TELKOMNIKA Telecommunication Computing Electronics and Control
Vol. 24, No. 1, February 2026, pp. 302~312
ISSN: 1693-6930, DOI: 10.12928/TELKOMNIKA.v24i1.27234

Performance analysis of a multi-level inverter fed permanent magnet synchronous motor for electric vehicles

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Article Info

Article history:

Received May 22, 2025
Revised Oct 26, 2025
Accepted Dec 8, 2025

Keywords:

Field oriented control
Multilevel converter
Permanent magnet synchronous motor
Pulse width modulation
Total harmonic distortion

ABSTRACT

Electric vehicle (EV) drive systems utilizing permanent magnet synchronous motors (PMSMs) often encounter performance limitations due to switching losses, voltage stress, and harmonic distortion. To address these challenges, this paper presents a compact 31-level multilevel inverter (MLI) topology designed to enhance drive efficiency and power quality. The proposed inverter minimizes switching devices and driver circuits, resulting in reduced total harmonic distortion (THD), lower voltage stress, and improved waveform fidelity. Advanced control strategies are employed to further optimize performance. field-oriented control (FOC) ensures precise torque and flux regulation, while direct torque control (DTC) delivers rapid transient response. To mitigate torque ripple and variable switching frequency inherent in conventional DTC, adaptive predictive control (APC) is integrated to refine switching behavior and enhance dynamic stability. Simulation studies conducted in MATLAB/Simulink demonstrate the effectiveness of the proposed system, revealing significant improvements in torque smoothness, reduced THD (0.85%) and elevated efficiency under variable load conditions. This integrated solution offers a practical and scalable approach for next-generation EVs, contributing to greater reliability, energy utilization, and overall system performance.

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1. INTRODUCTION

Electric vehicles (EVs) are at the forefront of sustainable transportation, driving innovation across energy systems, power electronics and motor control technologies. As the demand for cleaner mobility grows, improving the efficiency, reliability and dynamic performance of EV drive systems has become a critical research focus. Central to this effort is the selection and control of electric motors and their associated power conversion systems. Among the various motor types used in EV propulsion such as direct current (DC) motors, induction motors, and variable reluctance motors the permanent magnet synchronous motor (PMSM) has emerged as the preferred choice due to its high torque density, excellent efficiency, and precise controllability [1]. PMSMs consist of a stator with three-phase windings and a rotor embedded with permanent magnets, enabling smooth torque production through interaction with a rotating magnetic field. These characteristics make PMSMs ideal for high-performance EV applications [2]. The propulsion scheme of an EV typically comprises of several key components including an electrically powered motor, regulator, battery pack and power converters [3]. The core of PMSM control is the inverter, which contains permanent magnets embedded on its surface, creating a fixed magnetic field converts a DC power source, often sourced from a battery or DC bus into a precisely modulated three-phase alternating current (AC) voltage [4]. The application of this regulated AC voltage to the stator windings generates a magnetic field that thoughtfully interacts with the rotor's magnetic field, thereby facilitating rotation. To supply the required AC power to PMSMs, multilevel inverters (MLIs) are widely employed. The control circuit in these MLIs changes the output voltage through changing the number of levels used and the frequency of the output voltage, making them important power sources in many power systems [5], [6]. MLIs generate stepped voltage waveforms that closely approximate sinusoidal output, reducing harmonic distortion and improving power quality. However, conventional inverter-fed PMSM systems face several limitations, including-high torque and flux ripples, especially during steady-state operation, poor performance at low speeds, affecting drive smoothness and elevated switching losses, leading to reduced efficiency and thermal stress. These challenges motivate the need for advanced inverter topologies and control strategies. In this study, a novel 31-level MLI is proposed, designed to reduce the number of switches and driver circuits [7], while maintaining high-quality voltage output. This topology enables finer voltage resolution with fewer components, resulting in lower voltage stress, reduced total harmonic distortion (THD) and improved cost-effectiveness [8]. To further enhance PMSM performance, advanced control algorithms are integrated. Traditional methods such as field-oriented control (FOC) offer decoupled control of torque and flux, while direct torque control (DTC) is known for its fast dynamic response [9]. However, DTC suffers from variable switching frequency and torque ripple. To overcome these drawbacks, adaptive predictive control (APC) is introduced. APC uses a mathematical model to predict system behavior and minimize a predefined cost function, enabling smoother torque control and better current regulation. Figure 1 depicts the schematic of architecture of DTC of PMSM fed EV. Furthermore, MLIs are used to enhance DTC though they resulted in high switching losses [10]. However, it is important to notice that the reduction in torque and flux ripples during steady-state conditions has been relatively modest. Furthermore, the combination of APC with DTC is gaining interest due to its high performance and straightforward implementation [11], [12]. By employing a mathematical model to anticipate system behavior APC effectively minimizes a predefined cost function to achieve desired control objectives. In addition to decrease the THD of the PMSM current, an innovative control scheme has been suggested to lessen torque and flux ripples [13]. This holistic approach holds great potential for advancing the efficiency and effectiveness of DTC applications. The combination of APC with DTC is receiving noteworthy attention for its impressive performance and relative ease of implementation [14], [15]. APC utilizes a mathematical model to anticipate system behavior and strives to minimize a predetermined cost function to accomplish desired control objectives [16]. This paper presents the modeling, control and simulation of a 31-level MLI integrated with a PMSM drive, employing APC-enhanced DTC to improve torque stability, reduce harmonic distortion and boost the overall efficiency for electric vehicle applications.

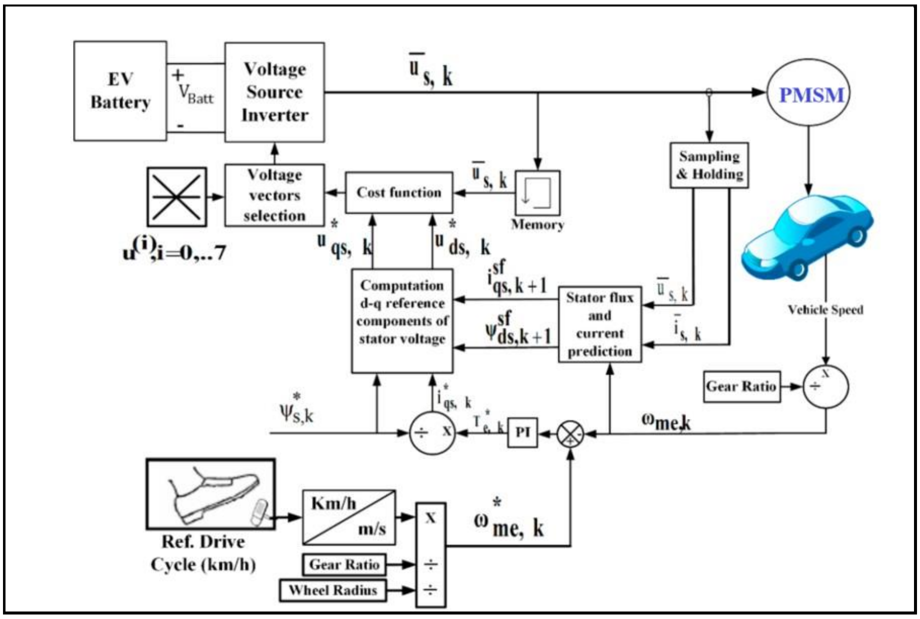


Figure 1. Architecture of EV configuration

2. PMSM DYNAMIC MODELING AND CONTROL STRATEGY

Dynamic modeling of PMSM is very vital for analyzing accurately its performance under fluctuating operational conditions [17]. A well-configured modeling strategy allows efficient control system strategy and it heightens the motor performance in the various applications viz. EVs, robotics and industrial automation. Figure 2 depicts the dynamic modeling of PMSM. Mathematical representation, reference frame transformations and control strategies are the crucial components of PMSM dynamic modeling [18]. The performance optimization of the electric machine requires selecting an appropriate control methodology which is very convoluted by the various operational parameters and performance characteristics. There has been limited exploration of advanced DTC techniques particularly for flux DTC (F-DTC) and its impact on battery performance when comparing with traditional DTC and its modified variants [19]. The main objective these approach to standardize the torque efficiently in accordance with vehicle-specific requirements. Control reference block is the critical element in this control strategy and it plays a pivotal role in computing d-axis and q-axis reference current values for optimization of maximum torque per ampere (MTPA) [20], [21]. Also this block facilitates field-weakening operations to ensure the efficiency improvement and overall performance in the electric drive systems [22]. By integrating these advanced methodologies, electric propulsion systems can achieve superior energy management and enhanced operational stability. It leads the way for further innovations in high-performance applications such as EVs and industrial automation [23], [24]. If the reference torque and feedback mechanical speed can be precisely defined then it allows the system to calculate the conforming d-axis and q-axis reference current values [25], [26]. At a given mechanical speed the system supports both maximum attainable torque and flexible reference torque values lower than that of rated.

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \tag{1}$$

$$v_q = R_s iq + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \lambda_m \tag{2}$$

$v_{d,} v_q$ = d-q axis voltages
$i_{d,} i_q$ = d-q axis currents
R_s = stator resistance
$L_{d,} Lq$ = d-q axis inductances
ω_e = electrical angular speed = $p.\omega_m$
λ_m = flux linkage from the permanent magnets
p = number of pole pairs

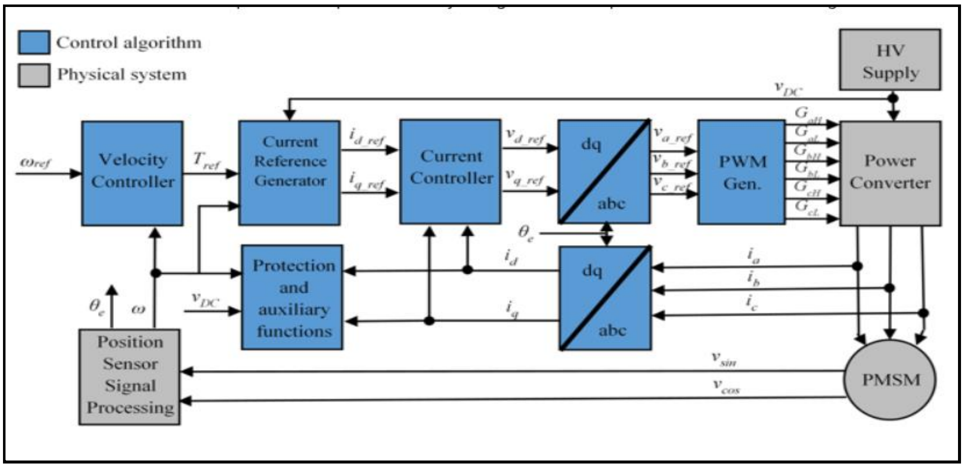


Figure 2. Dynamic modeling of PMSM

Electromagnetic torque T_e is given by:

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

For surface mounted motor:

$$L_d = L_q, \text{ thus, } T_e = \frac{3}{2} p \, [\lambda_m i_q] \tag{4}$$

The mechanical dynamic balancing is given by:

$$J \frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \tag{5}$$

J = moment of inertia
ω_m = mechanical angular speed (rad/sec)
B = viscous friction coefficient
T_L = load torque
Phase output voltage, v_{abc} is given by:

$$v_{abc} = v_{dc}.m(t) \tag{6}$$

$m(t)$ = modulation index
v_{dc} = input DC voltage per H-bridge cell

To integrate with the PMSM model in the d-q frame, transform the inverter output voltage v_a, v_b and v_c as:

– Clark transform:

$$v_\alpha = \frac{2}{3}(v_a - \frac{1}{2}v_b - \frac{1}{2}v_c) \tag{7}$$

$$v_\beta = \frac{2}{3}(\frac{\sqrt{3}}{2}v_b - \frac{\sqrt{3}}{2}v_c) \tag{8}$$

– Park transforms:

$$v_d = v_\alpha \cos(\theta_e) + v_\beta sin(\theta_e) \tag{9}$$

$$v_q = -v_\alpha \sin(\theta_e) + v_\beta \cos(\theta_e) \tag{10}$$

By substituting v_d and v_q in the (1) and (2) then:

$$\frac{di_d}{dt} = \frac{1}{L_d}(v_d - R_s i_d + \omega_e L_q i_q) \tag{11}$$

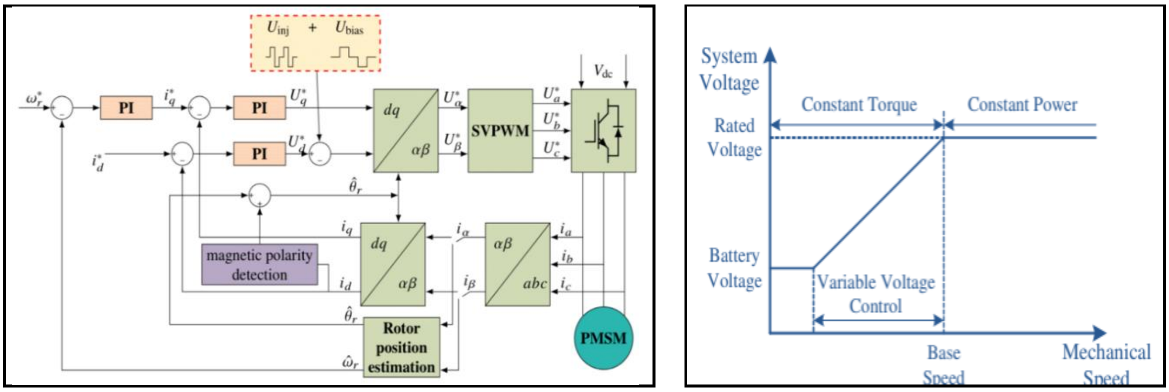
$$\frac{di_q}{dt} = \frac{1}{Lq}(v_q - R_s i_q - \omega_e L_d i_d - \omega_e \lambda_m) \tag{12}$$

The computation of these reference currents is based on established mathematical originations. Furthermore, V_{dc} input method parameter can be tailored to accommodate either a fixed reference DC-voltage [27], [28] via a predefined voltage setting or a variable reference DC-voltage through a dedicated input-port labeled V_{dc}. These equivalences are instrumental in determining the reference d-axis and q-axis currents to ensure optimum performance and efficiency of the motor [29].

3. PROPOSED SINGLE PHASE 31-LEVEL MLI FED PMSM CONFIGURATION

Electric motors offer precise controllability, which enables the use of advanced control methods to regulate the motor and improve the car’s kinematics. As a result, many researchers and automakers have considered the challenge of selecting the most suitable engine for an electric vehicle gearbox. The inverter plays a crucial role in converting the battery’s voltage from DC to AC to effectively command the motor. By functioning as a virtual device, it helps to ensure that the necessary parameters are met, thereby enhancing the overall quality of the gearbox. To reducing the THD, a single phase Multi level inverter is proposed.

Figures 3(a) and (b) illustrate the schematic view of PMSM with 31-level MLI and the corresponding mode of control of PMSM. The concept of MLI employs multiple small voltage levels for power conversion, which offers a range of beneficial attributes. This multilevel approach contributes to improved power quality, enhances electromagnetic compatibility (EMC), minimizes switching losses, and supports high voltage capabilities. While there are some considerations to keep in mind, such as the requirement for a larger number of switching semiconductors in lower-voltage systems, these challenges can be effectively managed. Furthermore, the small voltage steps on the DC side can be provided through the use of either a capacitor bank or isolated voltage sources, allowing for versatile design solutions that can optimize overall performance. A 31-level inverter exhibits very low THD, and by adding more voltage levels, the output voltage of a multi-level inverter can achieve a sinusoidal form with minimal THD.



(a) (b)

Figure 3. Schematic view of (a) PMSM with MLI and (b) Modes of control of PMSM

The methodologies are categorized into voltage-source and current-regulated approaches. Current-regulated technologies necessitate DC control, as higher-level controls (such as vector control, reactive power control, and active rectifiers) typically generate directed currents. Current controllers typically utilize event scheduling and often implement analog solutions, which may be most reliable at particular power levels. While there are a number of discrete current-regulated techniques available, exploring these options further could enhance their overall effectiveness. Voltage-source techniques offer superior harmonic performance due to their inherent characteristics. Furthermore, employing a programmable logic device (PLD) or digital signal processor (DSP) facilitates the implementation of voltage-source techniques. Figure 4 illustrates the schematic diagram of single phase 31-level MLI topology. Figures 5 and 6 depicts the corresponding output voltage and current waveforms respectively. Modifying the voltage supplied by the inverter through adaptable voltage control approach implemented with a bidirectional DC-DC boost converter can significantly enhance system efficiency by reducing losses based on the motor’s operating conditions.

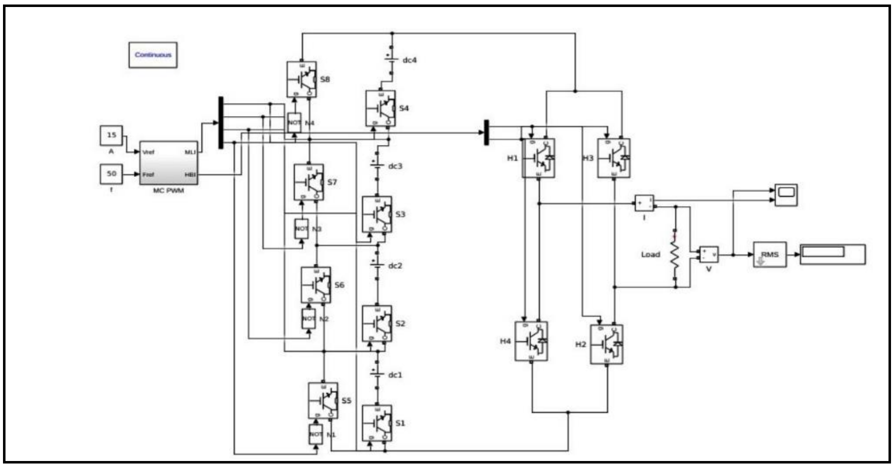


Figure 4. Proposed single phase 31-level MLI

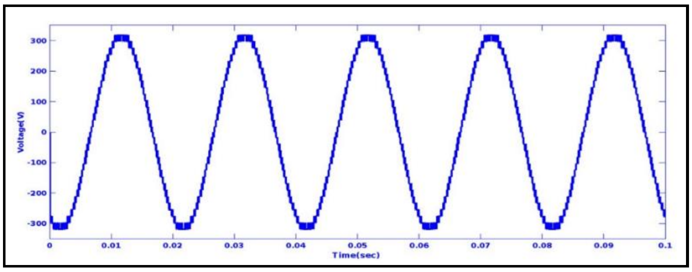


Figure 5. Output voltage waveform of 31-level MLI

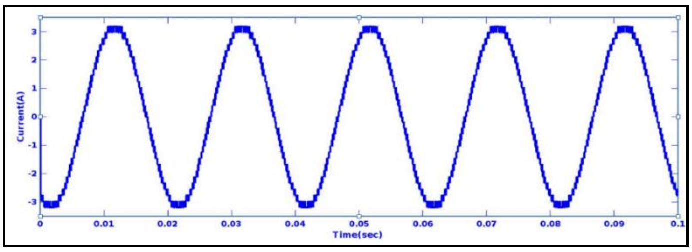


Figure 6. Output current waveform of 31-level MLI

It is noteworthy that, when the motor functions below its base speed, it is not essential for the system voltage to align with the rated inverter supply voltage. Consequently, to diminish the overall system losses, the voltage should be proportional to the PMSM's back-electromotive force (EMF). Back-EMF spawned by a PMSM typically varies in proportion to its motorized speed. At lower motor speeds, the inverter supply voltage corresponds to the minimum level offered by the boost converter, which is influenced by the battery's capacity. When the motor operates beyond its base speed and enters the persistent power region, the DC-DC converter is carefully regulated to provide the inverter with the regarded total system voltage. In the transitional speed range, the voltage is thoughtfully adjusted in alignment with the motorized speed. The high number of levels helps produce smoother waveforms, reducing harmonic distortion and improving efficiency.

The voltage waveform has a stepped pattern creating a signal close to a pure sine wave. Similarly, the current waveform is more stable to ensure better power delivery with minimal fluctuations. This improved waveform quality enhances system performance, making the 31-level MLI suitable for high-power applications that require efficient and clean energy conversion. Figure 7 depicts the fast fourier transform (FFT) analysis of a 1-phase 31-level MLI. This analysis helps identify the harmonic content in the output waveform providing insights into the inverter's efficiency and power quality. It is observed that the THD is 3.2% indicating the level of harmonic interference in the system. Lower THD means better waveform quality and improved system performance.

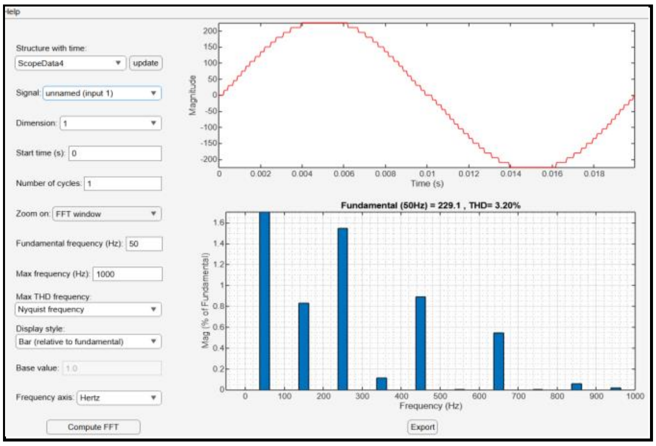


Figure 7. FFT analysis of 1-phase 31 level MLI

4. MATLAB/SIMULINK MODEL OF PROPOSED MLI FED PMSM

The operating model of a MLI to efficiently power a PMSM using MATLAB/Simulink as shown in Figure 8, presents an excellent opportunity for in-depth analysis of both the inverter and motor characteristics. It would be beneficial to include essential parameters such as voltage and current waveforms, control strategies and the dynamic response of the PMSM under diverse load conditions. By simulating these components within MATLAB/Simulink, we can gain valuable insights into their interactions, optimize performance and enhance the overall efficiency of the system. This collaborative effort can lead to significant advancements in our understanding and application of these technologies.

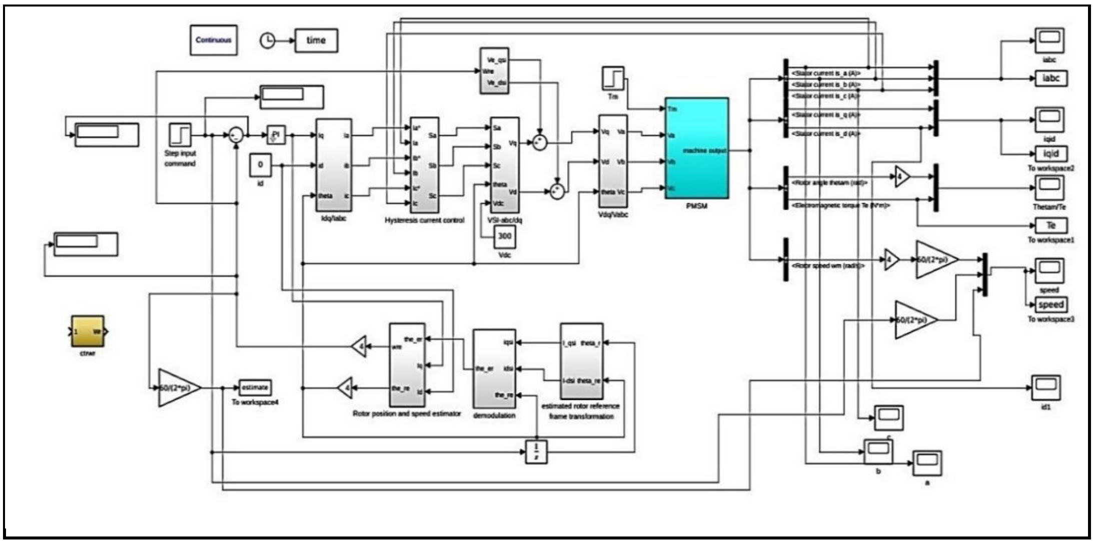


Figure 8. MATLAB/Simulink operating archetypal model of MLI fed PMSM

The Figures 9 and 10 depicts the torque and flux response of proposed DTC-space vector pulse width modulation (SVPWM) for PMSM, when the load torque has step change from negative to positive. The proposed control system and the proposed DTC-SVPWM system have good steady state and dynamic performance and are clearly observed from below torque/speed characteristics.

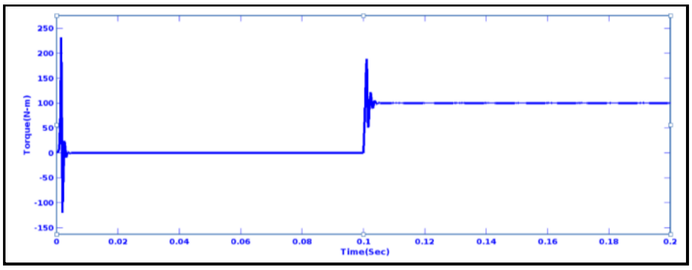


Figure 9. Torque characteristics of 3-phase 31-level MLI fed PMSM

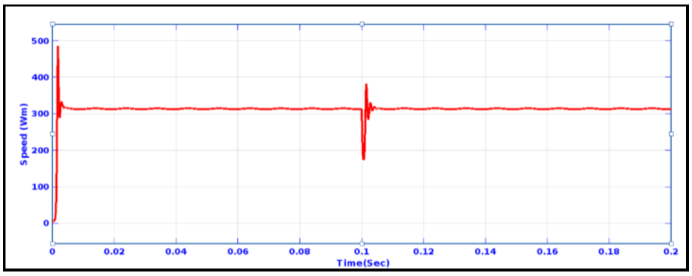


Figure 10. Speed characteristics of 3-phase 31 level MLI fed PMSM

Figure 11 presents the stator input currents i_a, i_b, and i_c of the PMSM. These currents are associated with the three-phase input power supply and play a vital role in governing the motor's operational characteristics including torque generation and overall efficiency. Figure 11 provides a visual representation of how these currents evolve over time, demonstrating their dynamic nature under varying load conditions, speed fluctuations and control strategies applied within the motor drive system. Understanding these variations is essential for optimizing motor performance, reducing losses and ensuring reliable operation.

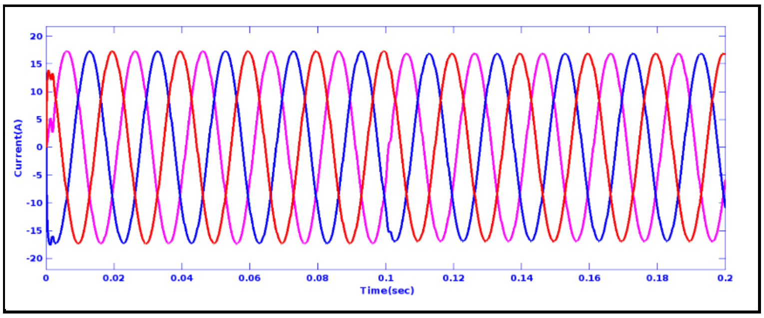


Figure 11. 3-phase stator current of PMSM

Figure 12 illustrates the FFT analysis of a 3-phase 31-level MLI. This analysis is instrumental in evaluating the harmonic distortion present in the system. From the Figure 12, it is observed that the THD is measured at 0.85% which is significantly lower compared to the THD observed in a 1-phase MLI. This reduction in harmonic distortion indicates improved power quality, enhanced waveform fidelity and better efficiency in power conversion making the 31-level MLI a more suitable choice for applications requiring minimal harmonic interference.

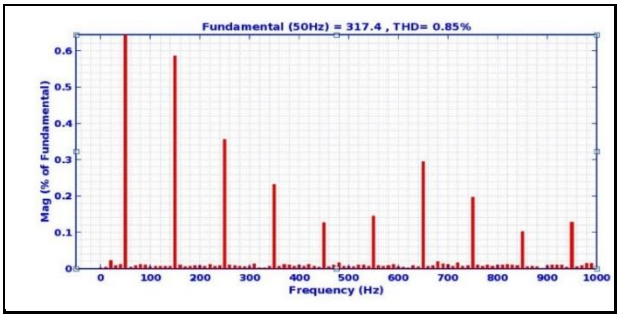


Figure 12. FFT analysis of 3-phase 31-level MLI

5. CONCLUSION

This study validates the effectiveness of a novel 31-level MLI topology integrated with a PMSM drive, specifically engineered for hybrid electric vehicle (HEV) applications. The proposed system achieves notable performance benchmarks, including a remarkably low THD of 0.85%, torque ripple confined within 4–5%, and enhanced speed stability under dynamic load conditions. These results underscore the system's ability to deliver high-quality voltage output and smooth mechanical operation, even in fluctuating environments. Compared to conventional inverter architectures, the 31-level MLI significantly reduces the number of switches, driver circuits, and auxiliary power supplies, leading to lower system complexity, reduced cost, and improved switching efficiency. This streamlined design also mitigates voltage stress and electromagnetic interference, making it highly suitable for compact, high-performance EV drive systems. Its compatibility with high-voltage operation, grid integration, and real-time responsiveness aligns well with the rigorous demands of modern electric drivetrains. The system's ability to maintain stable torque and current profiles under variable conditions highlights its potential for deployment in both hybrid and fully electric platforms. The achieved harmonic and torque performance confirms the inverter's capacity to balance control precision with hardware simplicity. Future work will focus on hardware prototyping, integration with advanced energy management systems, and real-time testing across diverse driving scenarios to further validate its practical viability and scalability.

To further validate and expand the applicability of the proposed 31-level MLI topology integrated with PMSM drives, future research will focus on several key areas. First, hardware implementation and real-time testing of the inverter-motor system are essential to confirm simulation results and assess practical feasibility. Integrating the drive system with advanced battery management systems (BMS) will enable coordinated energy control, enhancing overall efficiency and reliability. Additionally, evaluating the system under real-world driving cycles such as urban stop-and-go traffic and high-speed highway conditions will provide deeper insights into its dynamic performance and robustness. Finally, the development of adaptive control strategies will be explored to optimize system behavior across diverse environmental conditions and varying load demands, ensuring consistent performance and energy utilization in a wide range of EV applications.

FUNDING INFORMATION

No funding involved in this study.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Kondala Rao Parasa	✓		✓			✓	✓			✓			✓	✓
Mummidi Parvateeswara Subba Raju		✓			✓		✓		✓			✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors approve that the publication of this article causes no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [Donepudi Tata Rao]. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

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