International Journal of Applied Power Engineering (IJAPE)
Vol. 15, No. 3, September 2026, pp. 1264~1274
ISSN: 2252-8792, DOI: 10.11591/ijape.v15.i3.pp1264-1274

Performance analysis of multi carrier PWM techniques for a 5-phase three level NPC inverter in EV applications

Venu Yarlagadda[1], N. Kavitha[2], Chava Sunil Kumar[3], G. Naveen[4], Swetha Mareddy[5], S. Venkata Rami Reddy[6], K. V. Govardhan Rao[7]
[1]Department of Electrical and Electronics Engineering, VNR Vignana Jyothi Institute of Engineering and Technology, Hyderabad, India
[2]Department of Electronics and Communication Engineering, MVSR Engineering College, Hyderabad, India
[3]Department of Electrical and Electronics Engineering, BVRIT Hyderabad College of Engineering for Women, Hyderabad, India
[4]Department of Electrical and Electronics Engineering, Narasaraopet Engineering College, Narasaraopeta, India
[5]Department of Electrical and Electronics Engineering, Annamacharya University, Rajampet, India
[6]Department of Electrical and Electronics Engineering, JNTUA College of Engineering, Pulivendula, India
[7]Department of Electrical and Electronics Engineering, St. Martin's Engineering College, Secunderabad, India

Article Info

Article history:

Received Oct 17, 2025
Revised Apr 17, 2026
Accepted Jun 9, 2026

Keywords:

5-phase induction motor
5-phase multilevel inverter
MCPWM
PMSM
Pulse width modulation

ABSTRACT

Multi-phase multilevel inverters have become more popular in contemporary applications due to their many benefits, which include lower switching losses, decreased common mode voltage, and reduced stress from voltage on switches. This study focuses on enhancing total harmonic distortion (THD) performance in a five-phase multilevel neutral point clamped (NPC) inverter using various multi-carrier pulse width modulation (PWM) techniques, including PD, POD, APOD, IC, PSC, and VFC. These approaches are particularly suitable for electric vehicle and industrial motor applications. Several PWM approaches were used in the SIMULINK environment to model and simulate a 5-phase, 3-level NPC inverter. In this study, the performance of load voltage THD is compared using R and RL loads connected to a multilevel inverter. Additionally, 5-phase induction motor and permanent magnet synchronous motor models are developed as loads for electric vehicle applications, and variations in torque, speed, and stator current are analyzed. The PD modulation technique showed the lowest THD among the various PWM methods, demonstrating its effectiveness in maximizing inverter performance.

Corresponding Author:

K. V. Govardhan Rao
Department of Electrical and Electronics Engineering, St. Martin's Engineering College
Secunderabad – 500100, India
Email: kv.govardhanrao@gmail.com

1. INTRODUCTION

Multilevel inverters are capable of controlling high voltage and power drives more efficiently and with less electromagnetic interference [1]. They have become quite popular in the power industry. Multi-carrier pulse width modulation (MCPWM) approaches can further improve the performance of neutral point clamped (NPC) inverters [2], which are frequently employed in commercial uses. Multilevel inverters utilizing MCPWM techniques, such as interleaved carriers (IC), phase shifting carriers (PSC), variable frequency carriers (VFC), and alternative phase opposition disposition (APOD), can effectively mitigate power quality issues, common mode voltage, and DC-link capacitor imbalance. However, when compared to the PD PWM method [3], these methods may also result in increased total harmonic distortion (THD). The proposal is to improve the THD performance of a 3-level, 5-phase NPC inverter [4]. Lower THD levels in the inverter's output waveform are desired because they can result in increased efficiency, decreased losses, and higher quality power output [5], [6]. Multiphase inverters are preferred in high-power applications for their superiority over single-phase counterparts. These benefits include decreased harmonic distortion, enhanced output waveform quality, and increased dependability. Variable frequency motors have numerous applications, including high voltage DC transmission, conveyors, pumps, uninterruptible power supply (UPS) systems, and high-power applications [7]. Electric vehicles (EVs), where there is a growing need for dependable and high-power electrical drives, are one of the most important applications for multiphase inverters. Induction motors are frequently employed as the primary drive in EVs, and for best results, accurate speed control is crucial. Advanced control techniques like field-oriented control (FOC) and direct torque control (DTC) enable this capability [1]. Furthermore, five-phase motor drives are especially well-suited for industries like aerospace, automotive, and renewable energy systems that demand high power density, high speed, and high dependability [8]. Additionally utilized in EV applications, permanent magnet synchronous motor (PMSM) motors use FOC for speed control, which has benefits including high power density and great efficiency at low speeds. Multiphase motors are becoming more popular because they are better than standard three-phase motors in many ways, making them an attractive choice. These benefits include higher power density, enhanced fault tolerance, increased efficiency, and more control flexibility, which results in smoother operation. They are especially useful in traction (including electric and hybrid cars), electric ship propulsion, and aircraft [9]. Improved torque-speed characteristics, lower harmonic current, and reduced each phase's current without increasing each phase's voltage are all benefits of multi-phase motors. Due to its dependability and safety, multiphase induction motors with more phases are utilized in a wide range of applications [10], [11].

The existing literature on multilevel and multiphase inverters has predominantly focused on three-phase systems or higher-level inverters, with relatively limited attention given to five-phase, three-level NPC inverter configurations [12]. Most prior studies evaluate multi-carrier PWM (MCPWM) techniques primarily in terms of voltage waveform quality or THD under simplified resistive or RL load conditions, without extending the analysis to realistic motor-drive applications [13], [14]. Furthermore, comparative investigations often consider only a limited subset of PWM strategies, such as PD, POD, or space vector modulation, leaving a clear gap in comprehensive performance benchmarking across multiple MCPWM techniques within a unified framework [15], [16]. In addition, the majority of reported works do not simultaneously assess both electrical (voltage and current THD) and electromechanical (torque, speed, and stator current dynamics) performance metrics, which are critical for EV drive systems [17]. Another notable limitation in earlier research is the lack of integrated evaluation of different motor types, particularly five-phase induction motors and PMSMs, when fed from the same multilevel multiphase inverter topology [18], [19]. To address these research gaps, the present study offers a distinct and original contribution by providing a systematic and unified comparative analysis of six widely used MCPWM techniques, PD, POD, APOD, IC, PSC, and VFC applied to a five-phase, three-level NPC inverter [20], [21]. Unlike previous works, this study extends beyond static load analysis by incorporating both a five-phase induction motor and a PMSM as dynamic loads, thereby closely reflecting practical EV operating conditions. The uniqueness of this work lies in its integrated inverter–motor performance evaluation, where voltage and current THD characteristics are directly correlated with motor dynamic responses such as torque ripple, speed stability, and stator current quality. This comprehensive assessment establishes clear guidelines for selecting an optimal PWM strategy for high-performance, low-distortion, and reliable electric vehicle drive applications. This study will primarily focus on multi-carrier PWM approaches, including PD, POD, APOD, IC, PSC, and VFC. To obtain the waveforms of the load voltage, current, and THD analysis, a simulation analysis using Simulink with R and RL loads will be conducted. To illustrate potential EV applications, a 5-phase induction motor and a PMSM motor will also be modeled. The outcomes of this study will help choose the best PWM strategy for high-power applications by THD performance of various multi-carrier PWM strategies in NPC inverters. The remaining paper is organized into various sections as follows. Section two discusses the multi-phase multi-level inverter, section three talks about the simulation results and conclusions presented in section four.

2. MULTI PHASE MULTI LEVEL INVERTER

2.1. Block diagram

Figure 1 depicts the structure of the 3-level, 5-phase inverter [22]. It features 5 legs, with four switches on each leg that can only be used in two complementary combination pairs. Table 1 depicts the phase A switching configurations for 5-phase NPC Inverter. A 3L inverter employs a DC-link capacitor and neutral point to clamp the voltage stress on switches at Vdc/2. There is an NPC leg for each of the 5 phases (designated A, B, C, D, and E). Three output voltage levels can be generated by the inverter due to the two clamping diodes and four switches used to set up each leg: +Vdc/2, 0, and -Vdc/2. Effective multilevel inversion and control are made possible by specifically turning on switches S1A and S2A, which produce +Vdc/2, and turning on switches S3A and S4A, which produce -Vdc/2. When S1A and S4A are simultaneously turned on, the output becomes zero. Meanwhile, switch pairs S2A - S4A and S1A - S3A operate in a complementary manner. The switching table for the other phases will be identical.

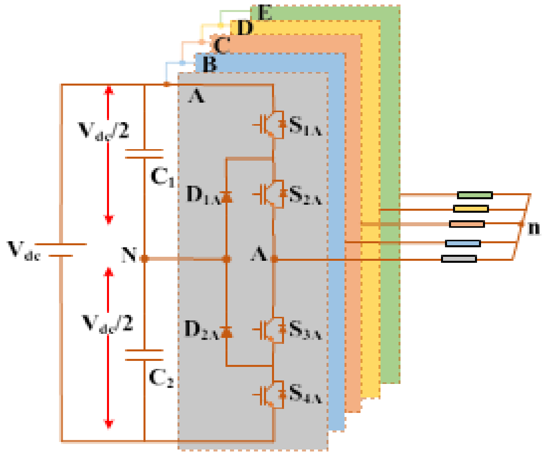

Figure 1. Simple diagram of the three-level NPC inverter for a load with five phases

Table 1. Phase A switching configurations for 5-phase NPC inverter

S1A	S2A	S3A	S4A	Output voltage	Mode
ON	ON	OFF	OFF	Vdc/2	High
OFF	ON	ON	OFF	0	Neutral
OFF	OFF	ON	ON	-Vdc/2	Low

2.2. Control logic

Multilevel inverter systems often employ sinusoidal pulse width modulation. A sinusoidal waveform's width is changed to adjust the output voltage level. Compared to conventional binary PWM techniques, this method offers more voltage levels, which improves power quality and lowers harmonic distortion. Sinusoidal PWM is also suitable for motor drives [22], [23], electric car charging, and renewable energy systems that need a steady and smooth output voltage waveform [24], [25]. Multilevel inverter systems can operate more dependably, efficiently, and with improved power consumption by utilizing sinusoidal PWM. The six categories of level-shifted PWM approaches are 'PD, POD, APOD, IC, PSC, and VFC'.

2.2.1. In-phase carrier disposition PWM

In the PD PWM method, multiple carrier signals with identical frequency and amplitude are positioned at different levels. This technique uses high-frequency carriers [26]. A certain formula can be used to quantitatively represent the ratio of frequency and index of modulation.

$$M_a = \frac{A_m}{(m-1).A_c} \tag{1}$$

$$M_f = \frac{f_c}{.f_m} \tag{2}$$

Where M_a provides a way to quantify the level of modulation and the relationship between the modulating and carrier frequencies [27]. The carrier and modulating signal frequencies are indicated by the parameters fc and fm, and their corresponding amplitudes are indicated by A_c and A_m. Figure 2(a) shows the waveforms of these signals using the phase PD - PWM approach.

2.2.2. Anti-phase carrier disposition PWM

The POD PWM technique employs carrier signals with uniform frequency and amplitude, where carriers above the zero reference are inverted (180-degree phase shift) relative to those below [28]-[30]. The phase opposition and phase disposition approaches are both incorporated into this approach. Carriers positioned above the zero axis generate positive output levels, whereas those below the zero axis produce negative output levels. No carrier signals are used in the production of the zero level. The POD PWM technique's modulating and carrier signals are displayed in Figure 2(b). Figure 2 illustrates the reference sinusoidal signal and the corresponding carrier signal arrangements for the six multi-carrier PWM techniques considered in this study, namely PD, POD, APOD, IC, PSC, and VFC. These carrier configurations are critical, as their phase relationships and frequency characteristics directly influence the harmonic distribution and THD performance of the five-phase, three-level NPC inverter.

2.2.3. Phase opposition PWM with alternating carriers

All carriers in APOD - PWM have uniform frequency and amplitude, but their phase angles are 180 degrees apart. This makes it possible to produce both positive and negative levels by using carriers above and below zero references. Figure 2(c) depicts the APOD PWM carrier and modulating signals. With this method, the voltage stress is somewhat decreased. For 3 level inverters, POD and APOD approaches will yield comparable findings; however, for higher level inverters, they will yield different outcomes.

2.2.4. Carrier interleaving PWM

All carrier signals in ICPWM have the same frequency and amplitude throughout the entire signal. On the other hand, there will be instances in which they overlap one another; specifically, there will be instances in which the higher and lower carrier signals will overlap. THD will be reduced with this method, and the output voltage will be increased. For the purpose of generating the positive and negative levels, upper and lower carriers will be utilized. An illustration of the arrangement of carrier and reference signals for the three-level IPC, PWM method may be found in Figure 2(d).

2.2.5. Carrier phase shift PWM

In the PSC–PWM technique, multiple carrier signals with identical frequency and amplitude are phase-shifted relative to each other. This process generates a stepped output waveform that reflects the combined effect of the shifted carriers. The number of carriers determines the phase shift amount, as illustrated in the 3-level PSC–PWM configuration shown in Figure 2(e).

2.2.6. Variable carrier frequency PWM

All carrier signals in ICPWM have the same frequency and amplitude throughout the entire signal and it is shown in Figure 2(f). On the other hand, there will be instances in which they overlap one another; specifically, there will be instances in which the higher and lower carrier signals will overlap. THD will be reduced with this method, and the output voltage will be increased. For the purpose of generating the positive and negative levels, upper and lower carriers will be utilized.

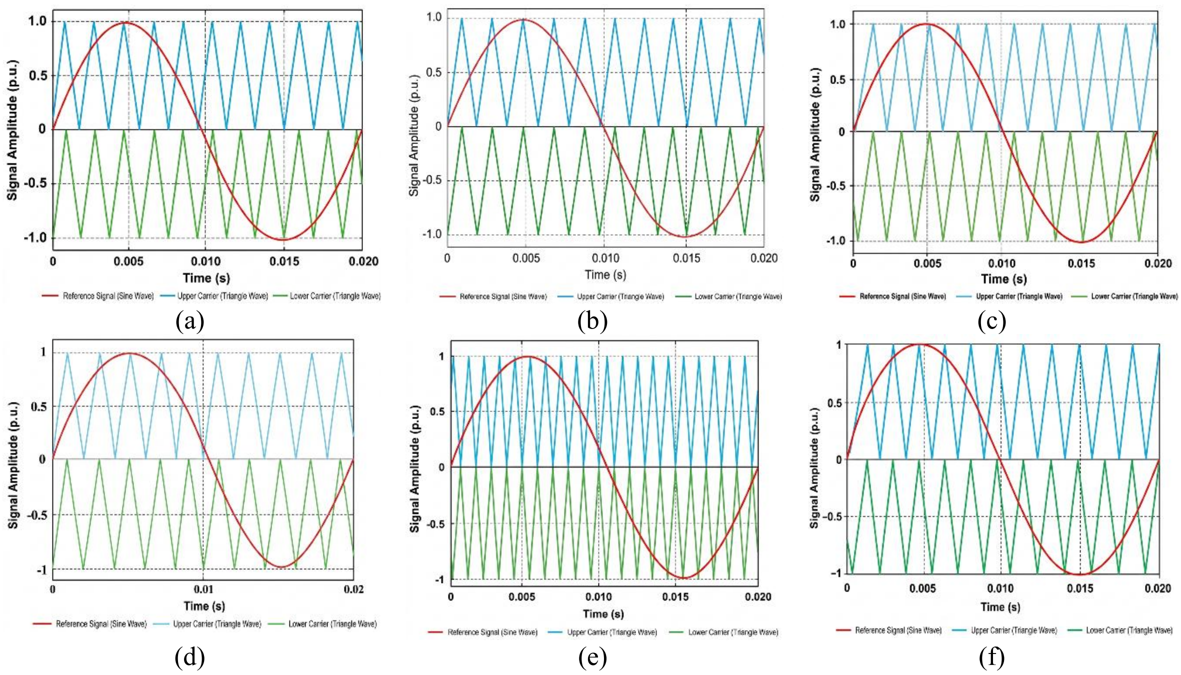

Figure 2. Three level NPC inverter reference and carrier signal configuration for (a) PD, (b) POD, (c) APOD, (d) IC, (e) PSC, and (f) VFC PWM approaches

An illustration of the arrangement of carrier and reference signals for the three-level IPC, PWM method may be found in Figure 2(d). A gate driver circuit receives this pulse-width modulated signal and uses it to create the gate pulse for every switching device. The PWM signal is amplified and transformed into a signal that may be utilized to regulate the gate voltage of the switching device by the gate driver circuit. The gate driver circuit activates the switching device when the PWM signal is high and deactivates the device when the PWM signal is low. The relationship between each multi-carrier PWM (MCPWM) technique and its corresponding impact on THD, the control logic, and results discussion sections describe the carrier arrangement, phase disposition, and frequency characteristics of each PWM method influence harmonic distribution in the inverter output. Specifically, the PD technique is explained as yielding lower THD due to the in-phase alignment of carriers, which promotes effective harmonic cancellation. In contrast, the POD and APOD techniques introduce phase reversals between carriers, leading to increased low-order harmonics and higher THD. The IC approach is discussed in terms of harmonic spreading caused by overlapping carriers, resulting in moderate THD reduction. Similarly, the PSC and VFC techniques are explained as redistributing harmonic energy across a wider frequency spectrum, which reduces dominant harmonic peaks but does not outperform PD in overall THD minimization. These clarifications strengthen the physical interpretation of the simulation results and improve the reader's understanding of how each PWM strategy affects harmonic performance.

3. SIMULATION ANALYSIS AND RESULTS

The software model of the 5-phase 3-level NPC inverter has been investigated using MATLAB/Simulink, and a number of different MCPWM techniques have been utilized. The switching frequency of the system is 10 kHz, and it is driven by a 300 V DC power source that is supported by a 100 μF capacitor during operation. Assuming that R is equal to 10 Ω and L is equal to 2 mH, we proceed to investigate an RL load. Figure 3 shows the line voltage waveforms and their corresponding FFT-based voltage THD spectra for the six MCPWM techniques. The comparison provides a quantitative assessment of how different carrier arrangements affect harmonic distortion and output voltage quality.

A comparatively smooth and symmetrical line voltage waveform with a fundamental voltage magnitude of approximately 170 V is shown in Figure 3(a) using the PD, PWM approach. A THD of 20.07%, the lowest of all researched approaches, is shown by the related FFT analysis, emphasizing PD PWM's exceptional harmonic performance. The POD, PWM approach, on the other hand, shows results in Figure 3(b), where the waveform shows more abrupt transitions because of the 180° phase shift between adjacent carriers. As a result, the THD is much greater at 40.87%. The output for the APOD, which has structural similarities to POD and produces a THD of 39.83%, is similarly illustrated in Figure 3(c). The Interleaved carrier PWM technique, shown in Figure 3(d), has overlapping carrier signals that somewhat lower harmonic content, although the THD is still more than the PD. Figures 3(e) and 3(f) illustrate the PSC and VFC methods, respectively. Because of their distinct carrier arrangements, both generate a variety of harmonic profiles, but neither outperforms the PD approach in terms of reducing distortion. When taken as a whole, these subfigures offer a comparative view of the effects of each PWM scheme on the quality of the voltage waveform. The PD approach is the most effective at reducing THD, which is crucial for enhancing inverter performance in EV applications.

Figure 4 depicts the dynamic performance of the PMSM drive, including motor speed, electromagnetic torque, and stator current waveforms. These results demonstrate the effectiveness of the inverter and PWM strategy in achieving smooth speed control and stable torque response. The simulation results for a three-phase PMSM operating under the proposed control approach are given in Figure 4. Figure 4(a) displays the motor speed in radians per second to illustrate the results. This indicates that the dynamic performance is efficient and that the reaction time is short. The speed profile demonstrates a consistent and smooth climb to the steady-state value that is planned. Figure 4(b) illustrates the electromagnetic torque that is produced by the motor. This torque is relatively stable and generates only a little amount of ripple, which indicates that the torque is controlled precisely. This is an essential characteristic for ensuring that electric car applications continue to function smoothly. The stator currents of the three-phase motor are shown in Figure 4(c), and they are balanced and sinusoidal. This demonstrates that the inverter is capable of delivering current waveforms of high quality. The results of the simulation show that the proposed control strategy is effective for controlling current as well as smooth speed and torque management. As a consequence, it is suited for electric vehicle drives that are based on PMSM technology.

A 5-phase induction motor's simulation results, including motor speed (rad/s and rpm) and torque values and stator currents, are shown in Figure 5. These results have been obtained using the paper outlines a control technique designed to maximize performance in five-phase induction motors. The simulation results provide a deeper understanding of the motor's behavior across different operating scenarios, informing design and control parameter optimization. Key metrics like motor speed and torque profile reveal the motor's dynamic response and load-handling capabilities, while stator current waveforms indicate efficiency and load operation.

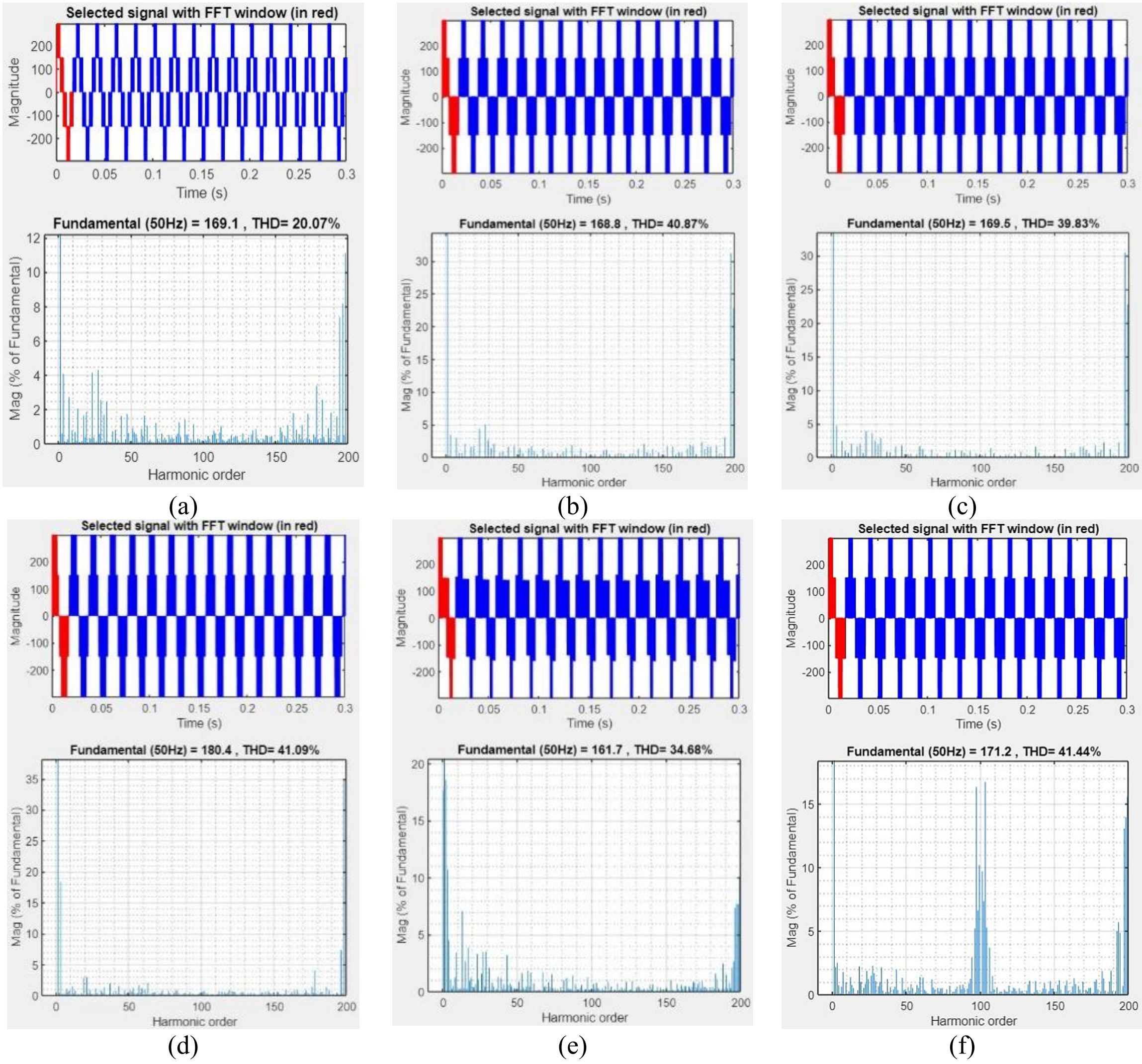

Figure 3. Voltage THD and line voltage results for (a) PD, (b) POD, (c) APOD, (d) IC, (e) PSC, and (f) VFC PWM approach

Figure 5 presents the simulation results of the 5-phase induction motor fed by the proposed inverter system, including speed response, torque characteristics, and stator current waveforms. This figure is crucial for evaluating the suitability of the proposed PWM strategy for EV traction applications. The torque and stator current responses are shown in Figure 5, demonstrating the effectiveness of the proposed PWM strategy in improving the 5-phase induction motor performance. The electromagnetic torque exhibits reduced ripple and faster settling time, indicating improved dynamic stability and smoother operation under load. The stator current waveforms are balanced and nearly sinusoidal, confirming reduced harmonic injection from the inverter. These characteristics directly contribute to lower copper losses, reduced thermal stress, and enhanced reliability of the motor drive, which are critical requirements for electric vehicle propulsion systems.

The results are shown in Figure 5, show how effectively the suggested control method works when controlling the speed and torque of a five-phase induction motor. With minimum torque and speed changes, the motor may function smoothly and efficiently, which is crucial for numerous industrial and renewable energy applications, according to the results obtained. All things considered, the findings offer insightful information about how well a five-phase induction motor performs, allowing us to enhance its design and control parameters for use in electric vehicles.

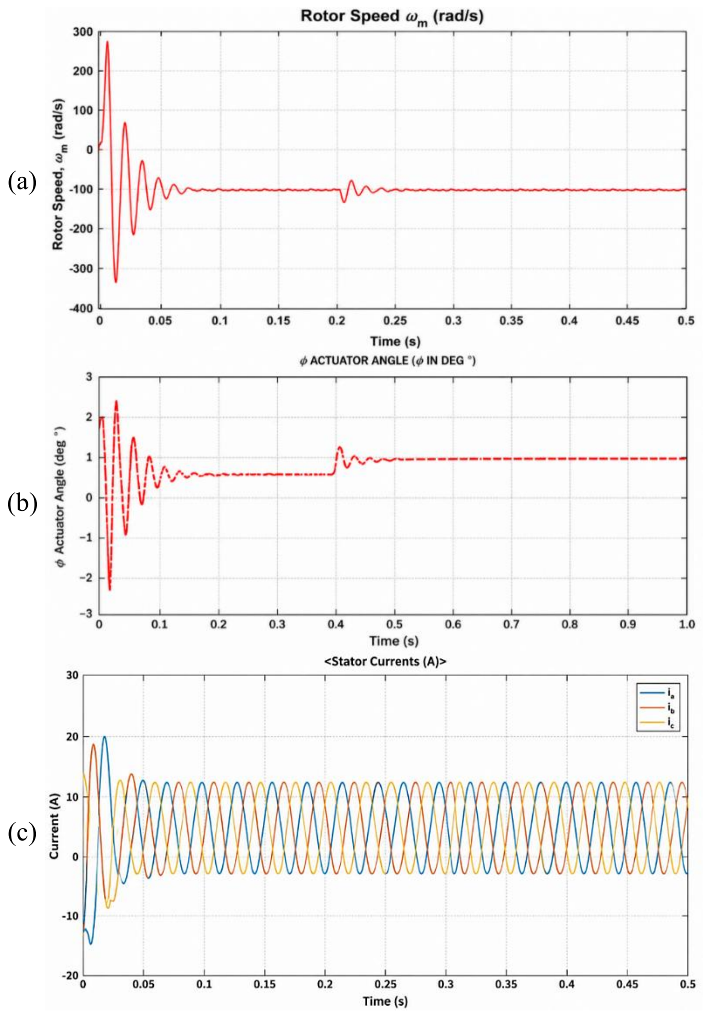

Figure 4. Simulation results three-phase permanent magnet synchronous motor: (a) speed in rad/s, (b) torque, and (c) stator currents

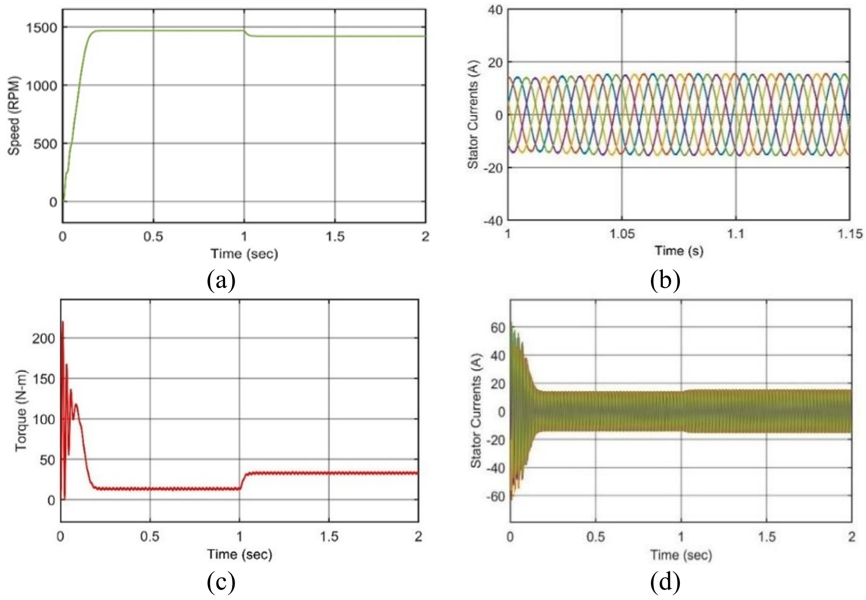

Figure 5. Simulation results, five phase induction motor: (a) speed in rad/s, (b) zoomed stator currents, (c) torque, and (d) stator currents

In Table 2, the values of the numerous parameters that are utilized in the process of simulating an electric machine are presented. These parameters include the base frequency, the number of poles, the moment of inertia, the friction factor, the rotor and stator resistance, the rotor and stator inductance, and the magnetizing inductance. Experimental or theoretical analysis is often used to identify these characteristics, which are essential for modeling and simulating the electrical, mechanical, and magnetic properties of the machine. These parameters are typically determined through the use of experiments. The values are subject to change based on the particular design of the machine and the application it is used for.

Table 2. Parameters used for simulation

Parameter	Value
Rotor resistance (R_r)	0.6
Stator resistance (R_s)	0.8
Rotor inductance (L_{Ir})	0.0026
Stator inductance (L_{Is})	0.0026
Magnetizing inductance (L_m)	0.151
Base frequency (f_b)	100
Number of poles (P)	4
Moment of inertia (J)	0.047

4. CONCLUSION

A performance study of a five-phase, three-level NPC inverter was provided in this work. The test was conducted for EV applications and utilized a variety of multi-carrier PWM approaches. The results of the simulation showed that the PD PWM method achieved the lowest THD of all the techniques, which made it the most effective method for increasing the quality of the output waveform. In further research, a comparison was made between the performance of a five-phase induction motor and a three-phase PMSM when they were used as loads. A maximum torque of 32.33 N-m and a speed of 277.7 rad/s, 1452 rpm were both demonstrated by the five-phase induction motor, which also exhibited balanced stator currents and improved transient response. These are only some of the dynamic properties that the motor exhibited. To summarize, the combination of the PD-PWM approach with a five-phase multilevel inverter and an induction motor provides an EV drive system that is both reliable and environmentally friendly. To improve the overall performance of the system, future work will concentrate on the installation of closed-loop control and advanced modulation methods such as space vector PWM.

FUNDING INFORMATION

The authors state no funding is involved.

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
Venu Yarlagadda	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
N. Kavitha			✓	✓	✓	✓			✓	✓	✓		✓	✓
Chava Sunil Kumar		✓						✓	✓	✓	✓	✓		
G. Naveen	✓	✓	✓			✓	✓	✓	✓	✓		✓		✓
Swetha Mareddy	✓			✓			✓		✓	✓		✓		
S. Venkata Rami Reddy	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓		✓
K. V. Govardhan Rao	✓	✓		✓		✓	✓		✓		✓		✓	✓

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

The authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

REFERENCES

[1] V. Jayakumar, B. Chokkalingam, and J. L. Munda, "Performance analysis of multi-carrier PWM and space vector modulation techniques for five-phase three-level neutral point clamped inverter," *IEEE Access*, vol. 10, pp. 34883–34906, 2022, doi: 10.1109/ACCESS.2022.3162616.

[2] J. Rodríguez, J. S. Lai, and F. Z. Peng, "Multilevel inverters: a survey of topologies, controls, and applications," *IEEE Transactions on Industrial Electronics*, vol. 49, no. 4, pp. 724–738, 2002, doi: 10.1109/TIE.2002.801052.

[3] A. A. Theresa and S. Malathi, "A multilevel inverter with streamlined components and reduced THD using the multiearrier sine pwm approach for resistive and inductive loads," in *2025 4th International Conference on Power, Control and Computing Technologies, ICPC2T 2025*, 2025, pp. 1–6, doi: 10.1109/ICPC2T63847.2025.10958668.

[4] H. Park, "ANN controller based single phase inverter in smart city," *International Transactions on Electrical Engineering and Computer Science*, vol. 2, no. 2, pp. 60–69, 2023, doi: 10.62760/iteecs.2.2.2023.51.

[5] K. V. G. Rao *et al.*, "Microgrid with, vehicle-to-grid and grid-to-vehicle technology for DC fast charging topology," in *Renewable Energy for Plug-In Electric Vehicles: Challenges, Approaches, and Solutions for Grid Integration*, 2024, pp. 45–57, doi: 10.1016/B978-0-443-28955-2.00004-4.

[6] M. Ye, L. Chen, L. Kang, S. Li, J. Zhang, and H. Wu, "Hybrid multi-carrier PWM technique based on carrier reconstruction for cascaded H-bridge inverter," *IEEE Access*, vol. 7, pp. 53152–53162, 2019, doi: 10.1109/ACCESS.2019.2912216.

[7] B. Chokkalingham, S. Padmanaban, and F. Blaabjerg, "Investigation and comparative analysis of advanced PWM techniques for three-phase three-level NPC-MLI drives," *Electric Power Components and Systems*, vol. 46, no. 3, pp. 258–269, 2018, doi: 10.1080/15325008.2018.1445142.

[8] D. V. Krishna, M. S. Kalavathi, and B. Ganeshbabu, "A novel NR-DA-based ANN for shepwm in cascaded multilevel inverters for renewable energy applications," *International Transactions on Electrical Engineering and Computer Science*, vol. 3, no. 3, pp. 135–143, 2024, doi: 10.62760/iteecs.3.3.2024.97.

[9] F. Guo *et al.*, "ANN-aided virtual-space-vector PWM strategy for three-level NPC inverter using sextant-coordinate mapping for heavy-duty EV applications," in *2024 IEEE Transportation Electrification Conference and Expo, ITEC 2024*, 2024, pp. 1–4, doi: 10.1109/ITEC60657.2024.10598953.

[10] M. A. Inayathullaah and R. Anita, "Simulation of five-phase voltage source inverter with different excitation for star connected load," *International Journal of Engineering and Technology*, vol. 6, no. 3, pp. 1573–1580, Dec. 2014.

[11] K. V. G. Rao *et al.*, "IOT-powered crop shield system for surveillance and auto transversum," in *2023 IEEE 3rd International Conference on Sustainable Energy and Future Electric Transportation, SeFet 2023*, 2023, pp. 1–6, doi: 10.1109/SeFeT57834.2023.10245773.

[12] L. Masisi, "Comparison between a three and two level inverter variable flux machine drives for traction applications," in *Proceedings - 2019 Southern African Universities Power Engineering Conference/Robotics and Mechatronics/Pattern Recognition Association of South Africa, SAUPEC/RobMech/PRASA 2019*, 2019, pp. 599–604, doi: 10.1109/RoboMech.2019.8704751.

[13] S. Payami, R. K. Behera, and A. Iqbal, "DTC of three-level NPC inverter fed five-phase induction motor drive with novel neutral point voltage balancing scheme," *IEEE Transactions on Power Electronics*, vol. 33, no. 2, pp. 1487–1500, 2018, doi: 10.1109/TPEL.2017.2675621.

[14] E. Levi, "Multiphase electric machines for variable-speed applications," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 5, pp. 1893–1909, 2008, doi: 10.1109/TIE.2008.918488.

[15] K. V. G. Rao and T. V. S. Kalyani, "An improved bidirectional DC / DC converter with split battery configuration for electric vehicle battery charging/discharging," *Aut Aut Research Journal*, vol. XII, no. 34, pp. 34–39, 2021.

[16] S. Mukherjee, S. Kumar Giri, S. Kundu, and S. Banerjee, "A generalized discontinuous PWM scheme for three-level NPC traction inverter with minimum switching loss for electric vehicles," *IEEE Transactions on Industry Applications*, vol. 55, no. 1, pp. 516–528, Jan. 2019, doi: 10.1109/TIA.2018.2866565.

[17] L. Sejpal, L. A. C. Lopes, M. Amar, and S. S. Williamson, "Neutral-point voltage balancing of three-level EV traction inverter using modified carrier-based SVM and THD comparison with a two-level inverter," in *2013 IEEE Transportation Electrification Conference and Expo (ITEC)*, IEEE, Jun. 2013, pp. 1–7, doi: 10.1109/ITEC.2013.6573490.

[18] J. Vinoth, C. Bharatiraja, P. Sanjeevikumar, and Z. Leonowicz, "A new five-phase three-level neutral point clamped inverter for two independent loads," in *2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*, IEEE, Sep. 2021, pp. 1–6, doi: 10.1109/EEEIC/ICPSEurope51590.2021.9584688.

[29] K. V. G. Rao and M. K. Kumar, "A literature review on reduction of harmonics using active power filter," in *AIP Conference Proceedings*, 2024, p. 020083, doi: 10.1063/5.0112028.

[20] R. Tejavathu, T. Bukkana, I. Tangirala, and D. K. Poondla, "DTC-SPWM-based realization of SVM with reduced carrier for three-level NPC fed five phase permanent magnet synchronous motor drive," in *2023 IEEE IAS Global Conference on Emerging Technologies (GlobConET)*, IEEE, May 2023, pp. 1–6, doi: 10.1109/GlobConET56651.2023.10149920.

[21] B. Chikondra, U. R. Muduli, and R. K. Behera, "Open-phase fault-tolerant direct torque control for five-phase three-level NPC VSI fed induction motor drive," in *2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, IEEE, Dec. 2020, pp. 1–6, doi: 10.1109/PEDES49360.2020.9379786.

[22] B. Chikondra, U. R. Muduli, and R. K. Behera, "Performance comparison of five-phase three-level NPC to five-phase two-level VSI," *IEEE Transactions on Industry Applications*, vol. 56, no. 4, pp. 3767–3775, 2020, doi: 10.1109/TIA.2020.2988014.

[23] C. Medina *et al.*, "Minimising torque ripple and harmonic distortion in open-circuit five-phase induction motors fed by NPC inverters using predictive current control," in *2025 IEEE/AIAA Transportation Electrification Conference and Electric Aircraft Technologies Symposium (ITEC+EATS)*, IEEE, Jun. 2025, pp. 1–6, doi: 10.1109/ITEC63604.2025.11098021.

[24] Y. Kumar, M. Goyal, and R. Mishra, "Modified PV-based hybrid multilevel inverters using multicarrier PWM strategy," in *Proceedings of the 4th International Conference on Electronics, Communication and Aerospace Technology, ICECA 2020*, IEEE, Nov. 2020, pp. 460–464, doi: 10.1109/ICECA49313.2020.9297450.

[25] L. Vancini, M. Mengonic, G. Rizzoli, L. Zarri, and A. Tani, “Impact of open-switch fault in five-phase three-level NPC inverters,” in *2024 IEEE Energy Conversion Congress and Exposition, ECCE 2024 - Proceedings*, IEEE, Oct. 2024, pp. 6523–6529, doi: 10.1109/ECCE55643.2024.10861807.

[26] P. S. Jamwal, S. Singh, and S. Jain, “Three-level inverters for induction motor driven electric vehicles,” *3rd International Conference on Energy, Power and Environment: Towards Clean Energy Technologies, ICEPE 2020*, 2021, doi: 10.1109/ICEPE50861.2021.9404444.

[27] L. Emil, B. Radu, P. F. Profumo, H.A. Toliyat and S. Williamson, “Multiphase induction motor drives-a technology status review,” *IET Electric Power Applications*, vol. 1, no. 5, pp. 643–656, 2007, doi: 10.1049/iet-epa.

[28] D. Dwivedi, I. Roy, and K. A. Chinmaya, “Investigation of three-level dual output t-type NPC for EV application,” in *SEST 2022 - 5th International Conference on Smart Energy Systems and Technologies*, IEEE, Sep. 2022, pp. 1–6, doi: 10.1109/SEST53650.2022.9898482.

[29] A. Bhowate, M. V. Aware, and S. Sharma, “Predictive torque control of five-phase induction motor drive using successive cost functions for CMV elimination,” *IEEE Transactions on Power Electronics*, vol. 36, no. 12, pp. 14133–14141, Dec. 2021, doi: 10.1109/TPEL.2021.3089741.

[30] M. G. Simões and P. Vieira, “A high-torque low-speed multiphase brushless machine - a perspective application for electric vehicles,” *IEEE Transactions on Industrial Electronics*, vol. 49, no. 5, pp. 1154–1164, Oct. 2002, doi: 10.1109/TIE.2002.803241.

BIOGRAPHIES OF AUTHORS

Venu Yarlagadda is currently working as a professor in the Department of Electrical and Electronics Engineering with over 25 years of teaching experience in VNR Vignana Jyothi Institute of Engineering and Technology, Hyderabad, India. He obtained his B.Tech. in electrical and electronics engineering, M.Tech. in electrical power engineering, and Ph.D. from Jawaharlal Nehru Technological University, Hyderabad. He has published more than 35 research papers in reputed journals and conferences. Published four patents and one patent was granted. He authored seven textbooks. His research contributions focus on enhancing voltage stability, FACTS, system reliability, power quality using advanced control, and optimization techniques. He can be contacted at email: venu_y@vnrvjiet.in.

N. Kavitha received the B.Tech. degree in electronics and communication engineering from Guru Nanak Engineering College, JNTU Hyderabad, the M.Tech. systems and signal processing from JNT University Hyderabad, Telangana, India in 2015, and is pursuing Ph.D. in JNTU Hyderabad. She has 16 years of teaching experience. She has been working as an assistant professor in ECE Department of MVSREC(A) since 2008. Her research interests are in signal processing and image processing. She can be contacted at email: nkavitha_ece@mvsrec.edu.in.

Chava Sunil Kumar received B.Tech. degree in electrical and electronics engineering in the year 2000 and M Tech degree in electrical power engineering in the year 2006 from JNTU College of Engineering, Kukatpally, Hyderabad, AP, India, and Ph.D. from JNTUH University, Hyderabad, TS, India, in 2013. He has 22 years of teaching experience. Presently working as professor in the Department of Electrical and Electronics Engineering at BVRIT HYDERABAD College of Engineering for Women, Hyderabad, Telangana, India since 2013. He has published total 50 research papers in international journals, conferences, book chapters, and national conference papers. His area of interest includes electrical power systems, power electronics, and electrical machines. He is a life member of Indian Society for Technical Education (ISTE). He can be contacted at email: ursunil25@gmail.com.

G. Naveen is working as an assistant professor in the Department of Electrical and Electronics Engineering, Narasaraopeta Engineering College (Autonomous), and has about 12 years of teaching experience. He received his B.Tech. degree in electrical and electronics engineering from JNTUK Kakinada and M.Tech. degree in power electronics and drives from JNTUK Kakinada, Andhra Pradesh. He is a life member of the Indian Society for Technical Education (ISTE). He has published 2 Scopus-indexed journals, 17 papers in refereed international journals, and 6 papers in the proceedings of various international conferences. He can be contacted at email: gubbanaveen231@gmail.com.

Swetha Mareddy received M.Tech. in electrical and electronics engineering from Saint Mary's College of Engineering and Technology, Hyderabad (Affiliated to Jawaharlal Nehru Technological University – Hyderabad) and is pursuing Ph.D. in JNTU Anantapur, Anantapuramu-515002 since 2023. She has 7 years of teaching experience. She has been working as an assistant professor in EEE Department of Annamacharya University, Rajampet, YSR Kadapa Dist since 2023. Her research interests are in power systems - microgrid. She can be contacted at email: danvikreddy012@gmail.com.

S. Venkata Rami Reddy received his B.Tech. degree in the Department of Electrical and Electronics Engineering from KSRM College of Engineering, Kadapa, Andhra Pradesh, India, in 2007. He procured his M.Tech. degree in the Department of Electrical and Electronics Engineering, specialized in electrical power systems from SITS College of Engineering, Kadapa, Andhra Pradesh, India in 2015. He was awarded his Ph.D. degree from Vels Institute of Science Technology and Advanced Studies, Chennai, Tamil Nadu, India, in 2025. He is currently working as an assistant professor in the Department of Electrical and Electronics Engineering at Jawaharlal Nehru Technological University Anantapur College of Engineering (Autonomous), Pulivendula, Kadapa, Andhra Pradesh, India. He has 10 years of teaching experience and two years of industrial work experience. His research interest is in renewable energy system, power system study, distributed generation, and microgrid. He has published around 20 papers in UGC, Scopus and SCI. He has got 4 Indian patents published. He is a member of the Institution of Engineers, India (IEI). He can be contacted at email: svrami@gmail.com.

K. V. Govardhan Rao is currently working as an assistant professor in the Electrical and Electronics Engineering Department, St. Martin's Engineering College, Dhulapally, Secunderabad, Telangana. He is pursuing a postdoctoral fellowship at SR University, Warangal, Telangana, India. He holds a Ph.D. degree from Koneru Lakshmaiah Educational Foundation (KL Deemed to be University), Vijayawada Campus. He completed his M.Tech. and B.Tech. at Abdul Kalam Institute of Technological Sciences, Vepalagadda, Kothagudem, affiliated to JNTU Hyderabad. He has more than 12 years of teaching experience. He published over 40 papers in various reputed journals, attended 10 conferences with ISBN number along with 04 best paper awards, and published 06 Indian patents. He guides 05 M.Tech. students and 18 B.Tech. students. He is also a life member of the Indian Society for Technical Education and the Indian Association for Engineers. His areas of research include power electronics, power systems, converters, and electric vehicles. He can be contacted at email: kv.govardhanrao@gmail.com.