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Multi-phase Multi-level inverter for EV Application

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KEYWORDS

5-phase multilevel inverter, MCPWM, 5-phase induction motor, Permanent magnet synchronous motor, Neutral point clamped inverter, and THD.

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 NPC inverter using various 'multi-carrier 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 THD, load voltage, and load current is compared using R, RL loads connected to a multilevel inverter. Additionally, '5-phase induction motor and Permanent Magnet Synchronous Motor (PMSM) models' are developed as loads for electric vehicle (EV) 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.

ABBREVIATION

3L	3Level.
APOD PWM	Alternate Phase Opposition and Disposition PWM.
MCPWM	Multi-carrier Pulse Width PWM.
MLI	Multi-Level Inverter.
PDPWM	Phase Disposition PWM.
PODPWM	Phase Opposition and Disposition PWM.
MCPWM	Multi-carrier Pulse Width PWM.
THD	Total Harmonic Distortion.

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 (PWM)' 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 IC (interleaved carriers), PSC (phase shifting carriers), VFC (variable frequency carriers), and APOD (alternative phase-opposition disposition), 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 Neutral Point Clamped (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 [8]. 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 [9]. Additionally utilized in EV applications, 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. With five stator windings and three voltage levels, the 5-phase three-level induction motor is a type of multi-phase motor that is perfect for demanding applications requiring excellent reliability. Over the past 20 years, multiphase motor drives have become more and more widespread. They are especially useful in traction (including electric and hybrid cars), electric ship propulsion, and aircraft [10]. Improved torque-speed characteristics, lower harmonic current, and reduce 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 [11].

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 & 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.

2. MULTIPHASE-MULTILEVEL INVERTER

A. BLOCK DIAGRAM

Fig. 1. depicts the structure of the 3-level, 5-phase inverter. It features 5 legs, with four switches on each leg that can only be used in two complementing combination pairs.

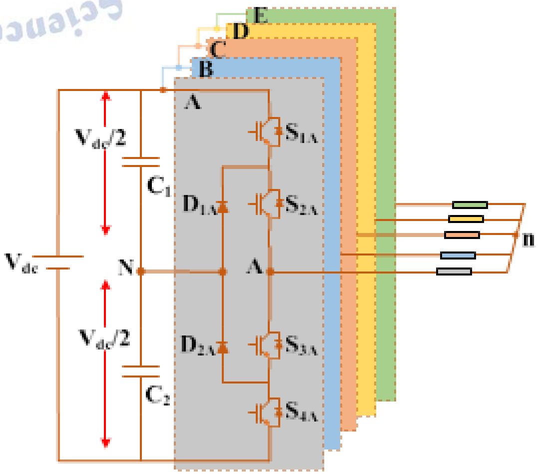


Fig. 1. 3L NPC inverter for a load with five phases.

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.

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

B. 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, electric car charging, and renewable energy systems that need a steady and smooth output voltage waveform. 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’.

A. 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. A certain formula can be used to quantitatively represent the ratio of frequency and index of modulation.

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

$$M_f = \frac{f_c}{.f_m} \quad (2)$$

Where M_a provides a way to quantify the level of modulation and the relationship between the modulating and carrier frequencies. The carrier and modulating signal frequencies are indicated by the parameters fc and fm, and their corresponding amplitudes are indicated by Ac and Am. Fig. 2(a) shows the waveforms of these signals using the Phase PD PWM approach.

B. 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. 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 Fig. 2(b)

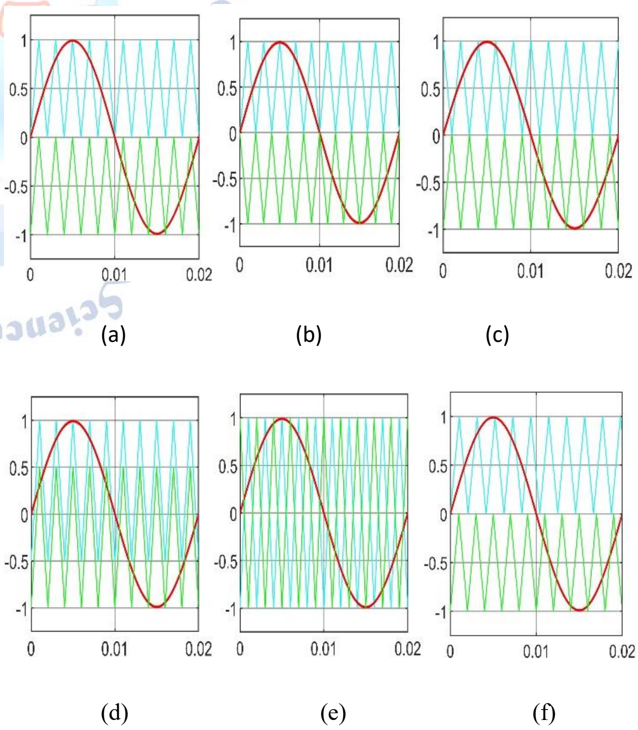


FIGURE2. 3L NPC inverter reference and carrier signal configuration for (a)PD, (b)POD, (c)APOD, (d)IC, (e)PSC, and (f)VFC PWM approaches

C. 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. Fig. 2(c) depicts the APOD PWM carrier and modulating signals. With this method, the voltage stress is somewhat decreased. For 3L inverters, POD and APOD approaches will yield comparable findings; however, for higher-level inverters, they will yield different outcomes. POD and APOD produce different results if the level is greater than three, with the APOD approach offering superior THD results.

D. CARRIER INTERLEAVING PWM:

In ICPWM, all Carrier signals have uniform frequency and amplitude. They will, however, overlap one another in some areas, there will be overlap between the higher and lower carrier signals. This method will lower THD and increase output voltage. Upper and lower carriers will be used to create the positive and negative levels. Figure 2(d) illustrates the arrangement of carrier and reference signals for the 3-level In-Phase Carrier (IPC) PWM method.

E. CARRIER PHASE SHIFT PWM:

In the Phase-Shifting Carrier (PSC) PWM technique, multiple carrier signals with identical frequency and amplitude are phase-shifted relative to each other, generating a stepped output waveform. The number of carriers dictates the phase shift amount, as seen in the 3-level PSC PWM configuration in Fig. 2(e).

F. VARIABLE CARRIER FREQUENCY PWM:

The Variable Carrier frequency (VFC) PWM technique utilizes carriers with diverse frequencies, where each carrier operates at a distinct frequency. The carrier and reference signal setup for 3-level VFC PWM is illustrated in Fig. 2(f), with carriers above the zero-axis corresponding to positive output levels and those below corresponding to negative levels.

For each switching device, the gate pulse is generated by comparing a high-frequency Carrier signal compared to a reference signal. When the reference signal exceeds the carrier signal in amplitude, the resulting pulse width is wider, whereas a lower reference signal amplitude yields narrower pulses. 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 greater and deactivates the device when the PWM signal is low.

3. FIVE-PHASE INDUCTION MOTOR FOR EV APPLICATION

Multi-phase induction motors have been increasingly developed to enhance the performance of variable-speed electrical drives operated through inverters. When operating under full load conditions, a five-phase induction motor typically reaches its steady-state values within approximately 1 second, whereas a conventional three-phase induction motor may require up to 1.5 seconds. This improvement in dynamic response is particularly important in applications characterized by frequent load variations, as it influences both system stability and reliability. Moreover, the peak torque achievable by five-phase induction motors can be significantly higher potentially up to 67 times greater than that of comparable three-phase machines. Due to these advantages, five-phase induction motors are widely utilized in demanding fields such as Traction systems, wind turbines, hybrid and electric vehicles, marine propulsion, and industrial rolling mills.

A. THEORETICAL ANALYSIS

Analyzing transients requires modelling mathematical machinery in state space form. The stationary frame model is currently being employed widely, even though the rotating frame model is widely utilized. The model's parameters can be configured as fluxes, current, or a mix of the two. The following displays the state space equations that were derived for the motor model is represented in a rotating reference frame, with flux linkages as the state variables.

Five phase voltages

$$V_{as} = V_m sin(\omega_e t) \quad (1)$$

$$V_{bs} = V_m sin\left(\omega_e t - \frac{2\pi}{5}\right) \quad (2)$$

$$V_{cs} = V_m sin\left(\omega_e t - \frac{4\pi}{5}\right) \quad (3)$$

$$V_{ds} = V_m \sin\left(\omega_e t - \frac{6\pi}{5}\right) \quad (4)$$

$$V_{es} = V_m sin\left(\omega_e t - \frac{8\pi}{5}\right) \quad (5)$$

The formula for five-phase voltages is displayed in the expression above. Each phase voltage has a distinct phase shift, which is represented by subtracting various multiples of 2π/5 from the angle ωe multiplied by t. The voltages are computed using the amplitude of Vm and the sine of ωe multiplied by a certain time value.

The decoupling transformation matrix is given below

$$\begin{bmatrix} V_{ds}^{s} \\ V_{qs}^{s} \\ V_{xs}^{s} \\ V_{ys}^{s} \\ V_{0s}^{s} \end{bmatrix} = \frac{2}{5}\begin{bmatrix} 1 & cos\alpha & cos2\alpha & cos3\alpha & cos4\alpha \\ 0 & -sin\alpha & -sin2\alpha & -sin3\alpha & -sin4\alpha \\ 1 & cos3\alpha & cos6\alpha & cos9\alpha & cos12\alpha \\ 0 & -sin3\alpha & -sin6\alpha & -sin9\alpha & -sin12\alpha \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \end{bmatrix}\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{ds} \\ V_{es} \end{bmatrix} \quad (6)$$

The stator voltage and current equations are divided into two independent equations by the decoupling matrix: one for the quadrature axis (q) and one for the direct axis (d). Because the stator current and voltage in the direct axis are utilized to maintain the rotor magnetic field rather than to generate torque, this separation is required. The machine's mechanical dynamics result from the torque generated by stator currents and voltages in the quadrature axis. A decoupling matrix transforms stator voltages and currents from the stationary frame to the rotating frame, facilitating the computation of stator quantities in the rotating frame.

The behavior of the stator circuit in an electric machine, like a synchronous or induction motor, is described by mathematical formulas known as stator circuit equations. The machine's electrical performance is modeled and examined using these equations.

The equations for the stator are described as

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\emptyset_{qs} + \omega_e \emptyset_{ds} \quad (7)$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\emptyset_{ds} - \omega_e \emptyset_{qs} \quad (8)$$

The rotor circuit equations connect the rotor voltage and current to the rotor resistance, rotor flux, and the relative angular velocity between the rotor and the electrical field, as opposed to the stator circuit equations.

The rotor equations are similarly described as

$$V_{qr} = R_r i_{qr} + \frac{d}{dt}\emptyset_{qr} + (\omega_e - \omega_r)\emptyset_{dr} \quad (9)$$

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\emptyset_{dr} - (\omega_e - \omega_r)\emptyset_{qr} \quad (10)$$

The conversion method listed below is used to transform these stationary two-phase variables into five-phase variables.

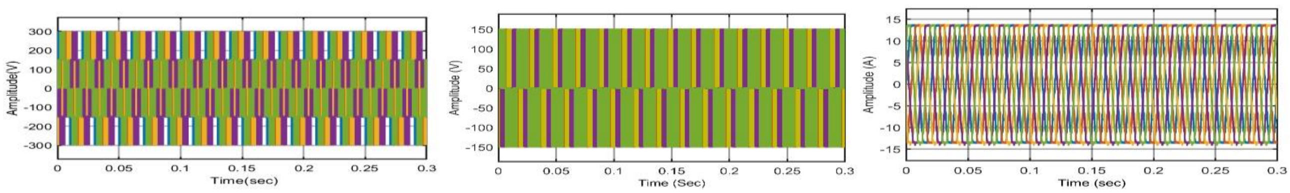
$$\begin{bmatrix} i_a \\ i_b \\ i_c \\ i_d \\ i_e \end{bmatrix} = \sqrt{\frac{2}{5}}\begin{bmatrix} 1 & 0 & 1 & 0 & 1 \\ cos\alpha & sin\alpha & cos2\alpha & sin2\alpha & 1 \\ cos2\alpha & sin2\alpha & cos4\alpha & sin4\alpha & 1 \\ cos3\alpha & sin3\alpha & cos6\alpha & sin6\alpha & 1 \\ cos4\alpha & sin4\alpha & sin8\alpha & sin8\alpha & 1 \end{bmatrix}\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{ds} \\ V_{es} \end{bmatrix} \quad (11)$$

The stator currents or voltages in the stationary (a, b) reference frame are typically used to represent the stationary two-phase variables of an electric machine, can be converted into a five-phase variable representation using the conversion approach previously demonstratedMore phases can help reduce the waveforms' harmonic content and improve machine performance in high-power situations, the five-phase variable representation is utilized to make machine analysis and control easier. The machine's electrical behavior, including torque generation and power flow, may be examined and managed using the resulting five-phase variables. The conversion technique facilitates the design and implementation of control algorithms that can benefit from the increased number of phases and simplifies the machine's mathematical analysis.

The PMSM model in MATLAB/Simulink typically employs d-q axis transformation in the rotor frame, assuming sinusoidal stator winding distribution. Voltage balance equations in the synchronous d-q frame form the basis of PMSM's governing equations.

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad (12)$$

$$V_q = R_s i_q + L_q \frac{di_d}{dt} - \omega_e (L_d i_d + \emptyset_m) \quad (13)$$



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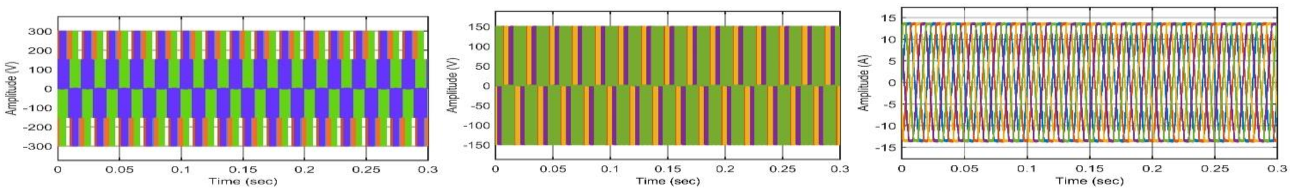

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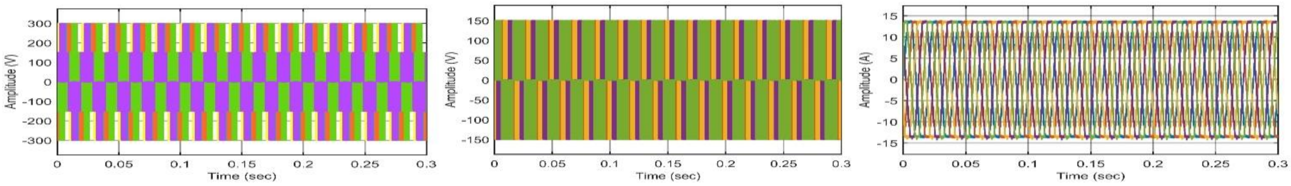

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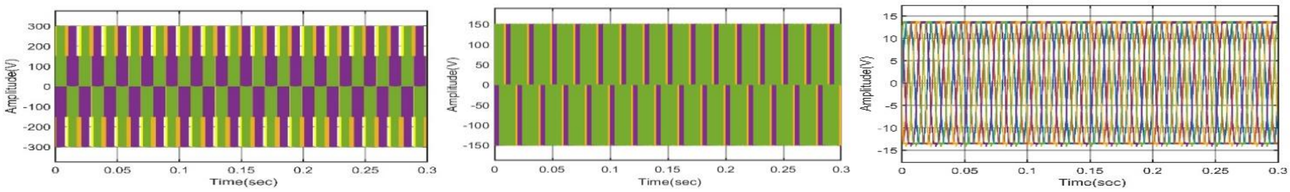

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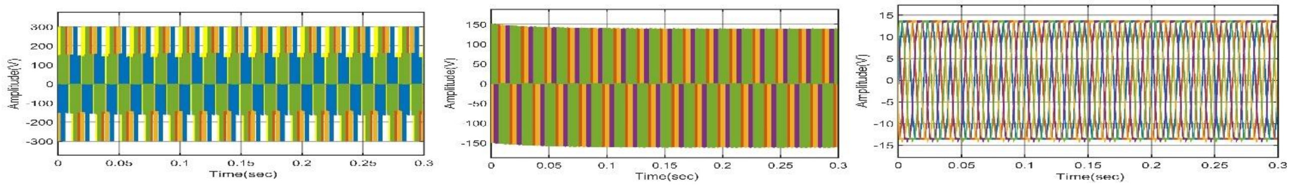

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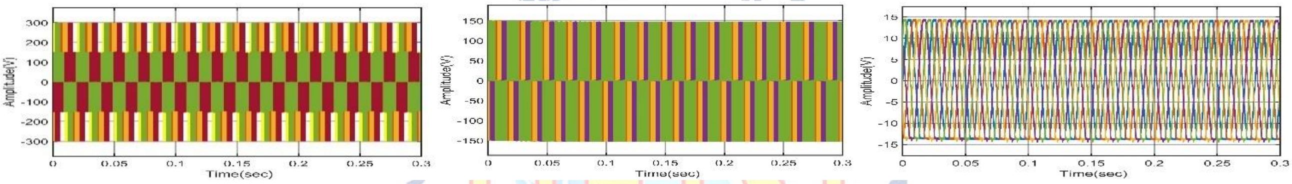


(f)

FIGURE3. Simulationresults– Five Line voltages, Five Phase voltages, Five Line currents for (a)PD, (b)POD, (c)APOD, (d)IC, (e)PSC, (f)VFC

4. SIMULATION ANALYSIS AND RESULTS

Utilizing MATLAB/Simulink, the software model of the 5-phase 3L NPC inverter has been examined utilizing a variety of MCPWM approaches. A 300V DC power source, supported by a 100µF capacitor, drives the system at a 10 kHz switching frequency. With R equal to 10Ω and L equal to 2mH, an RL load is considered. Figure 3 displays the simulation results for five-line voltages, five phase voltages, and five-line currents for the PD, POD, APOD, PSC, IC, and VFC techniques. The performance of each technique in terms of the generated waveforms and their properties has been assessed and compared using these data. The findings of the analysis and optimization of the 3L NPC inverter for various PWM techniques are presented in this work. These findings offer insightful information about the relative merits of various PWM strategies and can help choose the best approach for a particular use case. The success of the standard MCPWM approach, which makes use of sinusoidal reference signals, was demonstrated by the line voltages' symmetry over all five phases. However, because of the RL load that was utilized for the simulation, the line currents were found to have a sinusoidal shape, with each phase shifting by 72 degrees. It's interesting to note that the line currents remained constant at 15A for all PWM technique types, demonstrating the system's resilience.

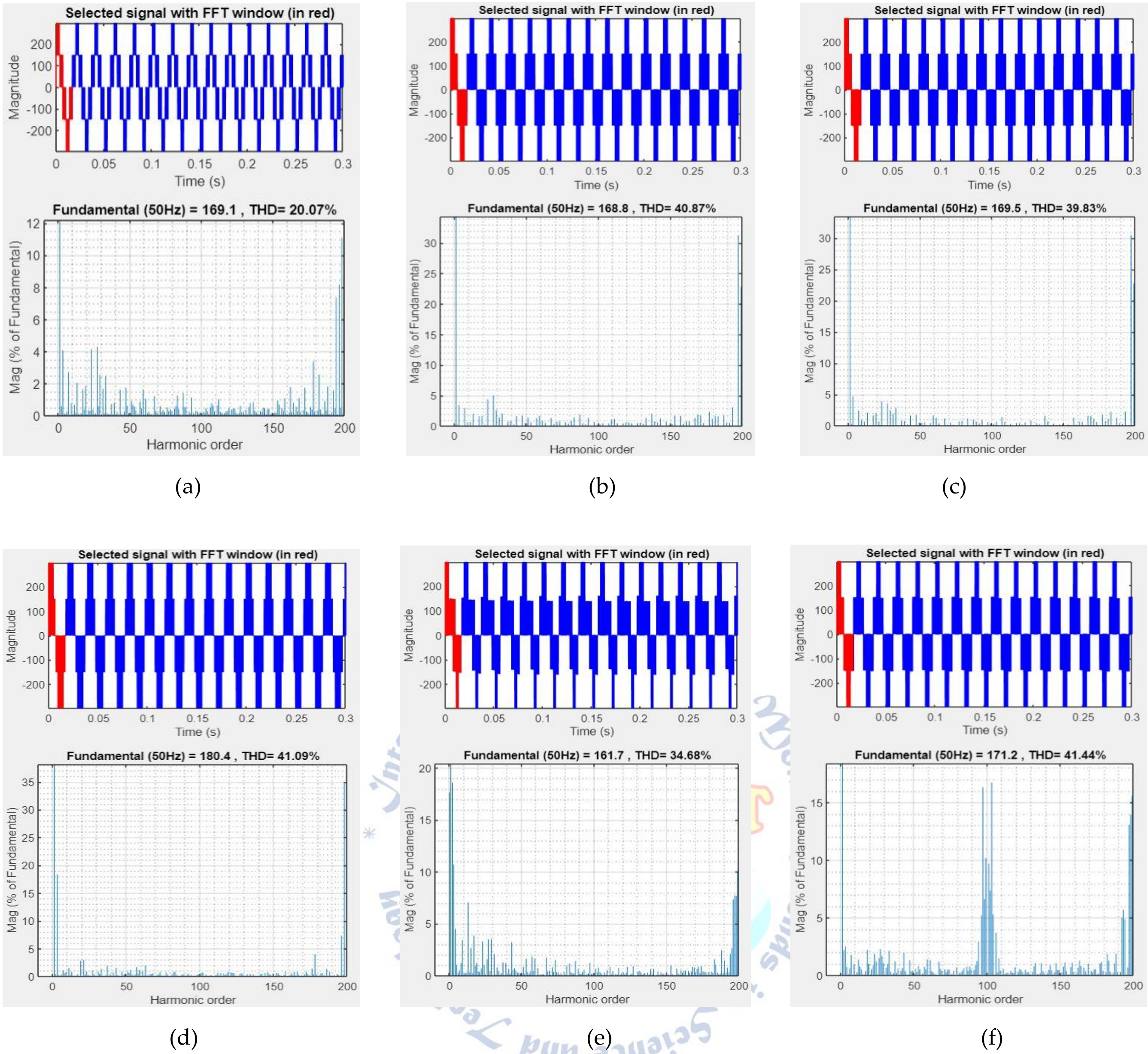


FIGURE4. Voltage THD and line voltage results for PD, POD, APOD, IC, PSC, and VFC techniques.

The line voltage waveforms and associated voltage THD for different multi-carrier PWM approaches applied to a '5-phase, 3-level NPC inverter' are shown in Figure 4. A comparatively smooth and symmetrical line voltage waveform with a fundamental voltage magnitude of approximately 170 V is shown in Figure 4(a) using the Phase Disposition (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 Phase Opposition Disposition (POD) PWM approach, on the other hand, shows results in Figure 4(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 4(c). The Interleaved Carrier PWM technique, shown in Figure 4(d), has overlapping carrier signals that somewhat lower harmonic content, although the THD is still more than the PD. Figure 4(e) and Figure 4(f) illustrate the Phase Shifting Carrier (PSC) and Variable Frequency Carrier (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 compared 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 electric vehicle (EV) applications.

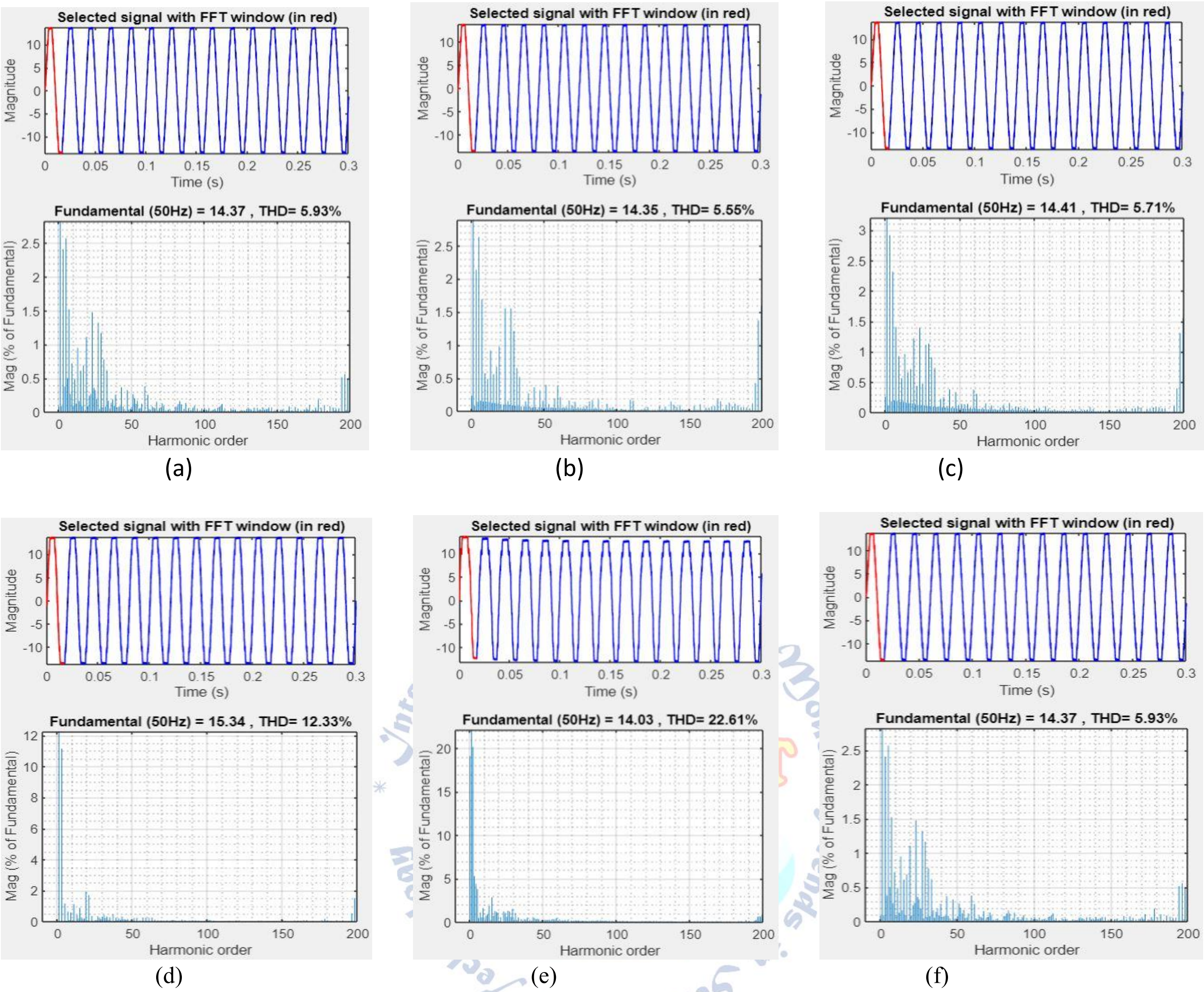
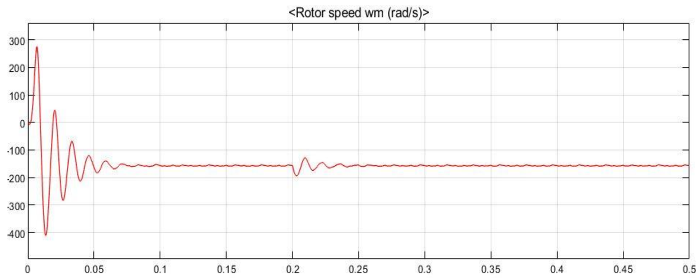
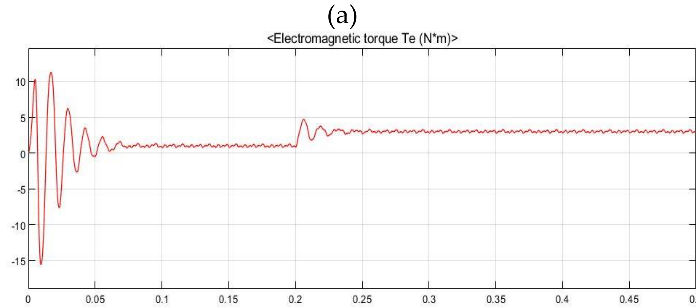


FIGURE5. Current THD and FFT analysis results for PD, POD, APOD, IC, PSC, and VFC PWM techniques

.Figure 5 presents the FFT and THD analysis results for the line current under different PWM methods applied to a 'Five-phase NPC three-level inverter'. With a clearly defined fundamental frequency component and considerably lower harmonic components, the Phase Disposition (PD) PWM technique shows the best results in Figure 5(a), resulting in the lowest current THD of all the techniques. This attests to PD PWM's ability to produce clear, sinusoidal current waveforms under RL loading circumstances. The POD PWM method is shown in Figure 5(b), exhibits a more distorted current spectrum with greater harmonic peaks and a noticeable rise in THD. This results from POD's carrier phase-shifting technique, which increases harmonic interference. Comparable to POD, Figure 5(c), which represents the Alternative Phase Opposition Disposition (APOD) PWM, shows a harmonic profile that is marginally less distorted but still significantly larger than that of PD. The Interleaved Carrier (IC) PWM approach produces an intermediate THD value in Figure 5(d) due to moderately dispersed harmonics. The FFT findings for the Phase Shifting Carrier (PSC) and Variable Frequency Carrier (VFC) approaches are shown in Figures 5(e) and 5(f). The phase- and frequency-variant carrier architectures of both methods result in large harmonic distributions, which raise the current THD in comparison to PD. The PD technique is the best PWM strategy for high-efficiency electric vehicle (EV) applications where low current distortion is essential for motor performance and thermal management.



(a)



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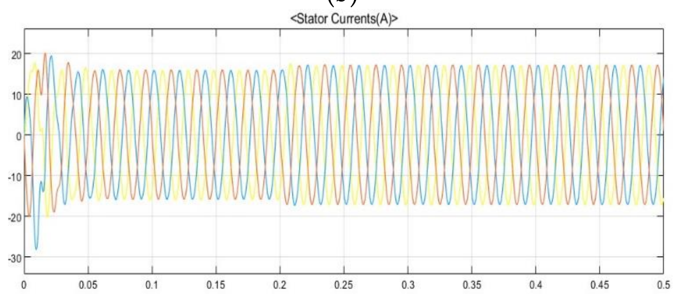


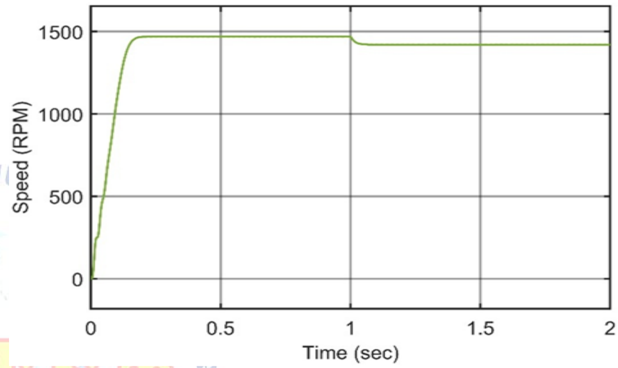
(c)

FIGURE6. Simulation results –'Three Phase permanent magnet synchronous motor'(a)Speed in rad/s,(b)Torque, (d) Stator Currents.

Figure 6 presents simulation results for a three-phase PMSM under the proposed control strategy, with motor speed in rad/s displayed in Figure 6(a). The speed profile shows a steady and smooth increase to the target steady-state value, indicating efficient dynamic performance and quick reaction. Figure 6(b) shows the electromagnetic torque generated by the motor, which remains relatively stable with minimal ripple, indicating precise torque control—an important feature for maintaining smooth operation in electric vehicle applications. Figure 6(c) displays the stator currents of the three-phase motor, which are balanced and sinusoidal, highlighting the inverter's ability to deliver high-quality current waveforms. Simulation results demonstrate the efficacy of the proposed control approach for regulating current as well as smooth speed and torque management, making it suitable for EV drives based on PMSM technology.

A five-phase induction motor's simulation results, including Motor speed (rad/s and rpm) and torque values and stator currents, are shown in Figure 7. 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.



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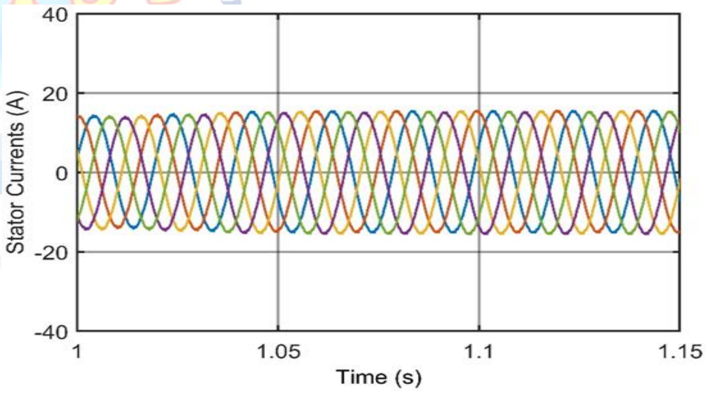

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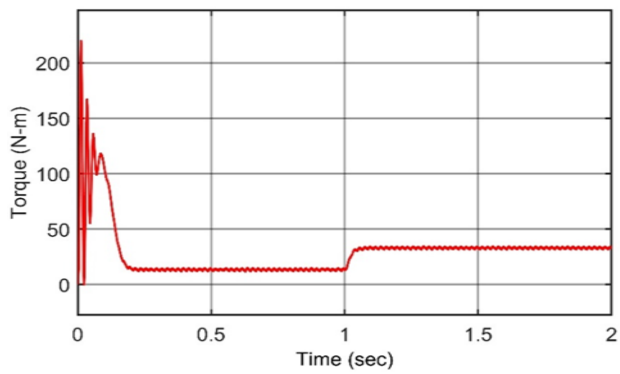

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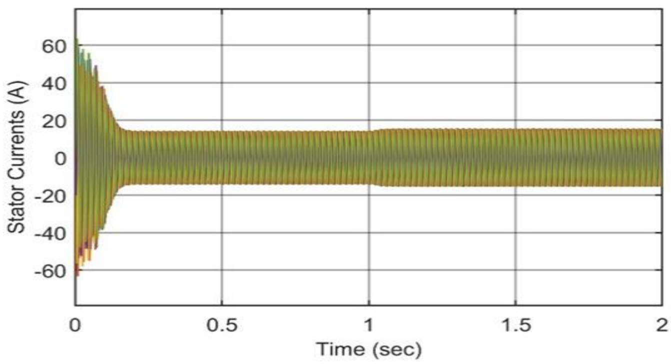

(d)

FIGURE7.Simulation results–Five Phase induction motor(a)Speed in rad/s, (b)Zoomed stator currents(c)Torque, (d) Stator Currents.

The results shown in Figure 7 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 shown in Figure 7 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.

TABLE 2. Parameters used for simulation

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

Table 2 provides the values of the various parameters used for simulating an electric machine comprising the base frequency, number of poles, moment of inertia, friction factor, rotor & stator resistance, rotor & stator inductance, and magnetizing inductance. These parameters are crucial for modeling and simulating the electrical, mechanical, and magnetic properties of the machine and are typically determined experimentally or through theoretical analysis. The values can vary depending on the specific design and application of the machine.

5. CONCLUSION

This paper presented a performance evaluation of a 'five-phase, three-level Neutral Point Clamped (NPC) inverter' using various multi-carrier PWM techniques for electric vehicle (EV) applications. Simulation results indicated that the 'Phase Disposition (PD) PWM method' achieved the lowest 'Total Harmonic Distortion (THD)' among all techniques, making it the most effective in improving output waveform quality.

Further analysis compared the performance of a 'five-phase induction motor' and a 'three-phase Permanent Magnet Synchronous Motor (PMSM)' as loads. The five-phase induction motor demonstrated superior dynamic characteristics, with a maximum torque of 32.33 N-m and speed of 277.7 rad/s (1452 rpm), along with balanced stator currents and better transient response.

Overall, the integration of the PD PWM technique with a five-phase multilevel inverter and induction motor offers a robust and efficient drive solution for EVs. Future work will focus on closed-loop control implementation and advanced modulation methods such as Space Vector PWM to enhance overall system performance.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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