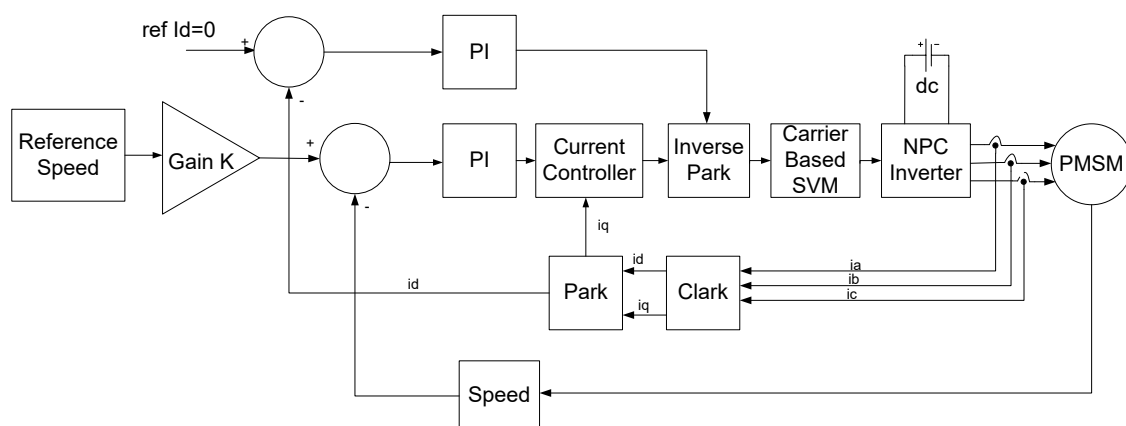


Figure 2. Block schematic of Field Oriented Control

5. Simulation Results Analysis

The output voltage and stator current with few high-order harmonic of DTC-DCMLI is purely sine wave in Fig.3 in the steady operation. The speed response of DTC-DCMLI PMSM drive shown in Fig.4. The reference speed runs from 0 to 1000 rpm at time $t = 0.05$ s. The speed is 1000 rpm (constant) in the range of $t = 0.05$ s sec to $t = 0.3$ s. The speed stepped from 1000 to 1500 rpm at $t = 0.3$ s sec to $t = 0.35$ s. Rotor speed was near the 1500 rpm at $t = 0.35$ s sec to $t = 0.6$ s. Due to speed controller quickly exited saturation, the motor goes in the steady operation. The performance parameter of the DTC-DCMLI in a transient -state condition in Fig.5 At 1sec, the torque (load) is added in the range of (1223-1238.5N.m) . At $t = 0$ sec to $t = 0.6$ s, it is suddenly increased in the range of (0.5N.m -1N.m) in Fig.4 at 1500 rpm speed range. As per the motor load, the motor torque change can be seen. The motor voltage reaches 100 V at the time 0.5s to 0.1s. The

motor voltage increased and reaches to 220V in the time range of 0.1s to 0.6s. Motor current is 1.2 amp. At the time $t = 1$ s, it reduces and again reaches to constant 1 amp up to 0.6 sec. The performance parameter of the DTC -DCMLI in a transient analysis The torque(load) is added in the range of (1223-1238.6N.m) at $t = 0$ sec to $t = 0.1$ s and is suddenly increased in the range of (0.6N.m -0.8N.m) at $t = 0.1$ sec to $t = 0.6$ s. At the time 0.1s to 0.4s, the motor voltage reaches 100 V, and in the time range of 0.4s to 0.6s, the motor voltage increased and reaches to 200V. Motor current is 1 amp at $t = 0.1$ s. It reaches 1.3 amp. At the time $t = 0.1$ sec to $t = 0.6$ s. Figure. 6 shows FOC -CBSVM transient analysis. The parameters of motor & inverter has been listed in Table 1 & Table 2. Total harmonic distortion (THD), torque and current ripples of twelve switch NPC inverter are listed in Table 3 and Table 4.

Table 1: PMSM Specification

Parameters	Values
Motor stator resistance(R_s)	4.865 Ω
Motor stator inductance(L_a)	0.0174H
Motor Torque(T_e)	0.544N-m
Movement of inertia(J)	0.000114 Kg/m ²
Viscous coefficient(f)	0.0000447 Nms
Number of pole(P) pair	2

Table 2: Inverter Parameter

Parameters	Values
Input Voltage	280 V (rms)
Output filter voltage	380 V dc
Supply Frequency	50 Hz
Inverter voltage	270V
Switching Frequency	2.5 KHz
Inverter rating	1.5 KVA
Resistive load	200 Watts
Inductive load	PMSM

A. DTC –CBSVM transient analysis

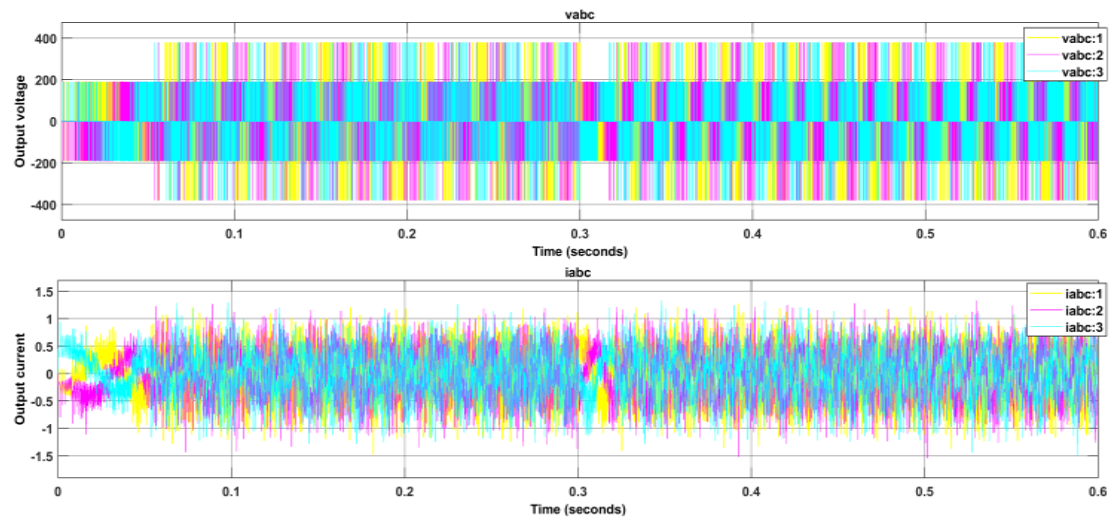


Figure 3. NPC inverter analysis

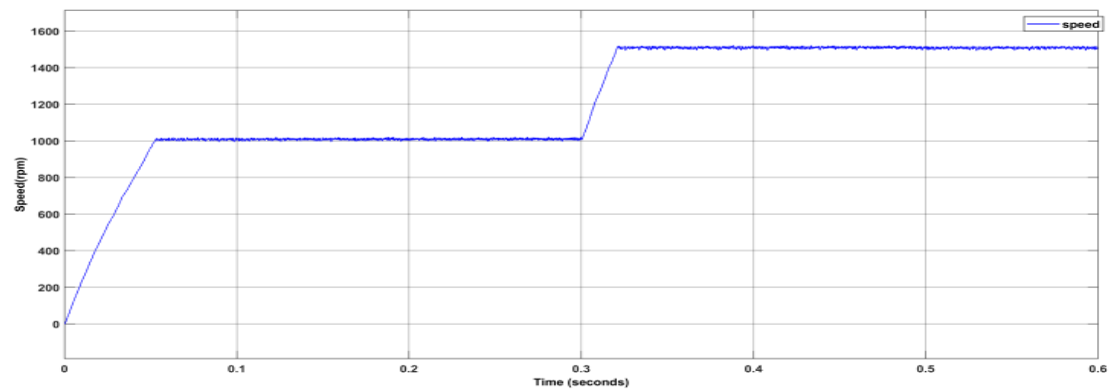
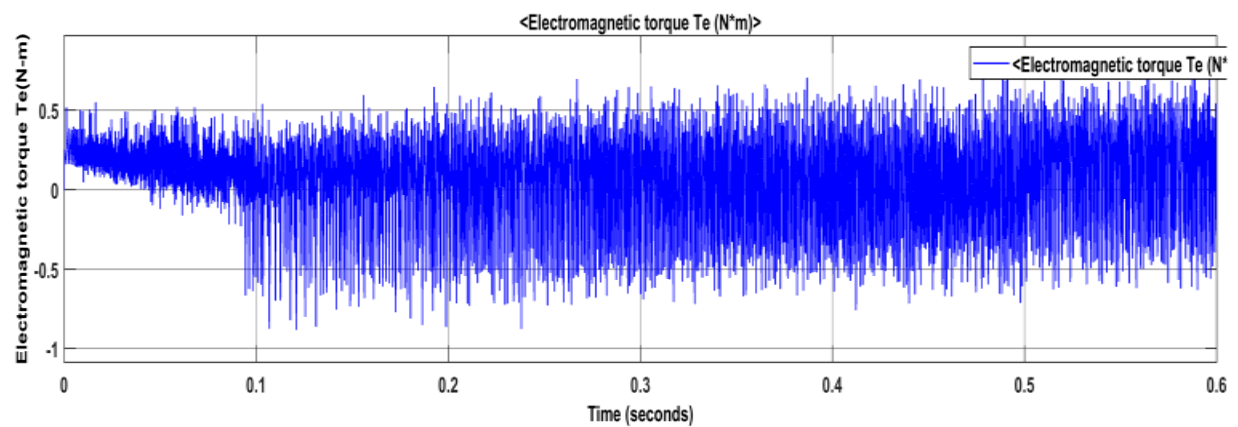
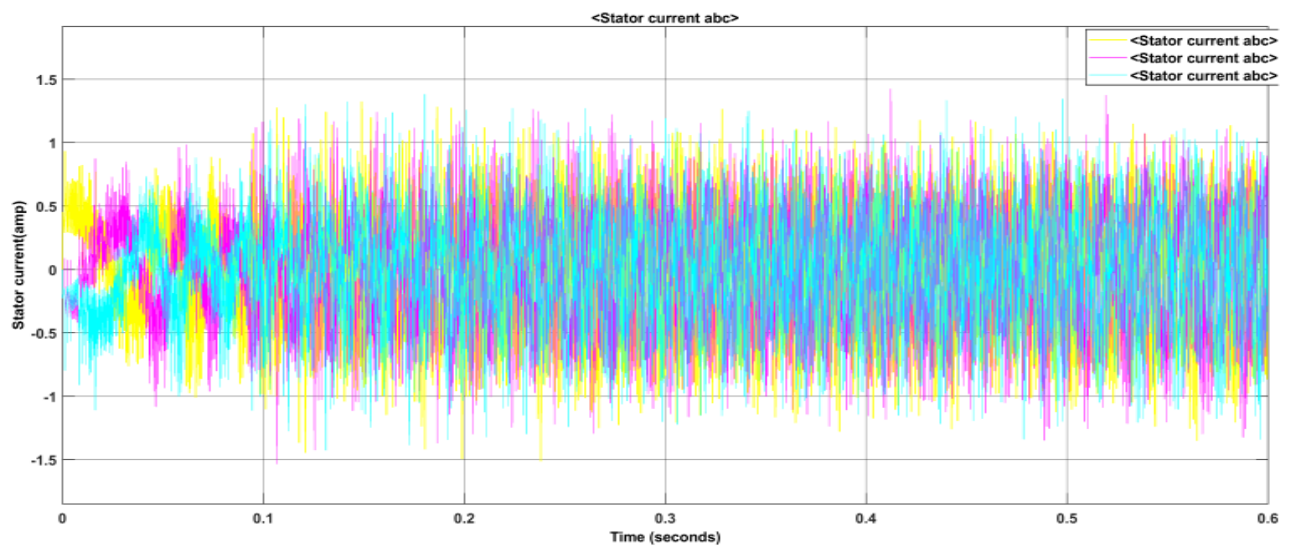


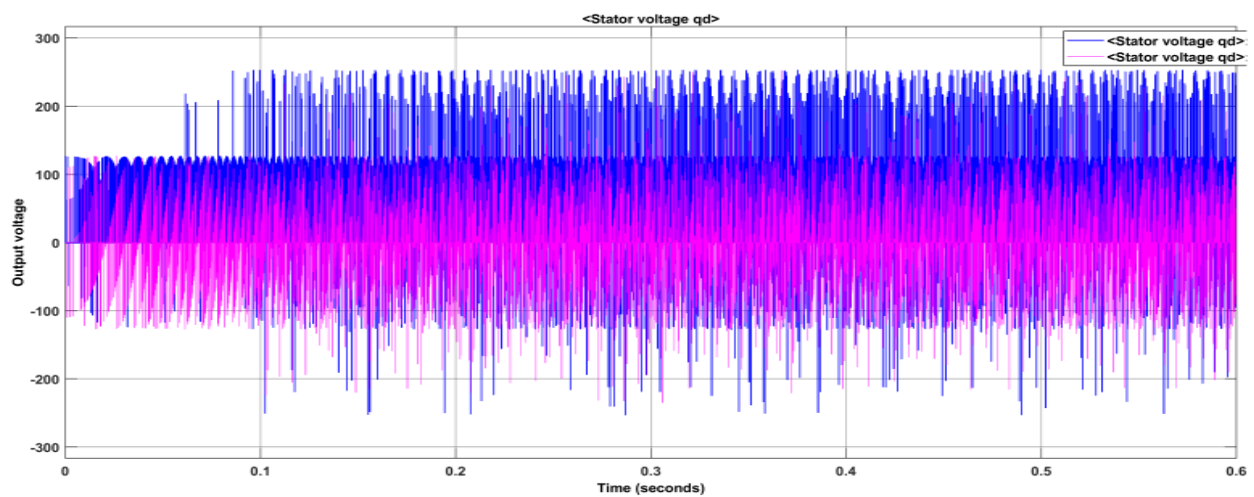
Figure. 4.Speed analysis



(a) Torque analysis



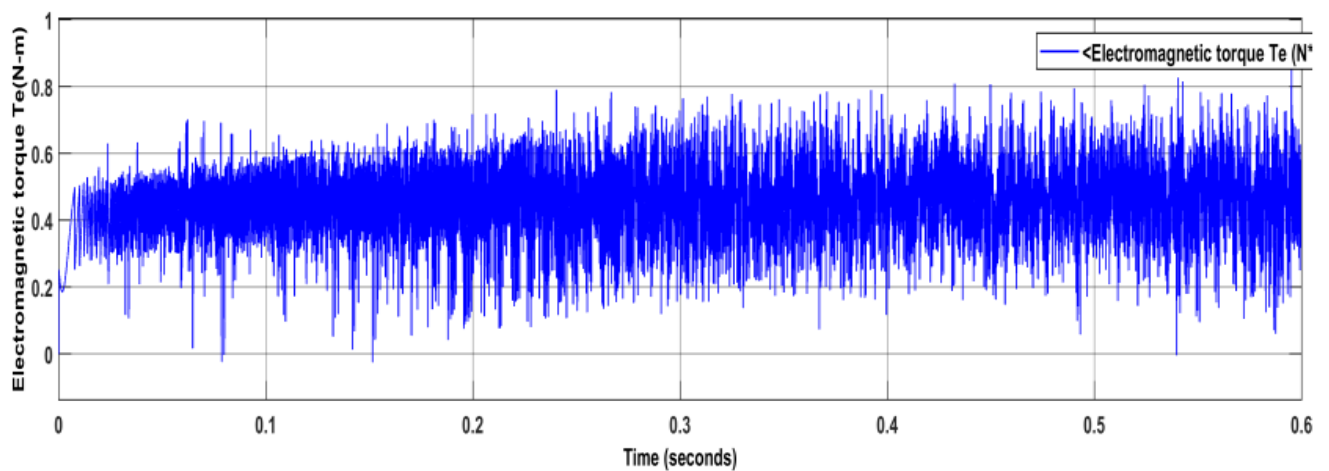
(b) Currents analysis



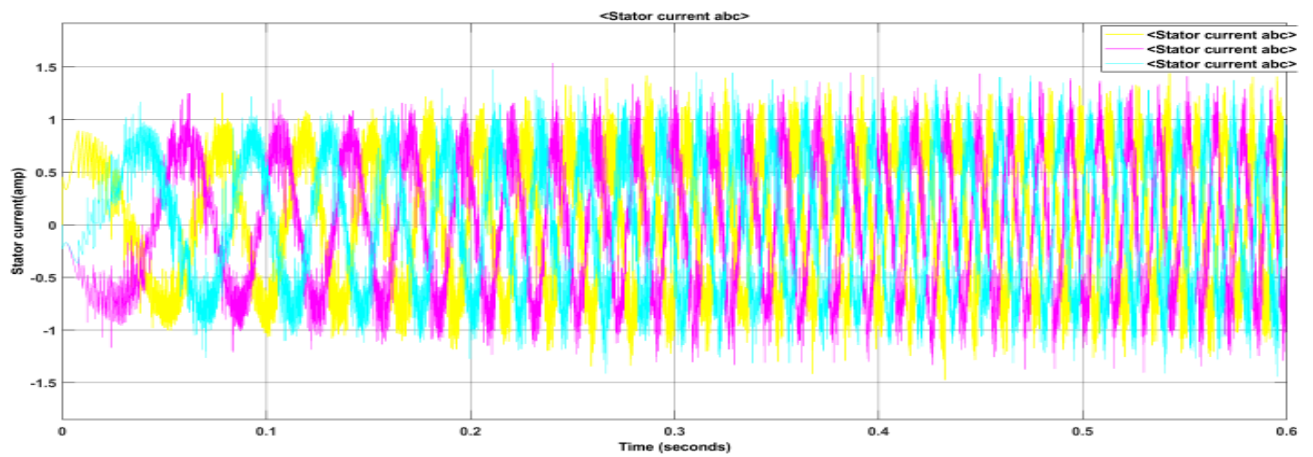
(c) Voltage analysis

Figure 5. DTC –CBSVM transient analysis

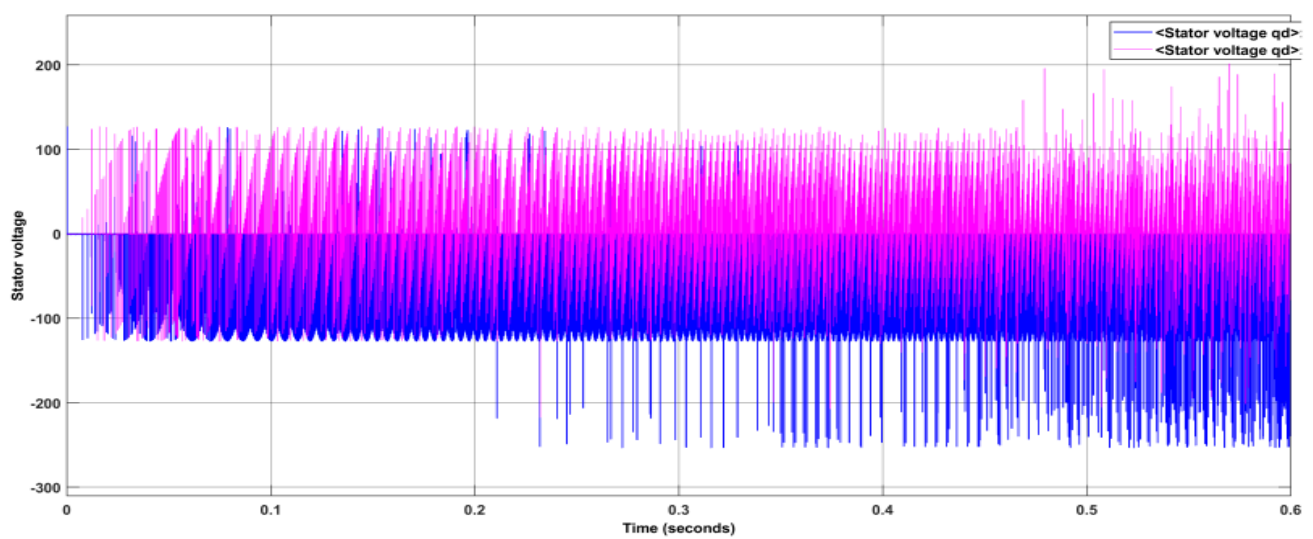
B. FOC–CBSVM Transient analysis



(a) Torque analysis

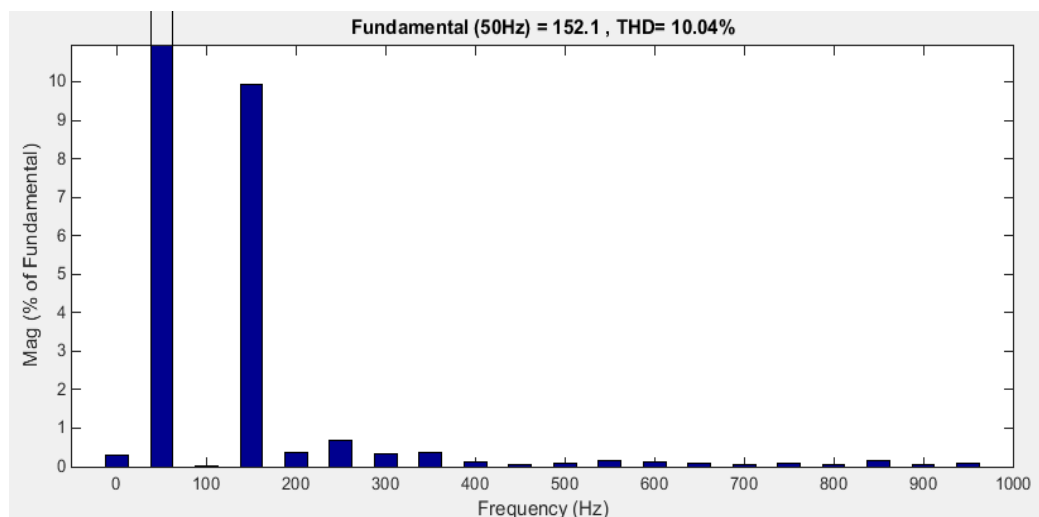


(b) Currents analysis

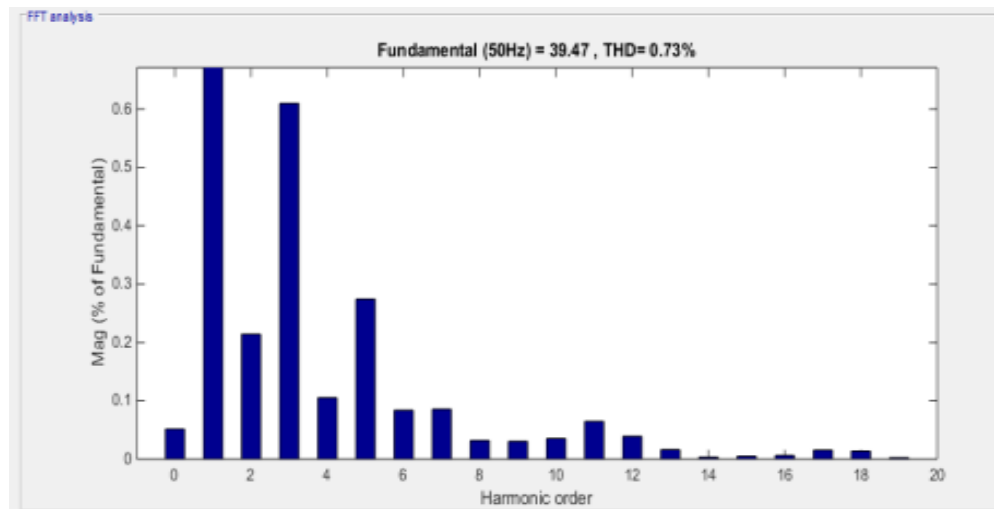


(c) Voltage analysis

Figure. 6. FOC –CBSVM transient analysis



(a) NPCI voltage



(b) NPCI current

Figure 7 NPCI THD analysis

Table 3: THD Analysis

Parameter	THD (%)
Voltage	10.0%
Current	0.7%

Table 4: Ripple analysis

FOC	1500 rpm
Motor Torque	0.21Nm
Motor Current	4.5mA

6. The Developed Hardware Model

Following are the component used in hardware design.

The schematic Developed Hardware Model of PMSM drive is shown in Figure8. The system is composed of a 3-phase PMSM, an Atmel ATxmega16D4 processor board, an Atmel low voltage motor control board, a USB-to-UART bridge cable and a 12 V universal power adapter. The firmware running on the ATxmega16D4 provides the control structure for PMSM sensorless FOC. The sensorless control

technique uses back EMF calculation to form a back EMF phase locked loop. Speed control is provided by a proportional integral controller. The back EMF sensing PLL, the current regulators and the speed control loop require configuration and tuning. The configuration utility is software running on a PC provided as a tool for configuring and tuning the sensorless FOC parameters. Figure8 & 9 shows Block diagram of Developed Hardware Model and Developed Hardware Model Implementation PMSM Drive respectively.

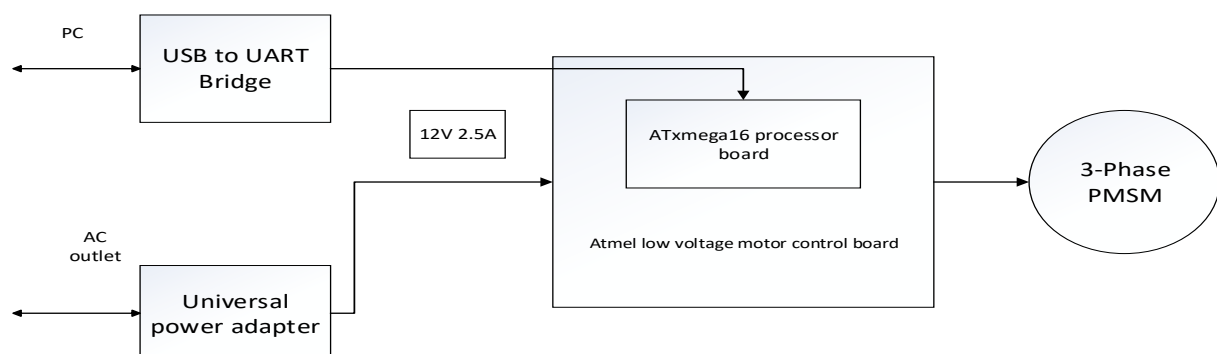


Figure 8 Block diagram of Developed Hardware Model

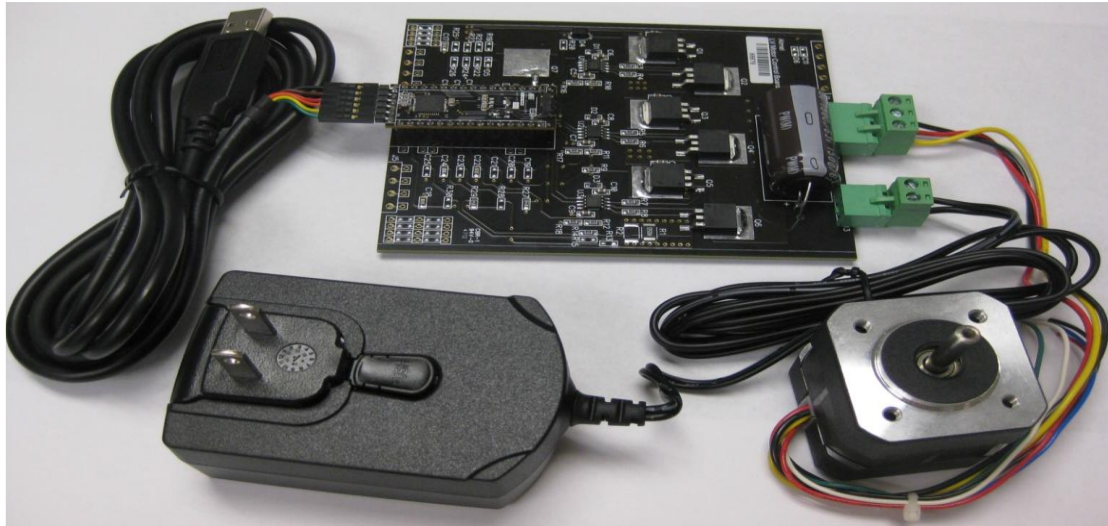


Figure 9. Developed Hardware Model Implementation PMSM Drive

The VSI fed three phase PMSM drive (2 kW, 6pole) Microcontroller with computer-system interface was implemented. Table No.5 shows the percentage of torque ripples at different speed. Hence proposed system has a good dynamic response for software and hardware implementation at high speed for automotive application. Figure 10 to Figure 12 shows hardware response of VSI fed three phase PMSM drive, at 500 rpm, 1500 rpm & 3000 rpm respectively. As per motor speed, torque current & D.C voltage variation, it conclude that motor speed increased and motor current and motor torque decreased but motor D.C voltage is always constant. So the production of torque is good for high speed in automotive application. Motor speed, torque current & D.C Voltage variation shows in table No.5. Table No.6 shows THD comparison variation. Table No.7 shows PMSM Parameters. Table 8 shows Speed Variation with Load at 50 Hz for motor. Table No.9: Variation in motor speed as a configuration of load at 50 Hz. Figure 13. shows torque - load power Characteristics at 50Hz Figure 14. Shows speed load power Characteristics at 50Hz. Figure 15. speed torque Characteristics at 50Hz

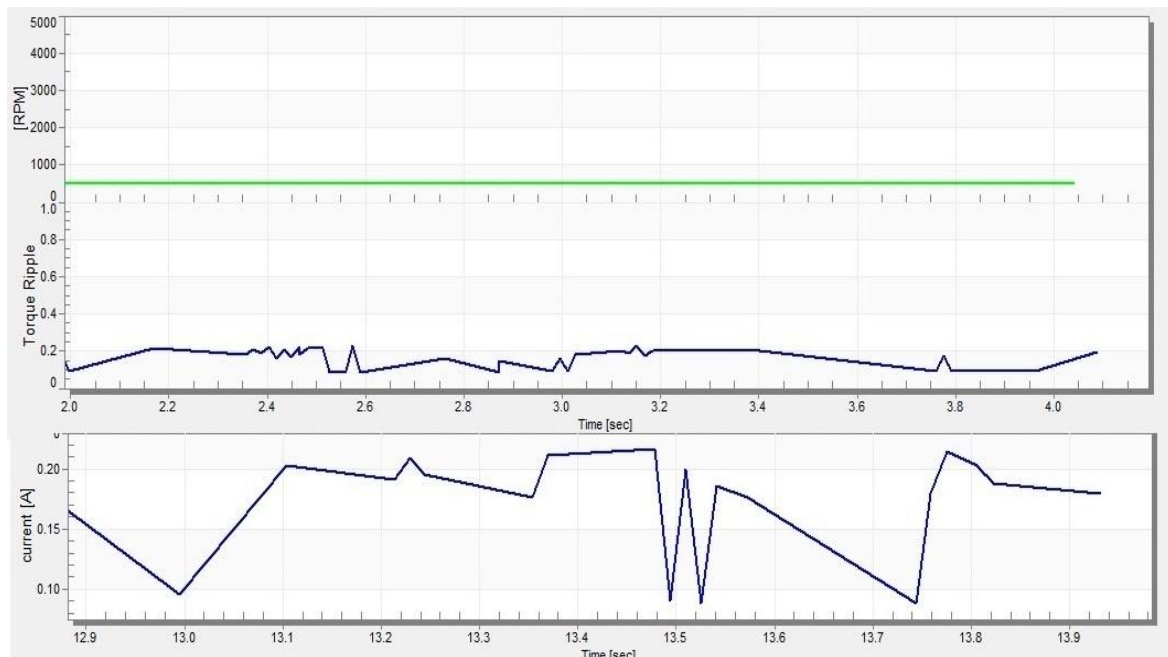


Figure 10. Hardware response of VSI fed three phase PMSM drive at 500 rpm

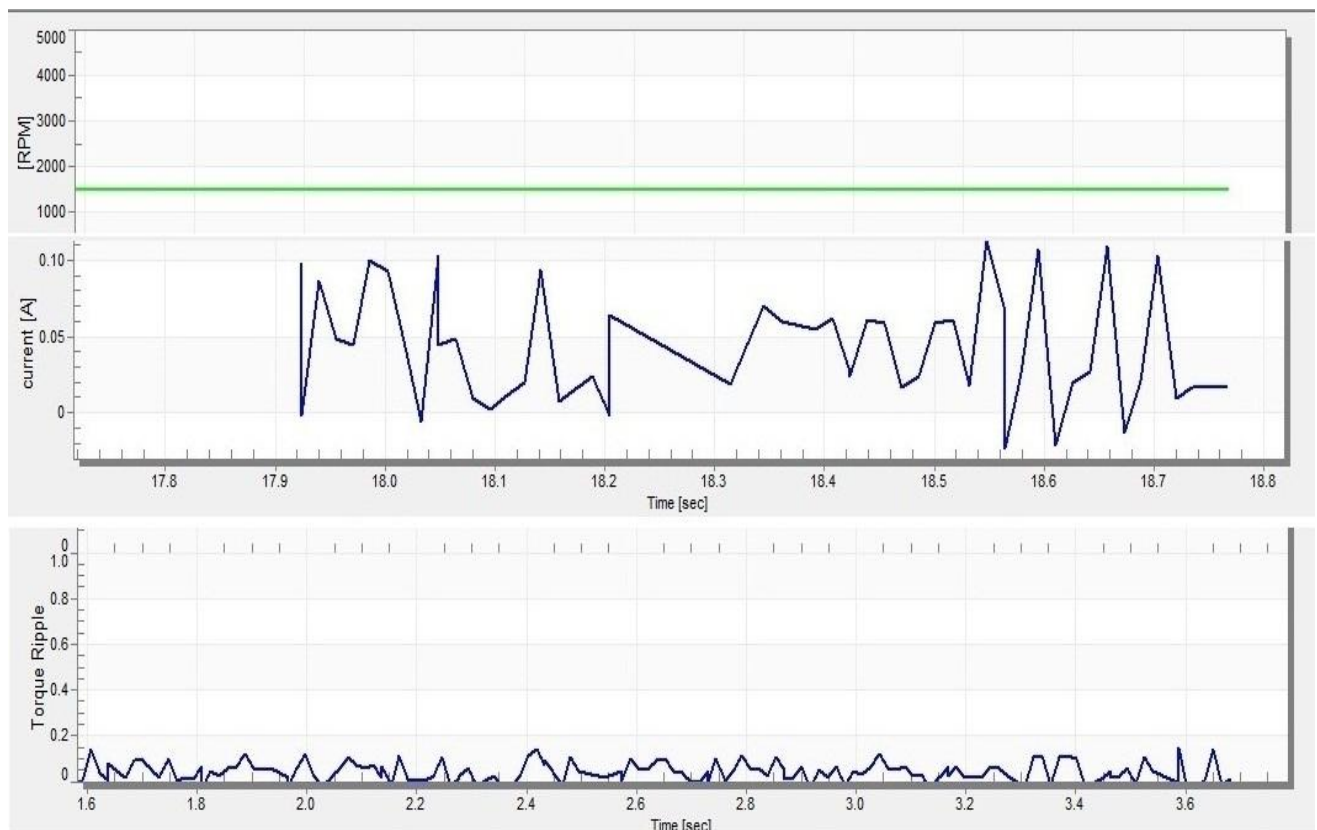


Figure11.Hardware response of VSI fed three phase PMSM driveat 1500 rpm

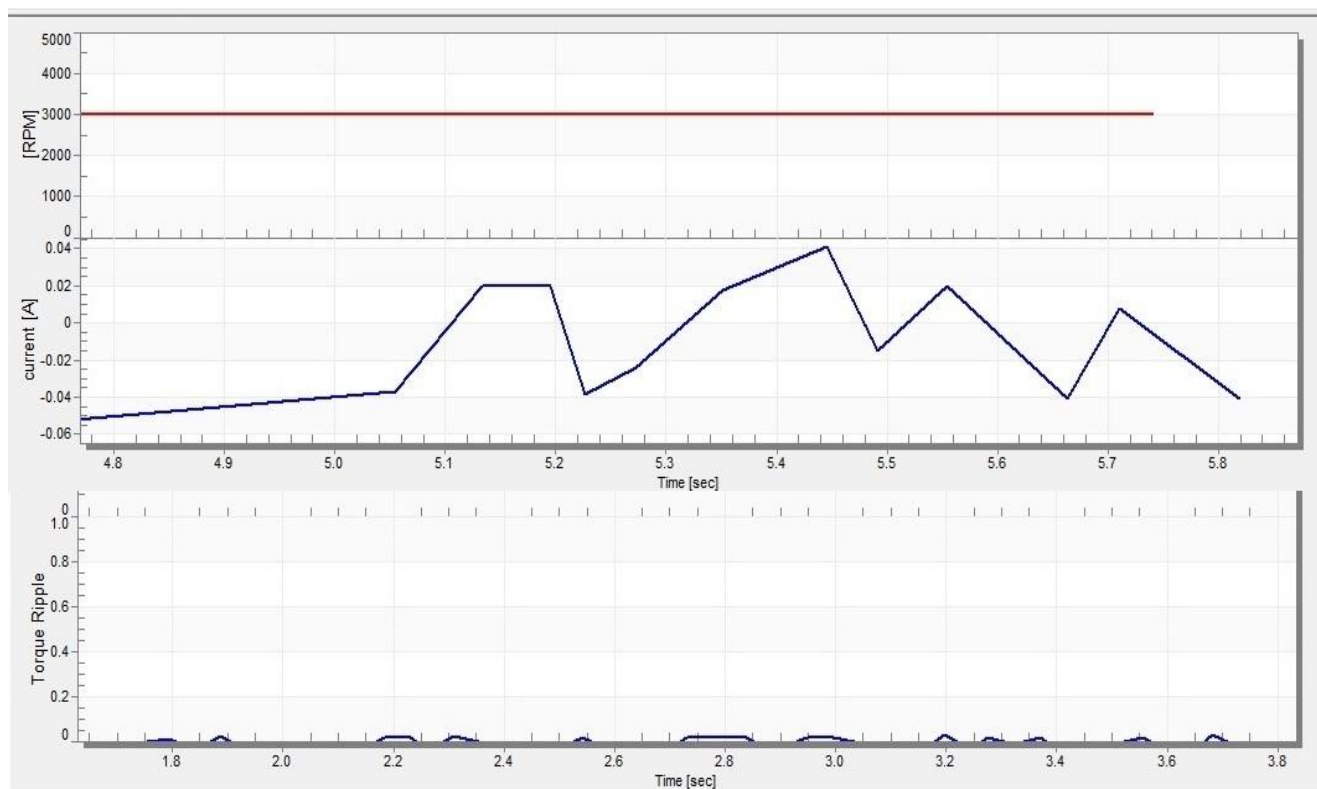


Figure12.Hardware response of VSI fed three phase PMSM drive,at 3000 rpm

Speed	FOC-CBSVM Torque Ripple	DTC-CBSVM Torque Ripple	FOC Current Ripple	DTC Current Ripple
500 rpm	21.58%	18.54%	8.4 mA	7.2 mA
1000 rpm	20.54%	17.26%	7.8 mA	6.7 mA
1500 rpm	18.27%	15.86%	7.5 mA	6.2 mA

Table No.5: Motor parameter variation

Table No.6: THD comparison variation

Parameter	FOC-CBSVM	DTC-CBSVM
Line-voltage THD	10.89%	10.04%
Line-current THD	2.41%	2.33%

Table No.7 PMSM Parameters

Parameter	Value
Stator resistance R_s	4.865 Ω
Stator inductance L_a	0.0174 H
Motor torque	0.544 N·m
Moment of inertia J	0.000114 kg·m ²
Viscous coefficient	0.0000447 N·m·s
Pole pairs	2

Table 8: Speed Variation with Load at 50 Hz for motor

Weight (Kg)	Voltage (V)	Current (A)	Power (W)	Measured Torque (N-m)	Actual Speed (rpm)	Calculative Speed (rpm)
0.5	264	1.13	300	2.08	1350	1380
1	264	1.13	300	2.08	1350	1380
1.5	264	1.17	310	2.15	1350	1380
2	264	1.21	320	2.22	1350	1380
2.5	264	1.25	330	2.29	1350	1380
3	264	1.25	330	2.29	1350	1380

Table No.9: Variation in motor speed as a configuration of load at 50 Hz

Sr. No.	Load (Kg)	Volt (V)	Current (A)	Load Power (W)	Torque (N-m)	Expected Speed (rpm)	Measured Speed (rpm)
1	0.5	270	1.01	272	1.68	1500	1540
2	1.0	270	1.09	295	1.81	1500	1540
3	1.5	270	1.13	305	1.89	1500	1540
4	2.0	270	1.20	325	2.01	1500	1540
5	2.5	270	1.28	345	2.14	1500	1540
6	3.0	270	1.35	365	2.26	1500	1540

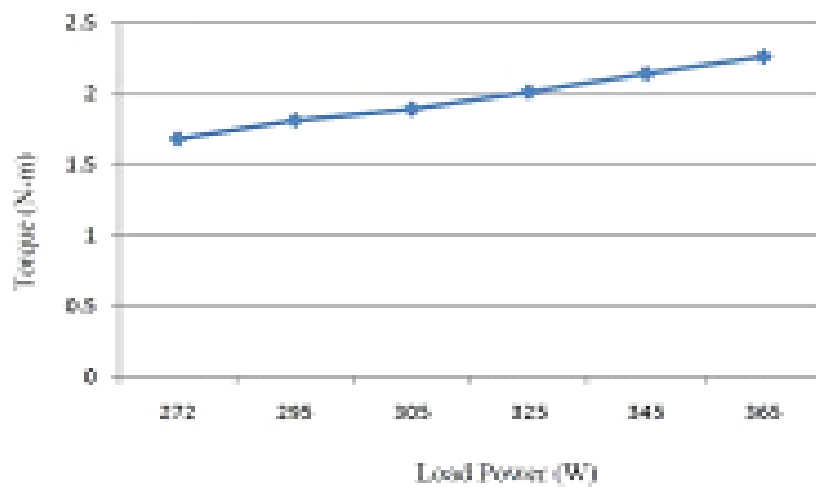


Figure13.Torque - Load power Characteristics at 50Hz

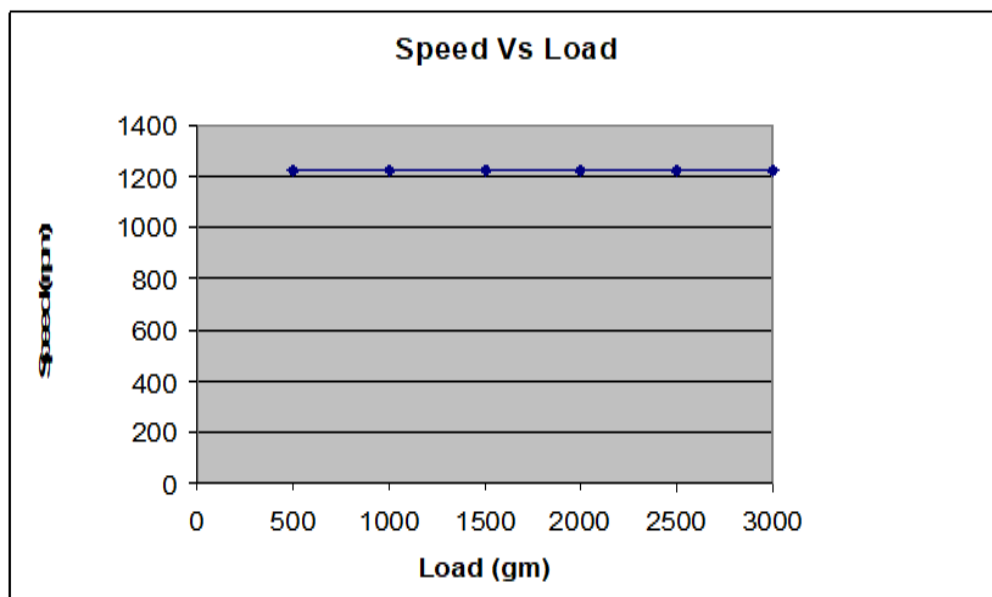


Figure14.Speed - Load power Characteristics at 50Hz

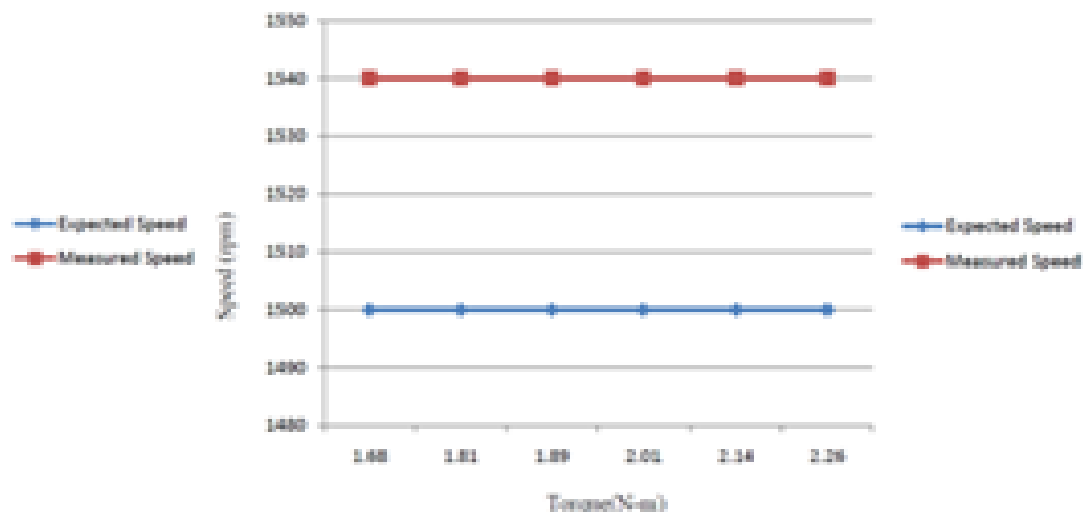


Figure15.Speed – Torque Characteristics at 50Hz

Conclusion

The comparative analysis of DTC-CBSVM and FOC-CBSVM controlled twelve-switch NPC inverter-fed PMSM drives demonstrates that the proposed DTC-CBSVM strategy provides improved transient performance for electric vehicle applications. The simulation results over the speed range of 500–1500 rpm indicate that DTC-CBSVM consistently achieves lower torque ripple than FOC-CBSVM. At 500 rpm, the torque ripple is reduced from 21.58% to 18.54%, while at 1000 rpm it decreases from 20.54% to 17.26%. Similarly, at 1500 rpm, the torque ripple is reduced from 18.27% to 15.86%. These improvements indicate better electromagnetic torque control and smoother PMSM operation.

In addition, the DTC-CBSVM approach provides improved power-quality performance. The line-voltage THD is reduced from 10.89% to 10.04%, while line-current THD decreases from 2.41% to 2.33% compared with FOC-CBSVM. The lower current ripple further contributes to reduced torque pulsations and improved motor operating performance. Overall, the results confirm that the combination of DTC, carrier-based space vector modulation (CBSVM), and a twelve-switch NPC inverter offers an effective control solution for PMSM drives. The improved torque characteristics and reduced harmonic distortion make DTC-CBSVM a promising alternative to conventional FOC-CBSVM for high-performance and energy-efficient electric vehicle propulsion systems.

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