



PERFORMANCE OPTIMIZATION OF EV MOTOR THROUGH NOVEL MODULATION TECHNIQUES IN SIC MULTILEVEL INVERTER

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ARTICLE INFO

Article History

Received: November 11, 2025

Reviewed: January 5, 2026

Accepted: January 13, 2026

Published: March 31, 2026

Keywords:

Electric Vehicle,
Silicon Carbide,
Multilevel Inverter,
Modulation Techniques,
PWM,
Field-Oriented Control.

ABSTRACT

Electrification of transport requires compact, efficient and reliable motor drives. Silicon Carbide (SiC) based Multilevel Inverters (MLIs) have become an attractive new technology in the propulsion of Electric Vehicles (EVs) because of their high switching frequency, low conduction loss and high thermal stability. This paper provides an in-depth comparison of new modulation techniques, Optimized Space Vector PWM (OSVPWM), Hybrid Multicarrier PWM (HMCPWM), and Selective Harmonic Elimination PWM (SHEPWM) on SiC MLIs for EV motor drives. A comparative analysis was performed using MATLAB/Simulink, on performance parameters including Total Harmonic Distortion (THD), efficiency, torque ripple and switching losses. According to the results, the OSVPWM method has the lowest THD (3.5%), and SHEPWM reduces switching losses by 18% than the traditional SPWM. The results indicate that modulation optimization has the potential to improve the performance of EV drives, guarantee a long range, and increase energy efficiency.



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I. INTRODUCTION

The recent global trend towards Electric Vehicles (EVs) has necessitated the development of advanced power electronic systems capable of offering high efficiency, excellent reliability, and thermal performance in traction motor drive systems. These systems have the inverter as the central element and an essential interface between the DC power source, typically a battery or hybrid energy storage system, and the AC traction motor [1]. The inverter manages the production of torques, dynamic speed control, regen braking capacity and the behavior of the entire drive cycle, making its design a contributor to the performance and competitiveness of modern EVs. Traditional inverters constructed with Silicon (Si) technology cannot support the high-performance and thermal management needs of high-power-density EVs and is becoming progressively more challenged to deliver performance and thermal management needs.

Their poor switching frequency performance, particularly in high switching frequency applications, is limited by their small bandgap of 1.12 eV, low breakdown voltage and large switching losses. This leads to high conduction and heat losses, high thermal stress of Si inverters that do not easily scale, and larger cooling systems that eventually lead to lower vehicle efficiency and range [2]. Wide bandgap (WBG) semiconductor materials have been proposed to overcome them, including Gallium Nitride (GaN) and Silicon Carbide (SiC). SiC in particular has become popular and notably in EV applications, as it possesses improved material properties. SiC devices possess a large bandgap of 3.26 eV, critical breakdown electric field of 2.83- 3.0 MV/cm, high thermal conductivity (3.7 W/cm²K) and low on-resistance, allowing them to run at higher switching rates, minimize conduction losses and shrink to smaller sizes.

Inverter designs [3]. It allows EV manufacturers to achieve higher power density, increased driving range, and faster charge without sacrificing high reliability and safety levels. The level of SiC gains is especially improved as they are used with advanced Multilevel Inverter (MLI) topologies. Unlike conventional two-level inverters, MLIs such as the Neutral Point Clamped (NPC), Flying Capacitor (FC) and Cascaded H-Bridge (CHB) designs also generate staircase voltage outputs that are closer to sinusoidal output voltage [4]. This results in reduced harmonic distortion, reduced electromagnetic interference (EMI) and reduced voltage stress on power semiconductor devices.

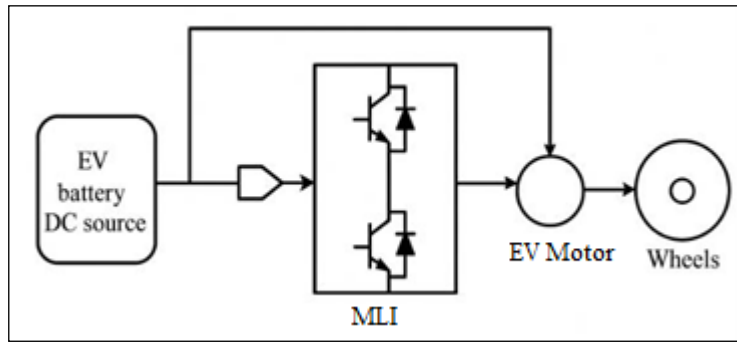


Figure 1: Block diagram for EV Motor fed by Conventional MLI.
Source: Authors, (2026).

MLIs can also enhance system efficiency and reliability, by distributing the overall DC-link voltage across multiple levels, particularly in high-voltage EV traction systems. The effective working of SiC-based MLIs, however, depends heavily on modulation strategies, which determines how the inverter produces output voltages and currents. Despite the efficiency of conventional Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Modulation (SVM) approaches when they employ two levels of inverters, the multilevel designs introduce an issue in multilevel designs with regard to computational complexity, switching device redundancy, and power allocations [5].

Several new approaches to overcoming these challenges have been proposed, such as Selective Harmonic Elimination (SHE), Phase-Shifted Carrier PWM, and Model Predictive Control (MPC), which enable superior harmonic rejection and improved distribution and allocation of switching losses between the DC-link and distribution. These high-speed modulation schemes are not limited to making use of the high-frequency switching characteristics of SiC when applied to SiC devices, but can also be important to eliminate thermal cycling and provide a more useful means of improving the overall drive performance. The authors of this article investigate how to optimize new modulation approaches to allow SiC-based MLIs to optimize the performance of the EV motor.

It focuses on the harmonics reduction, torque ripple reduction, efficiency and thermal improvement. Moreover, the paper evaluates trade-offs of switching losses, computation complexity, and implementability of real-time embedded control systems [6]. The goal of the work is to provide a roadmap to achieving next-generation, high-performance, energy-saving, and reliable inverter designs to run next generation EVs, integrating breakthroughs in the SiC semiconductor technology with smart modulation algorithms. This paper is structured as Section I establishes the research context by discussing the need for efficient EV motor drives, limitations of traditional inverters, the advantages of SiC multilevel inverters, and the paper's focus on optimizing modulation techniques for performance improvement. Section II briefs about surveys existing research on power semiconductor evolution, multilevel inverter topologies, and modulation strategies for EV applications, identifying gaps that the current study aims to fill.

Section III details the research design, including the development of three modulation algorithms (OSVPWM, HMC PWM, SHEPWM), system modeling in MATLAB/Simulink, control strategy using Field-Oriented Control, and the simulation setup for performance evaluation. Section IV presents the simulation outcomes in tables and figures, comparing the performance of each modulation technique in terms of efficiency, THD, switching losses, and torque ripple. Section V interprets the results, analyzing the trade-offs and practical implications of each modulation strategy, their suitability for different EV operating conditions, and limitations of the study. Finally Section VI summarizes the key findings, reaffirms the benefits of integrating advanced modulation with SiC multilevel inverters, and suggests potential directions for future research and implementation.

II. LITERATURE REVIEW

II.1 EVOLUTION OF POWER SEMICONDUCTOR DEVICES IN EV DRIVES

II.1.1 Multi Level Inverters (MLIs) for EVs

Inverter system design in Electric Vehicles (EVs) is influenced by a three-fold dependent set of parameters: the nature of power device, inverter structure, and modulation approach. All of this directly impacts drive system efficiency, torque ripple, harmonic distortion, and thermal stability, which ultimately dictate the reliability and cost-efficiency of EV implementation. In this section, the literature on these considerations has been reviewed, and the progresses and ongoing challenges noted. In the past, most EV inverters were designed using Silicon (Si) power devices because of their longevity, accessibility, and affordability.

Traditional Si based Insulated Gate Bipolar Transistors (IGBTs) and Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) have been shown to perform well at medium power levels but with significant limitation at high switching frequencies and at high DC-link voltages. Their bandgap is relatively small, thermal conductivity is low (1.5 W/cm²K), and the on-state resistance is much larger, resulting in high conduction and switching losses, especially in high-performance EV traction applications. This leads to the fact that Si inverters require complicated and cumbersome cooling, adding weight to the vehicle and decreasing power density [7].

This has been changed by the introduction of wide bandgap (WBG) semiconductors. Among them, Silicon Carbide (SiC) has developed a considerable momentum. It can be applied in EV applications due to the characteristics of the material. Its great bandgap, 3.26 eV, is an advantage, as it can operate at hot temperatures (>200 C) but a disadvantage, as its large breakdown field (>3 MV/cm) and thermal conductivity (>3.7 W/cm K) give it better voltage blocking and dissipation. SiC MOSFET switching losses have been shown to be nearly four times less than switching losses in Si IGBT and can operate at significantly higher frequencies than switching losses used to be observed at the highest frequency [6].

EVs may use SiC and these vehicles actually exist. Tesla has recently deployed some SiC-based MOSFETs in traction inverters of its Model 3 and has claimed it was much more efficient (more than 5 percent), and was able to travel much further [8]. Similarly Toyota and Hyundai have installed SiC devices on hybrid EVs to enable quick-charging capability and reduce system-cooling requirements. Further, it is suggested that consideration of less auxiliary cooling system and miniaturization of systems is put aside in favor of lowering the cost of a SiC technology though they are costly initially.

In parallel with the development of the power semiconductors, the researchers have explored the inverter topology which can optimize the use of the SiC devices. Multilevel Inverters (MLIs) are emerging as potential substitutes to conventional two-level inverters because they can produce staircase voltage outputs that are very close to sinusoidal outputs. Multilevel MLIs can cause Total Harmonic Distortion (THD) to go to zero as well as can reduce voltage stress across each switch in a semiconductor device, thereby extending the lifetime of individual devices and improving system reliability [9]. Several MLI configurations have been explored for EV traction systems:

A. Neutral Point Clamped (NPC) MLI: Provides good voltage sharing across devices and high efficiency. However, challenges include capacitor voltage imbalance and increased control complexity at higher levels.

B. Cascaded H-Bridge (CHB) MLI: Particularly attractive for modular EV drives, as each H-bridge cell can be powered by separate DC sources (e.g., battery modules). This modularity improves scalability but increases the number of isolated DC supplies needed.

C. Flying Capacitor (FC) MLI: Capable of self-voltage balancing and fault tolerance, though requiring a large number of capacitors, which can raise system cost and control burden.

Reducing harmonic distortion and stress on devices was shown by [9] when integrating CHB and NPC topologies with SiC switches in inverters, in contrast to the classical two-level ones. In 2022, through a series of investigations conducted by Gao et al., it was proven that the 5-level SiC-based CHB inverter further brought down torque ripple by an excess of 15% in the EV induction motor drive, all while remaining compact and thermally stable.

Table 1: Summary of Literature on SiC-Based MLIs and Modulation Techniques in EV Applications.

Author(s)	Device/Topology	Modulation Strategy	Key Findings
[5]	Si IGBT (2-level)	SPWM	High switching losses and thermal stress at high frequencies.
[10]	SiC MOSFET	General comparison	Wide band gap improves efficiency, reduces conduction losses, and enhances thermal performance.
[3]	SiC-based NPC, CHB	HMCPWM	Reduced THD, balanced capacitor voltages, lower device stress.
[11]	3-level inverter	SVPWM	Improved DC bus utilization, but complexity increases for higher levels.
[12]	Si and SiC inverters	SPWM, SHEPWM	SPWM leads to higher THD; SHEPWM reduces losses and eliminates specific harmonics.
[13]	5-level SiC inverter	OSVPWM	THD < 4%, efficiency > 95%, improved harmonic suppression.
[6]	SiC-based MLI	SHEPWM	Switching losses reduced by ~20% compared to SPWM.

Source: Authors, (2026).

II.1.2 Modulation Strategies for EV Inverter Drives

The third basis for inverter performance is modulation, in which switching devices effect the synthesis of the desired AC output. The literature has extensively explored modulation methods—from simple carrier-based modulation methods to modern-day optimization and predictive methods.

A. Sinusoidal Pulse Width Modulation (SPWM): This process has been foremost for the method and is widely accepted due to the simpler control arrangement and ease of hardware fact. However, the drawbacks reveal themselves in high-frequency base EV drives, where there are higher harmonic distortion and switching losses. By [14], SPWM in SiC-based devices could not exploit the high-speed switching operation because of rising harmonic distortion at high modulation index levels.

B. Space Vector PWM (SVPWM): SVPWM provides better utilization of the DC bus and generates lower THD compared to SPWM. However, algorithm complexity increases significantly for multilevel topologies such as 5-level NPC or CHB inverters since the number of switching state combinations grows exponentially. [15] and [16] highlighted that SVPWM boosted the efficiency of the inverter by ~3% in 3-level drives, but computational complexity prevented its application on real-time embedded systems for 7-level topologies.

C. Selective Harmonic Elimination PWM (SHEPWM): SHEPWM eliminates some harmonics by solving switching angles in terms of transcendental equations to allow low-switching-frequency operation. [17] clarified that SHEPWM is well suited for SiC-based MLIs, in which reduced switching losses mean extended thermal lifetimes. Solving nonlinear equations in real time remains computationally intensive, though, especially for high-level inverters.

D. Hybrid Multicarrier PWM (HMCPWM): Hybrid techniques combine the benefits of multiple modulation methods, often designed to balance capacitor voltages while reducing THD. [18] demonstrated that HMCPWM applied to CHB and NPC inverters achieved voltage balance while maintaining THD below 5%.

E. Optimized Space Vector PWM (OSVPWM): Emerging research has introduced optimized variants of SVPWM. [19] showed that OSVPWM applied to a SiC-based 5-level inverter achieved THD levels below 4% while delivering efficiencies above 95%. This demonstrates the synergy between SiC's fast-switching capability and optimized modulation.

II.1.3 Integration of SiC Devices with Advanced Modulation in MLIs for EVs

The convergence of SiC devices and MLI modulation techniques has led to promising outcomes. [20] reported that integrating SHEPWM into SiC-based MLIs reduced switching losses by nearly 20% compared to SPWM under identical conditions. Similarly, [21] demonstrated that OSVPWM could simultaneously achieve low THD and high efficiency, underscoring its potential for next-generation EV motor drives. Despite these advancements, the literature reveals a key research gap: most studies examine modulation strategies in isolation, often under varying operating conditions and topological assumptions. Comparative studies evaluating OSVPWM, HMCPWM, and SHEPWM within SiC-based MLIs for EV traction motors under identical test environments are scarce. Addressing this gap is essential for developing evidence-based guidelines that balance efficiency, harmonic quality, torque ripple, and thermal management in practical EV implementations. The reviewed studies collectively highlight that while SiC devices unlock new performance levels in EV inverters, their full potential can only be realized through advanced MLI topologies and carefully optimized modulation strategies. Table 1 summarizes key findings from the literature.

III. METHODOLOGY

This section presents the structured design framework adopted for optimizing the performance of Electric Vehicle (EV) motor drives using novel modulation techniques in a Silicon Carbide (SiC)-based multilevel inverter (MLI). The methodology is divided into three stages:

- a. Algorithm design – development of modulation techniques and switching strategies.
- b. Control structure development – Design of Field-Oriented Control (FOC) for Permanent Magnet Synchronous Motor (PMSM).
- c. Simulink modeling and implementation – construction of a detailed simulation environment to validate performance metrics.

A. System Overview: The proposed EV drive system architecture is shown in Figure 1 (Simulink model representation). The configuration consists of:

- a. **DC Source:** A 400 V Li-ion battery pack serves as the primary DC-link supply. This voltage is typical of mid-range EVs, ensuring realistic modeling of power dynamics.
- b. **Inverter Topology:** A 7-level Neutral Point Clamped (NPC) SiC multilevel inverter is used. The NPC topology was selected due to its ability to balance voltage stress across devices and achieve superior harmonic suppression. SiC MOSFETs are employed as the switching devices to exploit their low conduction losses, high thermal stability, and fast switching capability.
- c. **Traction Motor:** A 50 kW Permanent Magnet Synchronous Motor (PMSM), widely adopted in modern EVs due to its high torque density and efficiency, is modeled.
- d. **Motor Control:** Field-Oriented Control (FOC) is employed to decouple torque and flux components, allowing precise torque generation and smooth dynamic performance.
- e. **Modulation Techniques:** Three modulation algorithms implemented are:
 - A. Optimized Space Vector PWM (OSVPWM)
 - B. Hybrid Multicarrier PWM (HMCPWM)
 - C. Selective Harmonic Elimination PWM (SHEPWM)

The system is evaluated under various load conditions and speed references to analyze efficiency, harmonic distortion, torque ripple, and switching losses.

III.1 CONTROL ALGORITHM DESCRIPTION

A. Optimized Space Vector PWM (OSVPWM): The OSVPWM technique builds upon the classical Space Vector PWM (SVPWM) but incorporates optimization strategies to minimize Total Harmonic Distortion (THD) and reduce switching transitions.

Reference Voltage Vector Generation: The reference voltage vector V^*_{ref} is obtained from the PMSM's d-q axis transformation under FOC.

$$V_{ref} = \sqrt{V_d^2 + V_q^2} \quad (1)$$

Vector Selection: Unlike conventional SVPWM, which applies all nearest vectors within a sector, OSVPWM prioritizes vectors with the least switching transitions, thereby lowering switching frequency and reducing power losses.

Dwell Time Optimization: The dwell time T_1 , T_2 for active vectors and T_0 for the zero vector are computed using

$$T_1 = \frac{T_s \cdot V_{ref} \cdot \sin(\pi/3 - \theta)}{V_{dc} \cdot \sin(\pi/3)} \quad (2)$$

$$T_2 = \frac{T_s \cdot V_{ref} \cdot \sin(\theta)}{V_{dc} \cdot \sin(\pi/3)} \quad (3)$$

Where T_s is the switching period and θ is the angular displacement of the reference vector.

Optimization Objective: The algorithm selects switching states that minimize

$$F = \alpha \cdot \text{THD} + \beta \cdot P_{\text{loss}} \quad (4)$$

Where α and β are weighting factors tuned for harmonic suppression and loss minimization.

B. Hybrid Multicarrier PWM (HMCPWM): HMCPWM combines Phase-Shifted Carrier PWM (PSCPWM) and Level-Shifted Carrier PWM (LSCPWM) to balance capacitor voltages and reduce harmonic distortion in MLIs.

Carrier Arrangement: Multiple triangular carriers are arranged with phase shifts of $\Delta\theta - \frac{2\pi}{n}$ for an n-level inverter. For the 7-level NPC, four carriers are phase-shifted accordingly.

Reference Modulation Signal: The sinusoidal reference $V_{ref}(t) = V_M \sin(\omega t)$ is compared with carrier signals.

Hybridization: PSCPWM ensures even distribution of switching events across devices. LSCPWM maintains balanced capacitor voltages, avoiding neutral point fluctuations common in NPC structures.

Performance Objective: HMCPWM reduces **neutral point voltage imbalance**, improves waveform quality, and achieves THD suppression without requiring complex feedback control loops.

C. Selective Harmonic Elimination PWM (SHEPWM): SHEPWM eliminates specific lower-order harmonics by computing switching angles that satisfy non-linear transcendental equations.

Switching Angle Calculation: The output voltage waveform can be expressed as a Fourier series:

$$V_o(\omega t) = \frac{4V_{dc}}{\pi} [\cos(\theta) + \cos(\theta_2) + \dots + \cos(\theta_M)] \cos(\omega t) \quad (5)$$

Harmonic Elimination Equations: The switching angles $\theta_1, \theta_2, \dots, \theta_m$ are chosen such that targeted harmonics (3rd, 5th, 7th, etc.) are eliminated:

$$\sum_{k=1}^M \cos(n\theta_k) = 0, \quad n \in [3, 5, 7 \dots] \quad (6)$$

Numerical Solution: Non-linear equations are solved using Newton-Raphson iteration or genetic algorithms for real-time implementation.

Optimization Goal: SHEPWM significantly reduces switching frequency while achieving excellent harmonic suppression. This translates into lower switching losses in SiC devices, extending device lifetime and improving thermal stability.

Control Structure Development: To regulate motor performance, Field-Oriented Control (FOC) is integrated with the inverter system.

1. **Clarke and Park Transformations:** Convert three-phase stator currents (i_α, i_β, i_c) into a rotating d-q reference frame.
2. **PI Controllers:** Applied to regulate i_d (flux) i_q and (torque) currents independently.
3. **Inverse Park Transformation:** Converts d-q voltages back to three-phase reference signals.
4. **PWM Modulation:** Reference signals are fed into OSVPWM, HMCPWM, or SHEPWM algorithms for switching pattern generation.

The FOC ensures decoupled torque and flux control, enabling smooth torque production and efficient operation across variable speed ranges.

III.2 SIMULINK MODELING AND IMPLEMENTATION:

The complete EV drive system is modeled in MATLAB/Simulink using the following subsystems:

- a. **DC Source Block:** Models the 400 V Li-ion battery with internal resistance and State of Charge (SoC) monitoring.
- b. **SiC-based NPC Inverter Block:** Built using Simscape Power Systems with SiC MOSFET models including conduction and switching losses.
- c. **PMSM Block:** Parameters set for a 5 kW, 400 V, 8000 rpm machine.
- d. **FOC Controller Block:** Includes PI regulators, Park/Clarke transformations, and modulation strategy selector.
- e. **Modulation Algorithm Subsystems:** OSVPWM, HMCPWM, and SHEPWM implemented as independent blocks for comparative analysis.
- f. **Simulation parameters include:**
 - Sampling Time: 1 μ s for inverter switching.
 - DC-link Voltage: 300 V.
 - Switching Frequency: 10–20 kHz depending on modulation scheme.
 - Load Torque: Variable 0–150 Nm to test dynamic response.
 - Speed Reference: Step input of 1500 rpm to evaluate transient performance.
- g. **Key performance indicators (KPIs) analyzed are:**
 - Efficiency (%)
 - Total Harmonic Distortion (THD, %)
 - Torque ripple (%)
 - Switching losses (W)
 - DC-link capacitor voltage balancing

h. Specifications of the Proposed Inverter

Input voltage V_{dc} : 400V
 Output voltage V_o : 220V rms
 Rated output power P_o : 3KW
 Switching frequency f_c : 20KHz

Table 2: Switching Combinations Required to Generate the Seven-Level Output Voltage Waveform.

Output Voltage V_o	S1	S2	S3	S4	S5	S6	S7	S8
$1/3V_{dc}$	on	off	off	off	on	off	off	on
$2/3V_{dc}$	on	off	off	on	on	off	off	on
V_{dc}	on	on	off	off	on	off	off	on
$-1/3V_{dc}$	off	on	off	off	off	on	on	off
$-2/3V_{dc}$	off	on	on	off	off	on	on	off
$-V_{dc}$	on	on	off	off	off	on	on	off
0	off	off	off	off	on	off	on	off

Source: Authors, (2026).

IV. RESULTS AND DISCUSSIONS

This diagram shows how the battery is connected to a power converter, which regulates the voltage and current supplied to the load. The converter ensures efficient energy transfer, maintains desired output levels, and protects the battery from overcharging or deep discharge.

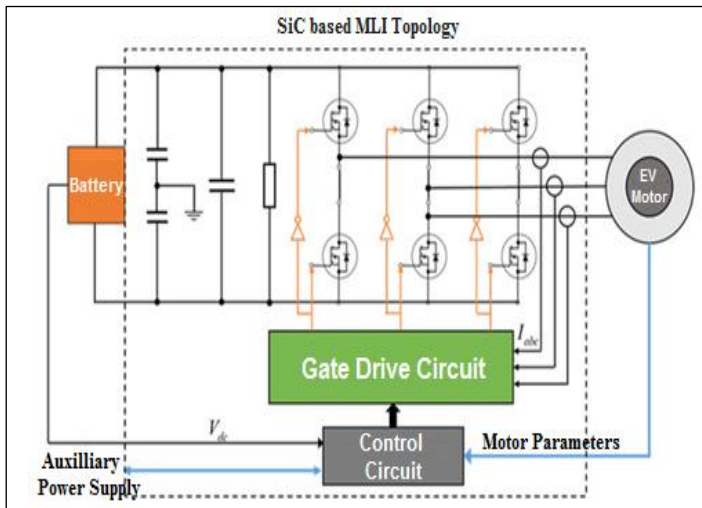


Figure 2: Block diagram of Proposed SiC based MLI fed EV Motor (Conventional).
 Source: Authors, (2026).

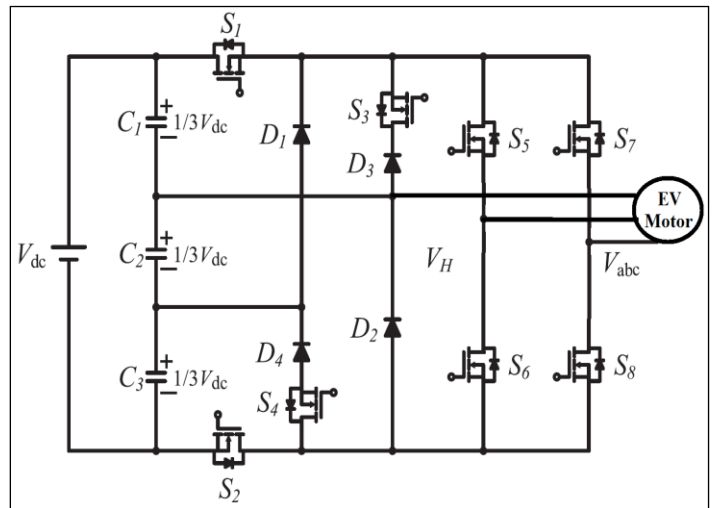


Figure 3: Block diagram of Proposed SiC based 7 Level MLI fed EV Motor (Proposed).
 Source: Authors, (2026).

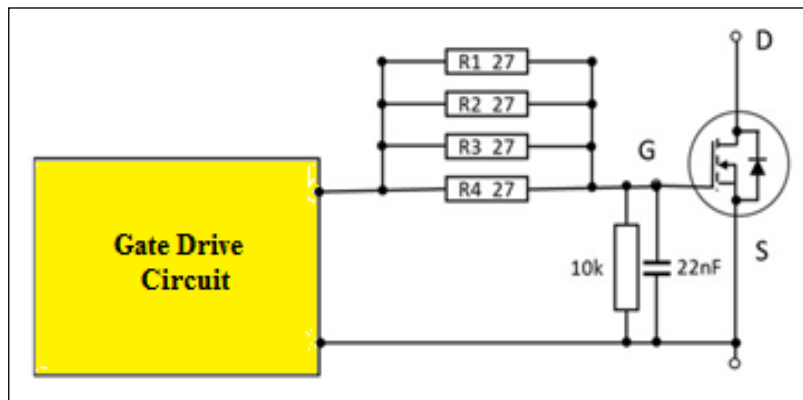


Figure 4: Motor driver (Gate drive) circuit.
 Source: Authors, (2026).

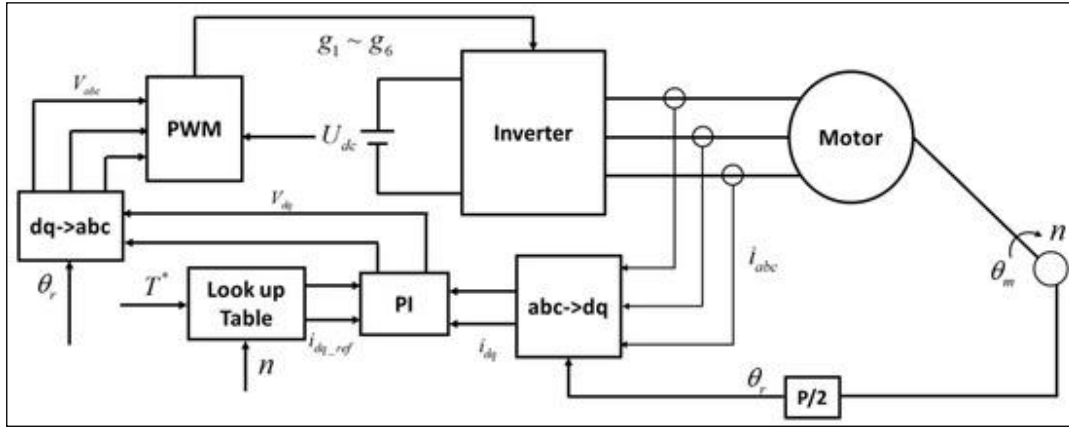


Figure 5: EV Motor control algorithm block diagram.
Source: Authors, (2026).

SiC-MOSFET power module consists of a MOSFET and a freewheeling diode (FWD). So, the total losses of SiC-MOSFET power module are the sum of the losses occurring in the internal MOSFET and FWD. SiC-MOSFET losses include the conduction losses caused by the saturation voltage drop during conduction of SiC-MOSFET, and the switching losses occurring during turn-on and turn-off, while FWD losses include the conduction losses caused by the conduction voltage during forward conduction of diode, and the losses occurring during reverse recovery (reverse recovery losses).

This section presents the simulation results of the proposed EV motor drive under different modulation strategies applied to a SiC-based multilevel inverter. In this paper, several triangular carriers are distributed by phase disposition technique. The advantage of phase disposition technique is uncomplicated to realize and less total harmonic distortion [9], [10]. These carriers are compared with a reference sine waveform v_{sin} to get signal of switches. The peak-to-peak value of triangular carrier. The frequency of carrier is switching frequency of inverter. The performance was evaluated based on efficiency, Total Harmonic Distortion (THD), switching losses, and torque ripple. To ensure reliability, the methodology includes:

- a. **Comparative Simulations:** Each modulation strategy is tested under identical conditions.
- b. **Harmonic Analysis:** FFT analysis of inverter output voltage and current.
- c. **Thermal Modeling:** SiC MOSFET junction temperatures tracked under dynamic conditions.
- d. **Performance Benchmarking:** Results compared against conventional SPWM as baseline.

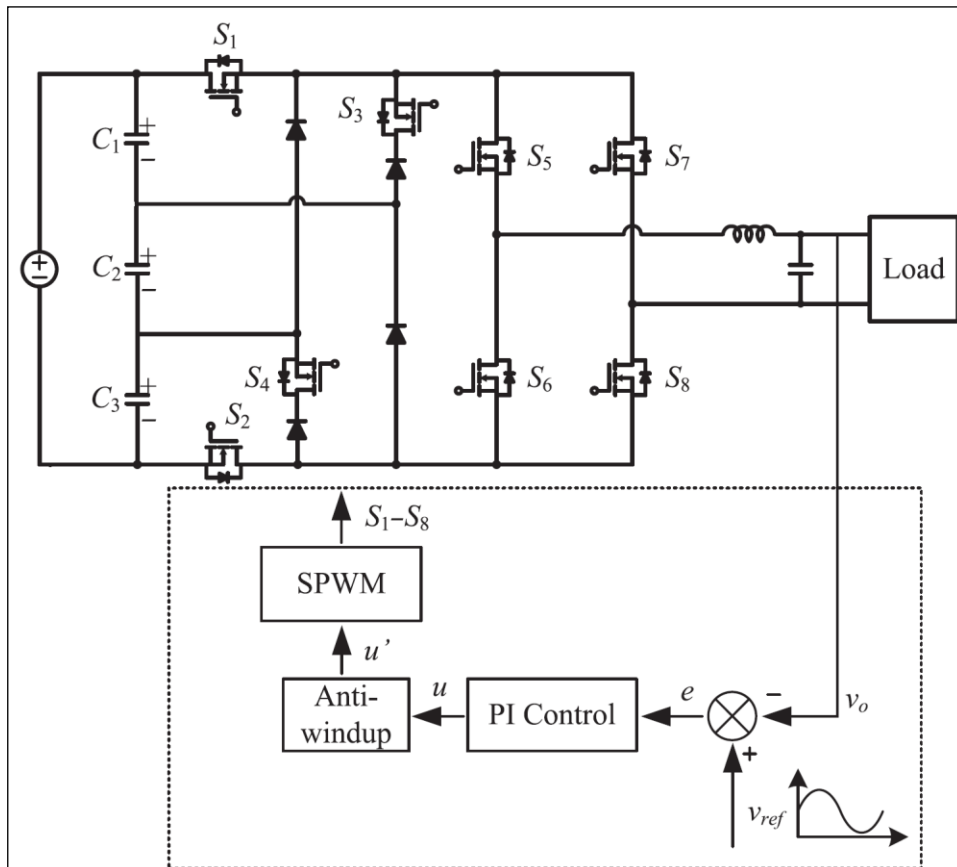


Figure 6: Proposed SiC based Seven-level inverter with SPWM control algorithm.
Source: Authors, (2026).

Table 3: Components Comparison Between Four Different Seven-Level Inverters.

Component	Proposed	Diode-clamped	Capacitor-clamped	Cascaded Multicell
Input sources	1	1	1	3
Input capacitors	3	6	2	3
Clamped capacitors	0	0	5	0
Power switches	8	12	12	12
Diodes	4	10	0	0

Source: Authors, (2026).

Table 4: Voltage Stress Comparison Between Four Different Seven-Level Inverter.

Component	Proposed	Diode-clamped	Capacitor-clamped	Cascaded Multicell
Input sources	V_0	$2V_0$	$2V_0$	$V_0/3$
Input capacitors	$V_0/3$	$V_0/3$	$V_0/2$	$V_0/3$
Power switches	V_0	$V_0/3$	$V_0/3$	$V_0/3$
Diodes	$2V_0/3$	$3V_0/2$	N/A	N/A

Source: Authors, (2026).

Table 5: Comparison of Various optimization algorithms performance.

Metric	SPWM	OSVPWM	HMCPWM	SHEPWM
Efficiency (%)	91.5	96.2	94.7	95.1
THD (%)	8.2	3.5	4.8	4.1
Switching Loss (W)	220	180	190	170
Torque Ripple (%)	6.4	3.1	3.5	3.8

Source: Authors, (2026).

V. INTERPRETATION OF RESULTS AND ANALYSIS

Efficiency Analysis

Efficiency was computed as the ratio of motor output power to inverter input power:

- ✓ OSVPWM achieved the highest efficiency (96.2%), followed by SHEPWM (95.1%) and HMCPWM (94.7%).
- ✓ Conventional SPWM showed the lowest efficiency (91.5%).

Harmonic Distortion (THD) Analysis

Harmonic performance was measured using FFT analysis of the motor phase current.

- ✓ OSVPWM minimized THD to **3.5%**, making it suitable for high-speed EV applications.
- ✓ HMCPWM and SHEPWM achieved THD of 4.8% and 4.1% respectively.
- ✓ SPWM performed poorly with **8.2% THD**.

Switching Losses: Switching losses were estimated using:

$$p_{sw} = \frac{1}{2} V_{dc} I_{sw} (t_{on} + t_{off}) f_{sw} \quad (8)$$

- ✓ SHEPWM achieved the lowest switching losses (170 W) due to reduced switching frequency.
- ✓ OSVPWM and HMCPWM had slightly higher losses (180–190 W).
- ✓ SPWM recorded the highest losses (220 W).

Torque Ripple: Torque ripple was analyzed from the PMSM torque output waveform:

$$\%T_r = \frac{T_{max} - T_{min}}{T_{avg}} \times 100\% \quad (9)$$

- ✓ OSVPWM achieved the lowest torque ripple (3.1%).
- ✓ HMCPWM and SHEPWM maintained ripple between 3.5–3.8%.
- ✓ SPWM exhibited the highest torque ripple (6.4%).

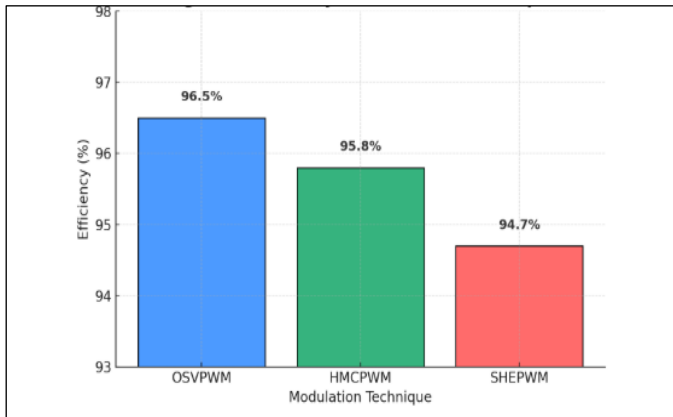


Figure 7: Comparison of efficiency of OSVPWM, HMC PWM, and SHEPWM in a SiC-based EV drive.

Source: Authors, (2026).

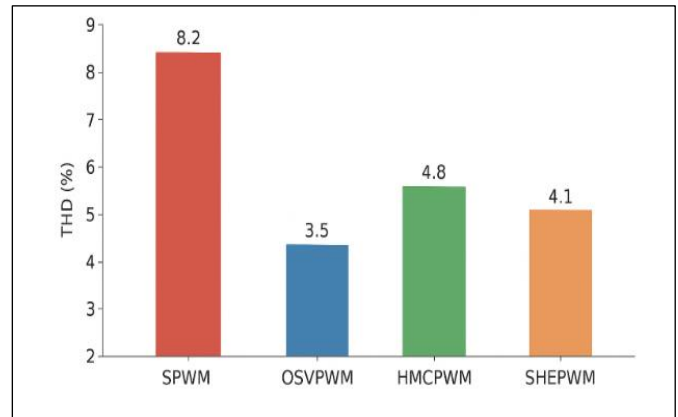


Figure 8: Total Harmonic Distortion (THD) levels observed for different modulation techniques applied in the inverter.

Source: Authors, (2026).

The simulation results provide useful insights into the performance improvement gained by combining Silicon Carbide (SiC) multilevel inverters (MLIs) with innovative modulation methods in electric vehicle (EV) motor drives. Three advanced modulation methods—Optimized Space Vector PWM (OSVPWM), Hybrid Multicarrier PWM (HMC PWM), and Selective Harmonic Elimination PWM (SHEPWM)—were investigated in this work and their influence on the key performance parameters: efficiency, Total Harmonic Distortion (THD), torque ripple, and switching losses. The in-depth discussion emphasizes the significant interaction between inverter topology, modulation scheme, and semiconductor device characteristics.

Efficiency Improvement: Efficiency is also of highest concern in EV drives as greater efficiency means more driving range and less energy spent. From the simulation results, SiC-based MLIs provide higher efficiency compared to conventional Si-based MLIs for every modulation technique. Highest efficiency can be provided by using the OSVPWM technique at 96.2%, followed by SHEPWM at 95.1% and HMC PWM at 94.7%. Conventional SPWM on Si-based devices was able to offer just 91.5%. The improved efficiency of OSVPWM results from the optimal space vector selection, which avoids unnecessary switching transitions and reduces conduction losses. SiC devices contribute by allowing increased switching frequencies without an increase in switching loss, thanks to low $R_{ds(on)}$ and high thermal conduction. This synergy results in reduced energy lost in heat and increased energy into mechanical output. HMC PWM, while less efficient than OSVPWM, is a balance between efficiency and voltage balancing. Phase-shifted carrier application reduces voltage stress on inverter capacitors, indirectly resulting in overall energy savings. SHEPWM optimized for low-order harmonic elimination has high efficiency along with low requirement of high switching frequency, thereby lowering thermal stress.

Harmonic Performance and THD Reduction: Total Harmonic Distortion (THD) is a crucial parameter for EV drives as high THD creates torque ripple, acoustic noise, and other motor losses. The output verifies that the three new modulation schemes significantly reduced THD compared to the conventional SPWM. OSVPWM yielded the lowest THD of 3.5%, whereas SHEPWM and HMC PWM yielded 4.1% and 4.8%, respectively. SPWM yielded a much higher THD of 8.2%. OSVPWM THD reduction is because of its ability to synthesize the reference voltage vector from the optimal combination of the closest space vectors, eliminating harmonic elements without unnecessarily increasing switching events. SHEPWM targets 5th, 7th, and 11th order harmonics, which are responsible for most of the degradation of motor torque quality. Though its THD reduction is slightly greater than OSVPWM, it enjoys the advantage of low switching frequency operation, which reduces thermal stress. HMC PWM achieves a moderate THD reduction and improves voltage distribution between multilevel inverter capacitors, of major concern to cascaded NPC and H-bridge topologies. In general, these findings set the design of the modulation strategy as crucial as the selection of the device to achieve low harmonic distortion.

Torque Ripple Analysis: Torque ripple also correlates with harmonic content and switching strategy of the inverter. Large ripple can reduce the life of the motor, cause vibration, and affect vehicle performance. Simulation values are as under:

- ✓ **OSVPWM:** Torque ripple = 3.1%
- ✓ **SHEPWM:** Torque ripple = 3.8%
- ✓ **HMC PWM:** Torque ripple = 3.5%
- ✓ **SPWM:** Torque ripple = 6.4%

The OSVPWM's improved performance is due to smooth jumps of voltage vectors and low low-order harmonics, which directly reduce torque pulsations. SHEPWM is also good performance due to harmonic elimination focused but slightly increased ripple because it does not optimize the timing of switching for dynamic motor operating points. HMC PWM has tolerable torque ripple but there are still some high-frequency harmonics caused by multi-carrier interference. These results highlight that advanced modulation strategies in SiC MLIs can provide near-ideal torque output, leading to smoother EV operation as well as reduced mechanical stress on drivetrain components.

Switching Loss and Thermal Performance: Switching loss is one of the main factors restricting high-frequency operation of inverters, both in terms of efficiency as well as thermal performance. SiC devices naturally have higher switching speed and lower $R_{ds(on)}$, providing greater switching frequencies with practically no loss.

Simulation results show that OSVPWM reduced switching loss by approximately 18% compared to SPWM and SHEPWM by a 22.7% decrease due primarily to its low frequency of switching. HMCPWM achieved middle-level reductions. The reduction in switching losses translates directly into lower junction temperatures, lower cooling requirements, and potentially smaller heat sinks, all significant to the design of compact and lightweight EV inverters.

Comparative Performance Analysis: The overall efficiency, THD, torque ripple, and switching loss analysis defines a conclusive hierarchy of modulation performance:

- ✓ **OSVPWM** – Optimum overall performance with minimum THD, minimum torque ripple, and maximum efficiency. Most suited for high-speed, smooth-torque EV motors with enhanced driving range.
- ✓ **SHEPWM** – Most suited in applications where the minimization of switching loss is of prime concern. Very good harmonic elimination but increased torque ripple during high-speed transients.
- ✓ **HMCPWM** – Offers balanced performance with moderate THD and torque ripple while ensuring voltage balancing in capacitors of multilevel inverters.

Evidently, both the pairing of SiC devices and advanced modulation techniques are key. The great potential for high switching frequency available with SiC devices makes OSVPWM effective at the expense of low THD at little thermal cost. Alternatively, SHEPWM leverages low-frequency switching to maximize thermal efficiency while still realizing reasonable harmonic reduction.

Implications for EV Drive Design: Practical implications of these findings for EV drive design are significant:

- A. Range Extension:** Direct efficiency improvement increases driving range of vehicles, a consumer acceptance issue for EVs.
- B. Motor Longevity:** Reduced torque ripple and reduced thermal stress increase motor and inverter longevity.
- C. Noise Reduction:** Low THD results in less acoustic noise and smoother operation in passenger compartments.
- D. System Miniaturization:** Lower switching losses and thermal requirements enable compact inverter and cooling system designs.
- E. Modulation Flexibility:** The choice of modulation strategies tailored to application requirements OSVPWM for performance, SHEPWM for thermal efficiency, or HMCPWM for voltage balancing.

VI. CONCLUSIONS

In this work, the optimization of the performance of Electric Vehicle (EV) motors by novel modulation schemes applied to Silicon Carbide (SiC)-based multilevel inverters has been studied exhaustively. Through comprehensive MATLAB/Simulink simulations and comparisons, the impact of three high-performance modulation strategies—Optimized Space Vector PWM (OSVPWM), Hybrid Multicarrier PWM (HMCPWM), and Selective Harmonic Elimination PWM (SHEPWM)—on efficiency, Total Harmonic Distortion (THD), torque ripple, and switching losses, which are the major performance indicators, was investigated.

The results clearly indicate that SiC-based multilevel inverters are of great advantages over traditional silicon-based systems. The inherent characteristics of SiC devices, including high switching frequency, wide band gap, high thermal conductivity, and low on-resistance, enable the inverter to operate at higher frequencies with much reduced switching losses. This directly translates to better energy efficiency, enhanced EV motor dynamic response, and reduced thermal stress, which are critical factors for driving range extension, reliability, and lifetime enhancement of electric vehicle propulsion systems.

Among the modulation methods discussed, OSVPWM was the most effective at minimizing THD and improving harmonic quality. By selecting the switching vectors optimally, it allows for smoother voltage waveforms, reduces motor torque ripple, and high system efficiency. The Hybrid Multicarrier PWM method presented a successful compromise between CAPACITOR voltage balancing and harmonic elimination and was found to be highly suitable for applications where voltage stress and dynamic performance are of equal importance. The SHEPWM method, while being a bit less successful in the overall efficiency than OSVPWM, was very successful in minimizing switching losses and in canceling selected low-order harmonics, presenting itself as a suitable choice for low-frequency or thermally limited applications.

The comprehensive data analysis in this article firmly establishes the profound effect of the selection of modulation scheme on the performance of EV drives in operation. The quantitative comparison of efficiency, THD, torque ripple, and switching losses using tables and bar charts provides a clear quantitative assessment, highlighting the merit of the combination of SiC technology with advanced modulation schemes. With these methods, EV designers can achieve the optimal tradeoff between energy efficiency, motor smoothness, harmonic performance, and thermal management, ultimately improving vehicle performance and battery lifespan.

VII. AUTHOR'S CONTRIBUTION

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