

Integrated SPWM and LC Filter for Harmonic Reduction in Three-Phase UPS Inverters

Dang Aina binti Jasmin, Mazliza binti Abdul Halim, Muhammad Afiq Hazwan bin Azizan, Nor Adni binti Mat Leh and Nur Atharah binti Kamarzaman*

Abstract— This paper presents an approach to improving Total Harmonics Distortion (THD) in a three-phase uninterruptible power supply (UPS) inverter through the integration of a Sinusoidal Pulse Width Modulation (SPWM) control strategy and an output LC filter. Initially, a comparative analysis was conducted between conventional Pulse Width Modulation (PWM) and SPWM techniques to evaluate their impact on voltage and current THD. The findings revealed that while SPWM achieved lower THD levels than PWM, the resulting THD values still exceeded the compliance limits set by IEEE 519 standards. To address this issue, an LC filter was incorporated into the system alongside the SPWM technique. Simulation results from MATLAB R2024a Simulink demonstrated a significant reduction in current and voltage THD to 0.34% and 0.38% respectively, ensuring smooth sinusoidal waveforms within IEEE 519 standards. This study highlights the effectiveness of the integrated SPWM-LC filter approach in enhancing UPS inverter performance and reducing harmonic distortion. Moreover, it contributes to Sustainable Development Goal 9 by enhancing power quality and infrastructure resilience through innovative SPWM-LC filter integration to improve UPS inverter efficiency for sustainable industrial development.

Index Term— LC filter, sinusoidal pulse width modulation, three-phase inverter, total harmonic distortion, uninterruptible power supply

I. INTRODUCTION

An Uninterruptible Power Supply (UPS) is a crucial electrical device that safeguards critical equipment and systems by providing emergency power during main power source failures, preventing data loss, equipment damage, and downtime [1]. UPS systems utilize various technologies like batteries, flywheels, and power electronic components such as insulated gate bipolar transistors (IGBTs) to ensure a stable and uninterrupted power supply to sensitive loads in sectors like manufacturing, communication, and healthcare [2].

Fig. 1 illustrates the block diagram of the UPS system configuration. The UPS system consists of a rectifier, which converts AC power to DC power, charges the batteries, and supplies power to the inverter. The batteries store energy to be used during outages, ensuring continuous power to load via

the inverter. The inverter converts the DC power from the batteries back to AC power for the connected load, maintaining a stable power supply during disturbances. Additionally, the static switch ensures a seamless transition between mains power and battery power, preventing any disruptions in power supply to the load during disturbances [3].

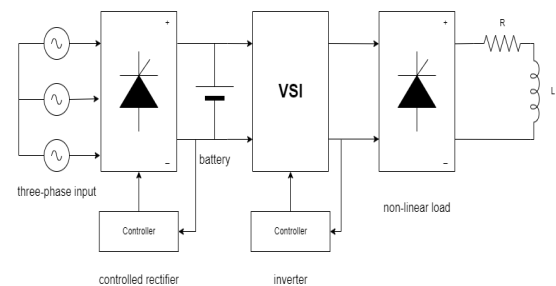


Fig. 1. Block diagram of the key components in the UPS system [4]

The inverter is one of the most critical components in a UPS system. A three-phase UPS inverter plays a critical role in ensuring uninterrupted power supply by converting DC to AC power for the load, significantly impacting power quality and system performance [5]. It is designed to generate high-quality voltage under different loads with fast dynamic response, high tracking accuracy, and robustness [6]. The UPS inverter ensures uninterrupted power supply by smoothly transitioning critical equipment, like oil pump motors, in case of power loss. This requires the inverter output to match the frequency and phase of the generator voltage [7]. In a UPS system, a Voltage Source Inverter (VSI) converts DC power from batteries into AC power to be supplied during power source failure.

Fig. 2 presents a schematic diagram of a three-phase Voltage Source Inverter (VSI). The switches (typically IGBTs or MOSFETs) are controlled using modulation techniques to generate a high-quality AC output with low Total Harmonic Distortion (THD). High THD in UPS inverters degrades power quality, distorts output voltages and increases system losses [9][10]. These issues are particularly severe in industrial settings, where power electronics and active rectifiers introduce high-order harmonics, which lead to significant voltage distortion in supply mains [11]. Consequently, conventional modulation techniques like Pulse Width Modulation (PWM) may fail to sufficiently reduce THD levels below acceptable limits as defined by IEEE 519 standards, with thresholds for harmonic distortion at 5% for low-voltage systems and 3% for high-voltage systems. Therefore, adopting effective modulation techniques is crucial to optimizing THD in three-phase UPS inverters [12].

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Dang Aina binti Jasmin, Nur Atharah binti Kamarzaman and Muhammad Afiq Hazwan bin Azizan are from Faculty of Electrical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.

Mazliza binti Abdul Halim and Nor Adni binti Mat Leh are from Faculty of Electrical Engineering, Universiti Teknologi MARA Cawangan Pulau Pinang, Permatang Pauh Campus, 13500 Seberang Prai, Pulau Pinang, Malaysia.

*Corresponding author
Email address: atharah8155@uitm.edu.my

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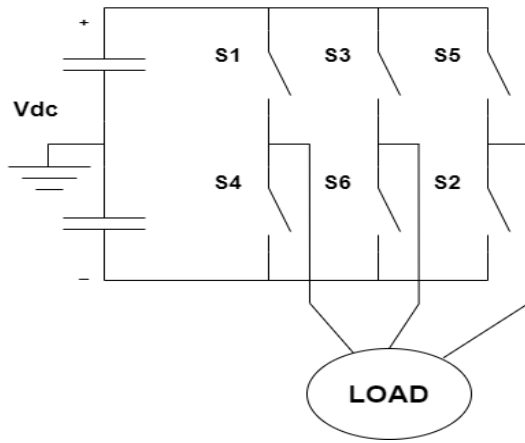


Fig. 2. Schematic diagram of three-phase Voltage Source Inverter (VSI) [8].

Several modulation techniques have been explored to optimize the performance of three-phase UPS inverters. Hysteresis Current Control (HCC) provides excellent dynamic response and robustness against parameter variations but results in variable switching frequencies, which complicates filter design and increases switching losses [13]. On the other hand, Selective Harmonic Elimination (SHE) effectively minimizes specific harmonics but requires complex calculations, making it unsuitable for real-time applications [14]. While these techniques provide advantages, challenges related to complexity, efficiency, and implementation are still presented.

Apart from that, Sinusoidal Pulse Width Modulation (SPWM) is widely used in Voltage Source Inverter (VSI) applications such as in adjustable speed motor control, UPS systems, and Photovoltaic (PV) systems [15]. SPWM is preferred over other techniques due to its ability to generate a high-quality sinusoidal output waveform, subsequently reducing harmonic distortion and enhancing system efficiency. Additionally, SPWM ensures high-quality power output, facilitating better grid integration and overall system efficiency [16]. These applications highlight SPWM's robustness and versatility in enhancing power quality in three-phase UPS inverters.

While SPWM improves output quality by reducing THD, integrating an LC filter at the inverter output further enhances performance. Composed of an inductor (L) and capacitor (C), the LC filter smoothens the output waveform, reduces high-frequency harmonics, and improves overall power quality [17]. Without this filter, voltage and THD levels would exceed IEEE 519 standards, resulting in unacceptable power quality. The integration of an LC filter ensures cleaner and more stable voltage delivery, which is critical for sensitive applications like medical devices and telecommunications [18]. Additionally, optimizing the filter structure and parameters will improve UPS efficiency and reduce system size and weight [19].

Therefore, this study aims to evaluate the effectiveness of integrating the SPWM technique and an output LC filter in three-phase UPS inverters to mitigate THD and improve power quality. Specifically, it seeks to assess how this integration enhances UPS performance in critical applications. The study focuses on the impact of SPWM and LC filter integration on THD reduction and power quality enhancement in three-phase UPS systems. It includes simulation-based analysis using MATLAB Simulink to validate the effectiveness of these techniques. However,

practical implementation and field-testing considerations are beyond the scope of this research.

The paper is organized as follows: Section II provides a detailed methodology outlining the simulation setup and parameters. Section III presents the results of THD reduction and waveform improvement achieved during the comparison of PWM and SPWM techniques and the integration of SPWM and an LC filter. Finally, Section IV discusses the findings, implications, and potential avenues for future research in enhancing UPS inverter performance.

II. METHODOLOGY

The methodology begins by evaluating the THD characteristics of PWM and SPWM techniques in a three-phase UPS inverter. Given its superior harmonic suppression capability, SPWM is selected for implementation. To further enhance power quality, an LC filter is integrated into the inverter output stage. The procedural workflow for comparing THD values between PWM and SPWM, along with the LC filter design and integration, is illustrated in Fig. 3.

The study employs MATLAB/ Simulink for modelling the three-phase inverter circuit. The simulation framework is structured into three stages.

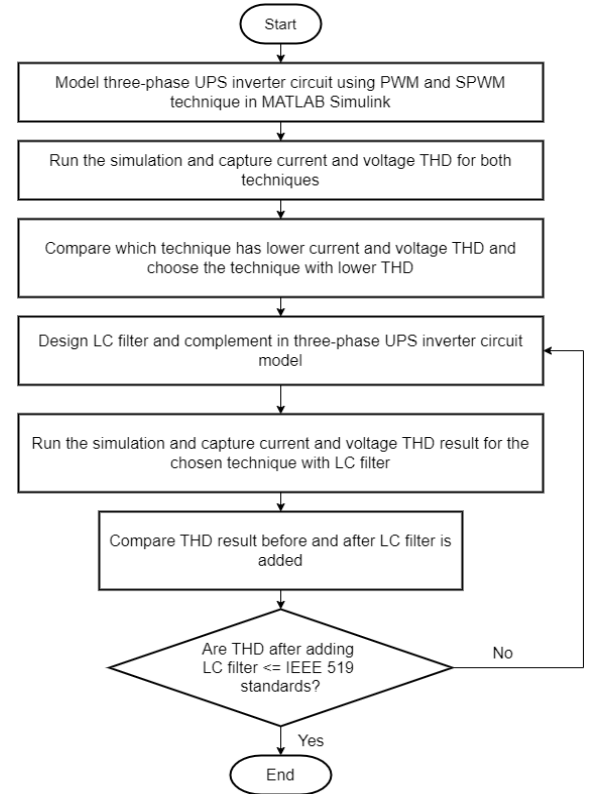


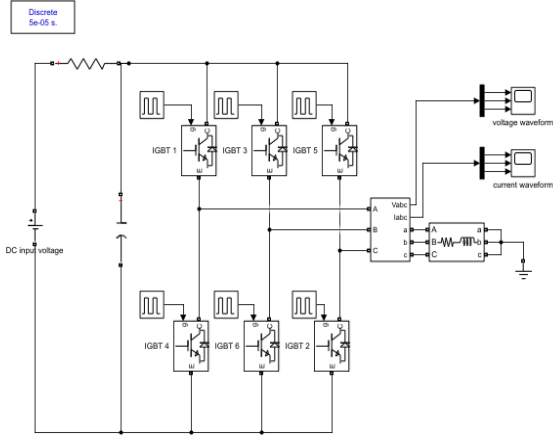
Fig. 3. Flowchart of the procedures for integrating SPWM with an LC filter in a three-phase UPS inverter

A. THD evaluation of PWM vs. SPWM

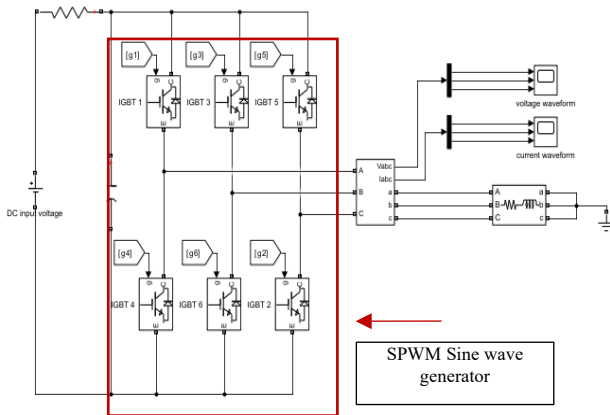
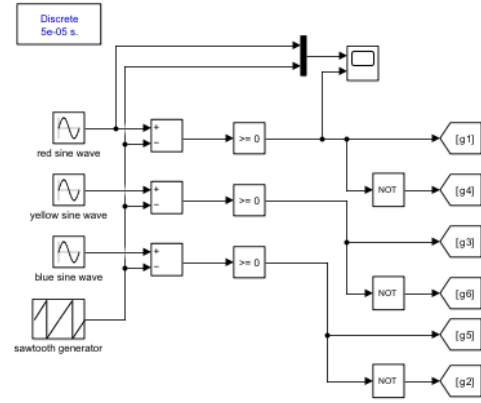
The inverter model is initially configured to operate with fixed-pulse and modulated-pulse SPWM techniques. In this stage, THD levels are analyzed and SPWM is selected due to its lower harmonic content. Fig. 4 shows the construction of a three-phase UPS inverter circuit model using the PWM technique, where fixed-width pulses are generated by a pulse generator, resulting in a more rectangular and less sinusoidal output. Table I presents all the parameters used in the simulation work.

TABLE I. SIMULATION PARAMETERS and SPECIFICATIONS [20]

Parameter	Value
DC input voltage	600V
Resistor, R	1 Ω
Inductor, L	1 mH
Capacitor, C	1 μ F
Switching frequency	2 kHz

**Fig. 4.** Circuit configuration of three-phase UPS inverter using PWM technique

To improve waveform quality, SPWM is employed by incorporating a sine wave generator and a triangular wave comparator, producing modulated pulse widths that more closely approximate a sinusoidal waveform. Fig. 5 illustrates the circuit construction of a three-phase UPS inverter using the SPWM technique, while Fig. 6 demonstrates the SPWM sine wave generator.

**Fig. 5.** Circuit configuration of three-phase UPS inverter using SPWM technique**Fig. 6.** Circuit construction of SPWM sine wave generator

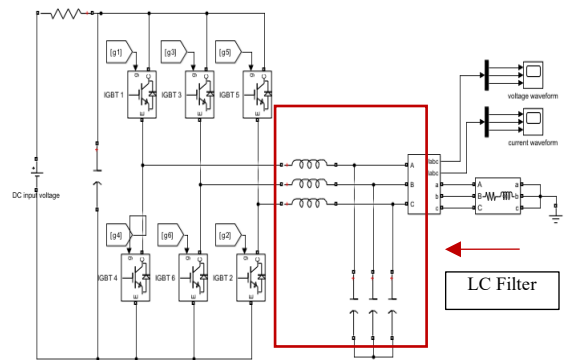
The generator produces gating signals $g1$ to $g6$ by comparing three phase-shifted sinusoidal references with a common triangular carrier. Each inverter leg is driven by a complementary pair of signals, i.e.: $g1/g4$ for Phase A, $g3/g6$ for Phase B and $g5/g2$ for Phase C, to ensure proper switching sequence. This gating method ensures synchronized operation of the switches to enable balanced three-phase output with reduced harmonic distortion.

B. LC Filter Design and Integration

Fig. 7 shows the circuit modelling of a three-phase UPS inverter using the SPWM technique after integrating an output LC filter. The LC filter is designed to attenuate high-frequency harmonics and refine the inverter's output waveform. The component values for the inductor (L) and the capacitor (C) are determined using the resonance frequency equation:

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

where f_o is the fundamental frequency, typically 50 Hz.

**Fig. 7.** Circuit configuration of three-phase UPS inverter using SPWM technique with LC filter

The parameters of the output filter are shown in Table II, with the inductor and capacitor values set to 2.16 mH and 4700 μ F, respectively.

TABLE II. THE PARAMETERS USED FOR OUTPUT LC FILTER

Parameter	Value
Inductor, L	2.16 mH
Capacitor, C	4700 μ F

The LC filter parameters were selected through an iterative simulation-based optimization process. Several L and C combinations were tested in MATLAB to evaluate their impact on the THD, waveform quality and compliance with IEEE 519 standards. The chosen values produced a resonance frequency close to 50 Hz and enabled effective attenuation of higher-order harmonics and efficient power transfer. Additionally, practical constraints such as voltage rating and system stability were considered. The final design achieved a good balance between harmonic suppression and overall inverter performance.

C. Post-Filter THD validation

The THD performance of the SPWM-based inverter with LC filtering is evaluated against IEEE 519 harmonic distortion standards to ensure compliance.

III. RESULTS AND DISCUSSIONS

This section presents the simulation results and evaluates the performance of PWM and SPWM techniques in a three-phase UPS inverter system. Additionally, the integration of an LC filter with SPWM is analyzed for its effectiveness in mitigating THD and enhancing power quality.

A. Comparison of Current and Voltage Waveforms between PWM and SPWM Technique

Fig. 8 shows the output current waveforms of PWM and SPWM. From the figure, it is observed that the SPWM technique produces a waveform that closely approximates a pure sinusoidal signal, whereas the PWM technique results in a more rectangular waveform with an abrupt transition. Despite maintaining a 120° phase shift across all three phases, PWM exhibits higher harmonic content due to its uniform pulse width, whereas SPWM minimizes high-frequency harmonics by modulating pulse widths dynamically within each cycle.

Fig. 9 presents the voltage waveforms for PWM and SPWM techniques. The SPWM technique achieves superior waveform smoothness by varying pulse widths in synchronization with the reference sinusoidal signal, effectively suppressing harmonic distortion. In contrast, PWM retains a constant pulse sine wave which leads to significant harmonic content and a waveform that deviates substantially from an ideal sine wave.

Based on the figure, it is observed that SPWM pulses vary in width within each cycle to approximate a sinusoidal waveform more closely. This variation helps in reducing harmonic content and achieving a smoother output waveform. On the other hand, PWM maintains a more uniform pulse width within each cycle, resulting in a waveform that is less smooth and more rectangular. This characteristic leads to higher harmonic components in the output waveform compared to SPWM.

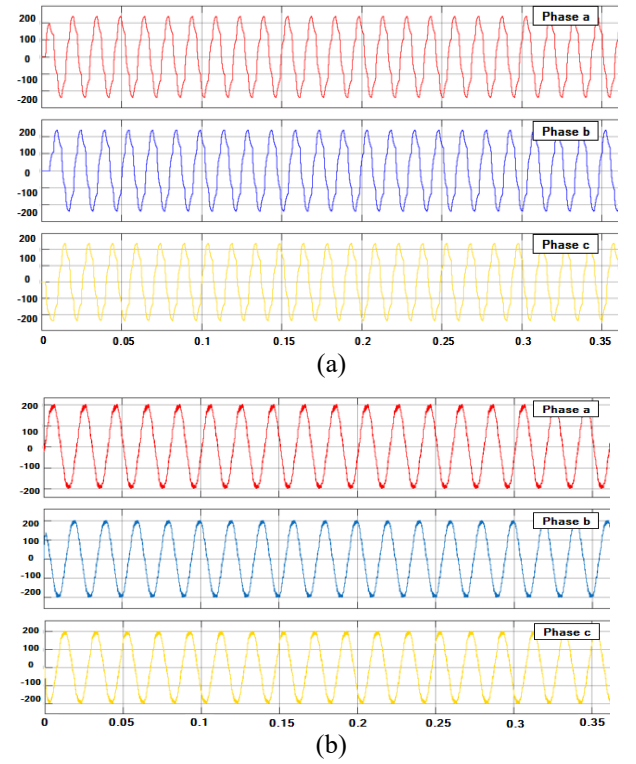


Fig. 8. Output current waveforms: (a) PWM; (b) SPWM

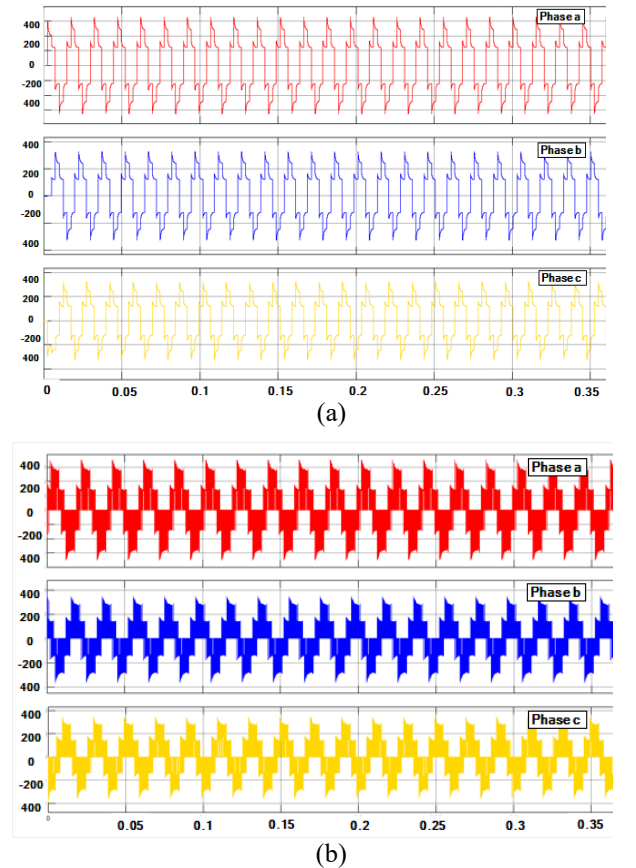


Fig. 9. Output voltage waveforms: (a) PWM; (b) SPWM

B. Comparison of Current and Voltage Total Harmonic Distortion between PWM and SPWM Technique

Fig. 10 and Fig. 11 show the comparison of current and voltage THD for PWM and SPWM, respectively. PWM has a current THD of 69.73% and a voltage THD of 98.40%, while

SPWM has a current THD of 5.94% and a voltage THD of 74.30%, indicating that SPWM produces a lower current and voltage THD compared to the PWM technique. However, despite the improvement with SPWM, the value of THD still exceeds the IEEE 519 standard THD limit of 5% due to the presence of high-order harmonics. Therefore, the three-phase UPS inverter with the SPWM technique requires further adjustment to reduce the THD percentage to comply with the standard.

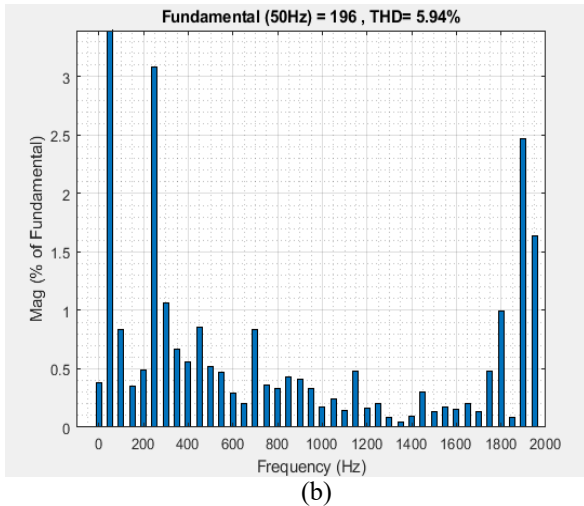
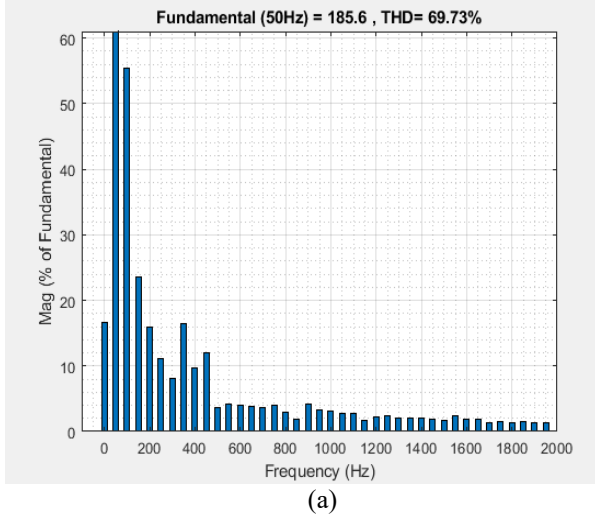


Fig. 10. Percentage of current THD: (a) PWM (69.73%); (b) SPWM (5.94%)

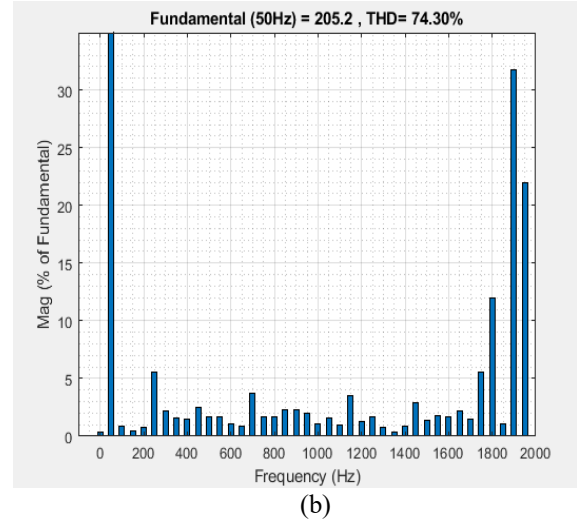
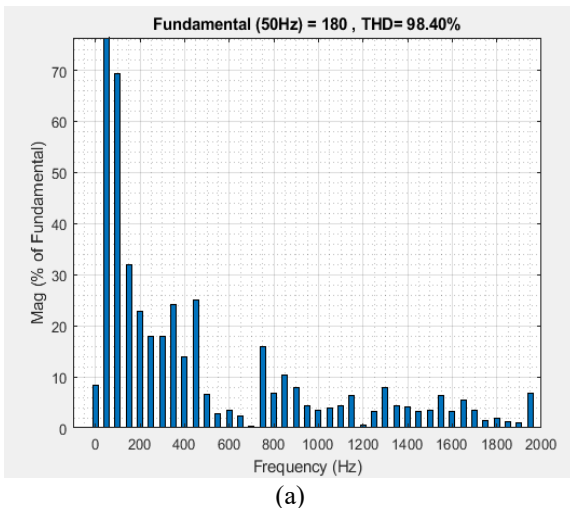
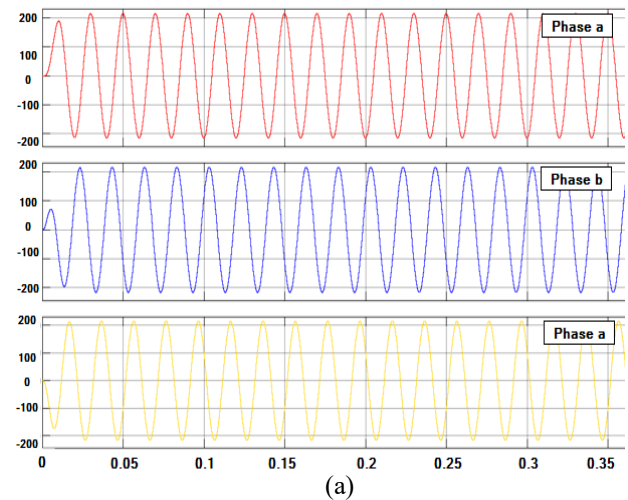


Fig. 11. Percentage of voltage THD: (a) PWM (98.40%); (b) SPWM (74.30%)

C. Integration of LC Filter with SPWM Technique

An LC filter is integrated into the three-phase UPS inverter system operating with SPWM to further mitigate harmonic distortion. The LC filter is designed to attenuate high-frequency harmonics. Simulation validation confirmed that these values provide the desired frequency response, stable load regulation, and compliance with industry standards, ensuring optimal performance of the three-phase UPS inverter system using the SPWM technique.

Fig. 12 illustrates the improved current and voltage waveforms of the SPWM with an LC filter, which are smoother compared to the SPWM without an LC filter shown in Fig. 8(b) and Fig. 9(b). The Fast Fourier Transform (FFT) analysis in Fig. 13 demonstrates a significant reduction in harmonic content, with a current THD of 0.34% and a voltage THD of 0.38% after integrating the LC filter with SPWM, compared to a current THD of 5.94% and a voltage THD of 74.30% before integrating the LC filter. The LC filter effectively reduces the THD percentage to comply with IEEE 519 standards, significantly improving power quality by attenuating high-frequency harmonics, resulting in smoother and more sinusoidal waveforms.



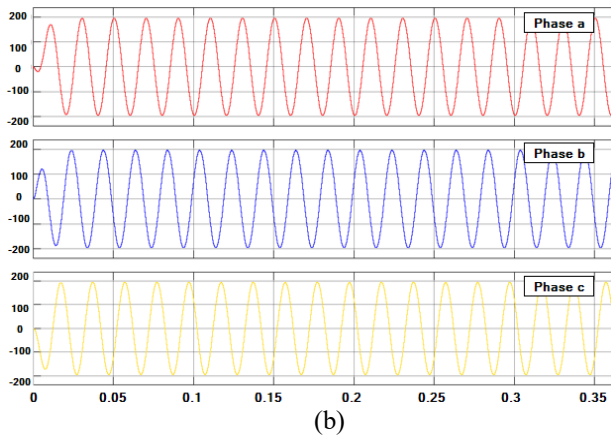


Fig. 12. SPWM with LC filter: (a) current waveform; (b) voltage waveform

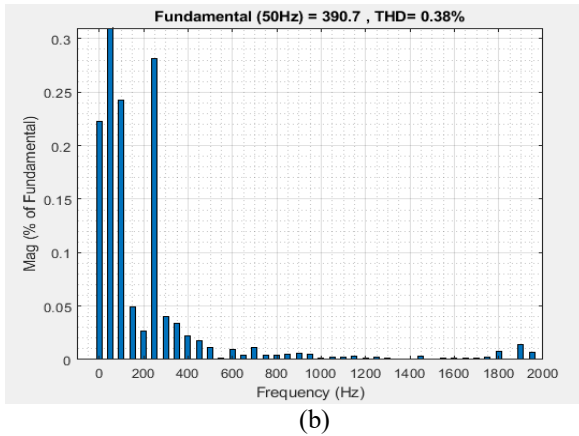
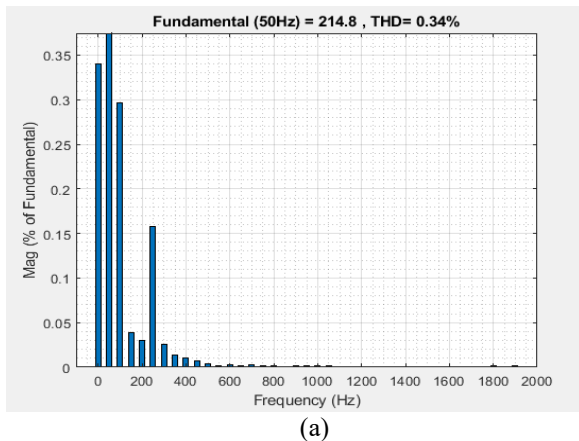


Fig. 13. Percentage of THD using SPWM with LC filter: (a) current THD (0.34%); (b) voltage THD (0.38%)

D. Comparative Analysis of Total Harmonic Distortion Reduction

Table III compares the THD values for PWM, SPWM, and SPWM with an LC filter. The integration of the LC filter with SPWM shows the lowest THD values, highlighting the effectiveness of the combined approach.

TABLE III. THD VALUES FOR PWM, SPWM and SPWM WITH LC FILTER

Technique	Current THD (%)	Voltage THD (%)
PWM	69.73	98.40
SPWM	5.94	74.30
SPWM with LC filter	0.34	0.38

Based on Table III, the PWM technique exhibits the highest THD, indicating it produces waveforms with substantial harmonic content, resulting in less smooth, more rectangular waveforms. These elevated THD values suggest that PWM may not be suitable for applications requiring high power quality and minimal harmonic distortion.

In contrast, the SPWM technique shows notable improvement in THD compared to PWM, due to its ability to generate varying-width pulses that closely approximate a sinusoidal waveform. However, the voltage THD remains relatively high, indicating further optimization is needed to meet the IEEE 519 standard's 5% THD limit.

Integrating an LC filter with the SPWM technique results in the lowest THD values. This significant reduction highlights the effectiveness of the combined approach in attenuating high-frequency harmonics and producing smoother, more sinusoidal waveforms. The THD values achieved comply with the IEEE 519 standard, demonstrating that SPWM with an LC filter is highly effective in improving power quality.

The comparative analysis indicates that the SPWM technique, when combined with an LC filter, provides the most effective solution for reducing THD in three-phase UPS inverter systems. The integration of the LC filter with SPWM not only meets the stringent IEEE 519 standard of below 5% but also significantly enhances overall power quality by minimizing harmonic distortion in its current output and voltage waveforms. This observation underscores the importance of using advanced modulation techniques and appropriate filtering mechanisms to achieve optimal performance in power electronics applications.

IV. CONCLUSION

This study examines the integration of an LC filter with SPWM to improve power quality in three-phase UPS inverters. Comparing THD values, SPWM significantly reduces THD compared to PWM. However, SPWM alone exceeds IEEE 519 standards. Incorporating an LC filter with SPWM effectively mitigates harmonic content where THD values are reduced to current THD of 0.34% and voltage THD of 0.38%, well within the IEEE 519 limit of 5%. The simulation results confirm the LC filter's effectiveness in reducing harmonic distortion and enhancing power quality.

This study contributes to advancements in power electronics and UPS systems, supporting Sustainable Development Goal 9 (SDG9) by promoting innovation in power electronics and enhancing industrial infrastructure. The findings demonstrate SPWM's effectiveness in reducing THD and highlight the LC filter's role in meeting industry standards. By improving UPS performance, particularly in the medical and telecommunications sectors, the study aligns with SDG9 objectives. Future research should compare SPWM with advanced techniques like Space Vector Pulse Width Modulation (SVPWM) and Predictive Control to evaluate their performance in three-phase UPS inverters. These studies will identify the best methods for optimizing power quality and reducing harmonic distortion.

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