

Analysis of Total Harmonic Distortion in Inverter Systems: A Comparative Study of Square Wave, Phase Shift and Multilevel Inverters

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Abstract

This study investigates the total harmonic distortion (THD) in inverter systems, comparing square wave, phase shift, and multilevel inverters. The performance of inverters is crucial for efficiently converting direct current (DC) to alternating current (AC), especially in renewable energy applications and electric vehicles. The research identifies gaps in understanding THD performance across different inverter configurations under various input conditions and modulation techniques. Utilizing MATLAB/Simulink, the study simulates a proposed multilevel inverter's output voltage characteristics in both filtered and unfiltered scenarios. The objectives include stimulating THD performance under square wave inputs, SPWM and phase shifts while analyzing the multilevel inverter's output voltage. Findings aim to enhance inverter designs for better power quality and efficiency, highlighting multilevel inverters' advantages over traditional two-level inverters. The implications of filtering techniques on voltage quality are also discussed, contributing valuable insights to the field of power electronics.

1. Introduction

Power electronics is essential in modern applications such as renewable energy production, electric vehicles, and smart grid technologies, focusing on the conversion and control of electrical power. Inverters, which convert direct current (DC) to alternating current (AC), are crucial components in this field. They enable off-grid living by powering AC devices from DC sources, enhancing the quality of life for individuals in remote settings. Renewable energy, derived from rapidly replenishing resources like solar, wind, water, biomass, and geothermal sources, is increasingly recognized for its sustainability benefits [1]. Its applications extend beyond electricity generation to heating and cooling systems, with innovative uses emerging in desalination plants and electric ships. Multi-level inverters have advanced the efficiency of power conversion by allowing for multiple voltage levels and offering benefits such as lower harmonic distortion and higher efficiency compared to traditional two-level inverters [2]. These features make them suitable for various applications, including motor drives and renewable energy systems. In conclusion, the integration of power electronics, renewable energy technologies, multilevel inverters, and FPGAs is vital for achieving a sustainable future. These technologies not only improve living standards but also contribute to reducing environmental impacts. The problem statement highlights the significant interest in multilevel inverters (MLIs) within power electronics due to their ability to produce high-quality output voltage waveforms with lower total harmonic distortion (THD). However, there is a lack of comprehensive research on THD performance across different inverter configurations, particularly regarding the effects of phase shifts square wave and SPWM inputs. This gap limits the optimization of inverter designs for

improved power quality and system efficiency. Additionally, the effectiveness of filtering methods to enhance output voltage quality remains underexplored, despite the potential for unfiltered signals to introduce inefficiencies. To address these issues, this study aims to utilize MATLAB/Simulink to simulate and analyze a proposed multilevel inverter's performance, focusing on THD under various conditions and the characteristics of filtered versus unfiltered outputs. The goal is to provide insights that can optimize MLI designs for better performance and reliability in practical applications.

2. Literature Review

2.1 Single Phase Versus Multi-Level Inverters

This literature review examines the advantages and disadvantages of single-phase and multilevel inverters used for transforming DC electricity from renewable sources, such as solar panels and batteries, into AC power suitable for households, businesses, and the grid. Single-Phase Inverters are typically simpler and more cost-effective for low-power applications, making them suitable for residential systems. However, they may produce higher harmonic distortion and have limitations in efficiency compared to more advanced inverter technologies. Multi-level Inverters, on the other hand, offer significant benefits for high-voltage and high-power applications. They reduce harmonic distortion, improve efficiency, and enhance power quality by producing a stepped output voltage waveform. This capability makes them ideal for integrating renewable energy sources into various grid configurations. Despite their advantages, multilevel inverters can be more complex and costly to implement due to their intricate design and additional components. Table 1 outlines the benefits and drawbacks of single-phase and multilevel inverters, highlighting that the choice between them is influenced by factors such as performance characteristics, budget, and application requirements. Single-Phase Inverters are well-suited for residential photovoltaic (PV) systems due to their simplicity, affordability, and high efficiency at moderate power levels [3, 4]. Multi-level Inverters, conversely, are more appropriate for industrial applications and high-power renewable energy systems, offering advantages like low total harmonic distortion (THD) [5], high output voltage quality [6], and efficiency at elevated power levels. Ultimately, selecting the appropriate inverter type requires a careful assessment of the specific demands and priorities of each application.

Table 1 Advantages of single-phase inverter and multi-level inverter

Feature	Single-phase inverter	Multi-level inverter
Cost	Lower	Higher
Complexity	Simpler circuitry	More complex circuitry
Efficiency (Low power)	High	High
Efficiency (High power)	Lower	Higher
Size and weight	Smaller and lighter	Larger and heavier
THD	Higher	Lower
Output voltage quality	Lower	Higher

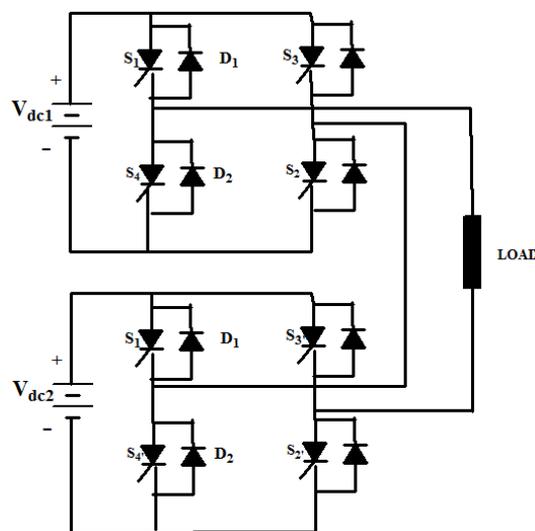


Fig. 1 Design of five-level cascaded h-bridge multi-level inverter

2.2 Cascaded H-Bridge Multi-Level Inverters (CHB-MLIs)

Cascaded H-Bridge Multilevel Inverters (CHB-MLIs) are highly effective for power conversion, particularly in renewable energy applications, due to their advantages over traditional two-level inverters. They offer higher efficiency by minimizing switching losses through lower switching frequencies and reduced voltage stress [7]. Additionally, CHB-MLIs produce near-sinusoidal waveforms with significantly lower harmonic distortion, enhancing grid compatibility and reducing electromagnetic interference (EMI) [8, 9]. Their modular design allows for easy addition or removal of H-bridges, enabling flexibility in adjusting voltage levels and power capacity to meet specific application requirements. These features make CHB-MLIs an adaptable and efficient choice for modern energy systems. Figure 1 illustrates the design of a five-level cascaded h-bridge multi-level inverter.

2.3 Pulse Width Modulator Switching Method

Pulse Width Modulation (PWM) is a versatile technique for controlling power delivery in electronic and power systems by adjusting the duty cycle of a pulse train. Common methods include Sinusoidal PWM (SPWM), which generates smooth, low-harmonic signals by comparing a reference sine wave with a carrier triangle wave. Space Vector PWM (SVPWM), an advanced method using three-phase voltage vectors for high voltage utilization and low harmonic distortion, ideal for multilevel inverters. Carrier-Based PWM, a simpler approach comparing reference signals with multiple carrier waves, though it may result in higher harmonic distortion and Hysteresis PWM, a straightforward method for low-power applications that switches based on output-reference differences but can cause fluctuating frequencies and instability. Each technique balances complexity, efficiency, and harmonic performance to suit specific applications.

3. Methodology

For the methodology, this section outlines the methodology employed to accomplish the first and second objectives of the study. The primary goals are to propose a multi-level inverter with 3 different modulations that are square wave, phase shift and SPWM and compare the THD performance including the output waveform filter and unfiltered. This study focuses on two main objectives: evaluating the total harmonic distortion (THD) performance of a 5-level multilevel inverter using MATLAB/Simulink and analyzing the output voltage performance of the proposed inverter using three different PWM switching techniques. Figure 2 shows the flowchart of the project.

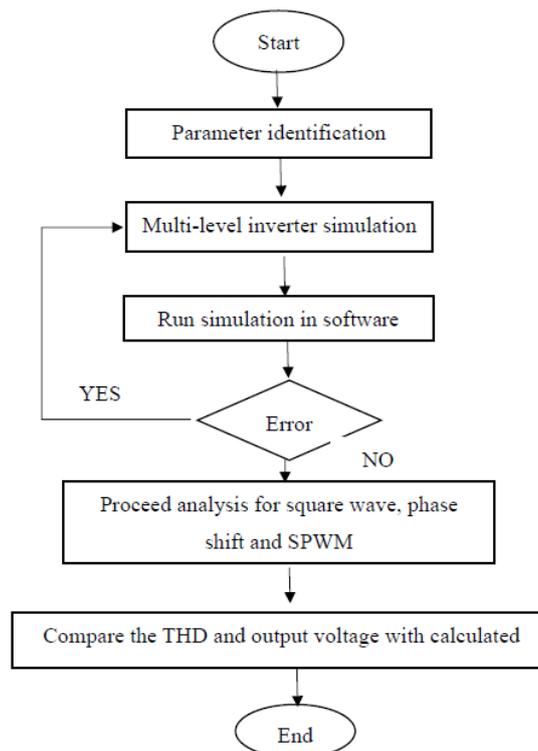


Fig. 2 Flowchart of project

3.1 Operation of Multi-Level Inverter

The multi-level inverter operates to produce an AC waveform using PWM control. It consists of four switching devices (e.g., MOSFETs), denoted as S1, S2, S3, and S4. During operation, S1 and S4 switch together to generate a positive pulse, while S2 and S3 switch together to generate a negative pulse. This process is repeated cyclically to form the desired output. Table 2 shows the operation of the multi-level inverter.

Table 2 Operation of multi-level inverter

S1	S2	S3	S4	VA	VB	VD
ON	ON	-	-	Vd	0	+Vd
-	-	ON	ON	0	V0	-Vd
ON	-	ON	-	Vd	V0	0
-	ON	-	ON	0	0	0

3.2 Semiconductor Devices Selection

In the selection of semiconductor devices for multilevel inverters, various switching devices such as MOSFETs, IGBTs, BJTs, and TRIACs can be utilized to achieve higher quality output waveforms. The choice of switching frequency is crucial as it affects output ripple and switching losses, making the appropriate selection of switches essential for optimal inverter operation. Among these devices, MOSFETs are identified as the most suitable for this project due to their shorter rise and fall times, enabling faster switching frequencies and making them ideal for high voltage and current applications. Additionally, MOSFETs exhibit stability at elevated temperatures and demonstrate excellent resistance characteristics. Their superior power dissipation capabilities, combined with increased switching rates and lower thermal impedance, contribute to enhanced dynamic performance while requiring less power from the driver. Overall, the selection of MOSFETs is justified based on their advantageous features that align with the project's requirements for effective multilevel inverter performance. Table 3 shows the comparison of switches device.

Table 3 Parameter of switches devices comparison

Parameters	IGBT	MOSFET	BJT
Circuit designs	Complex	Easy	Complex
Control input	Voltage	Voltage	Current
Switching speed	Medium	High	Low
Gate drive power	Medium	Low	High
Voltage blocking capability	Medium	High	Low
Switching Frequency	High	Very high	Low
Maximum Voltage Rating	3.5kV	1kV	1.5kV

4. Results and Discussion

In this section, the overall project's result was explored in depth. Objective 1- to stimulate the performance of total harmonic distortion (THD) on a square wave, phase shift, and multi-level inverter using MATLAB/Simulink software will be shown and compared with calculated analysis. Objective 2- To analyse the performances of the output voltage of the purposed multi-level inverter in filtered and unfiltered signal will be shown.

Table 4 Design specification

Description	Design parameter values
Input voltage	100V
Input current	2-8 A
Output voltage range	200 - 400V
Output power max.	1600 W
Load current max.	4A
Switching frequency	1KHz
Inductance	168µH
Capacitance	60.2µF
Load Resistance	100 Ω
Frequency	50Hz

4.1 Parameter for the Multi-Level Inverter

The multi-level inverter is designed to switch at a 1 kHz frequency. 100V is the input voltage that is used. The figures below illustrate output voltage, input current, output current, and output power waveforms. A load resistance of 100 Ω is chosen, the output power is based on the switching design used and the electricity is applied. Table 4 shows the design specification for the proposed multi-level inverter.

Figure 3 shows the design for square wave multi-level inverter with and without the LC filter. Same goes for Figure 4 and 5 that shows the phase shift and the SPWM multi-level inverter.

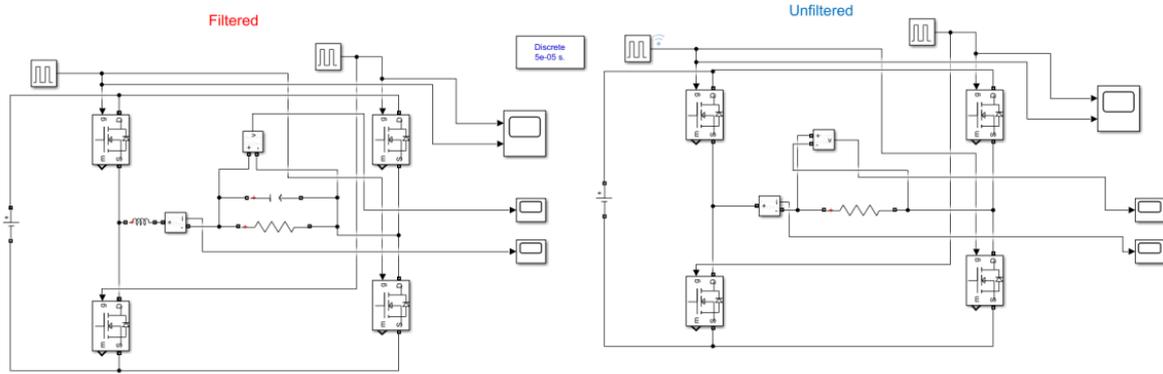


Fig. 3 Square wave multi-inverter design

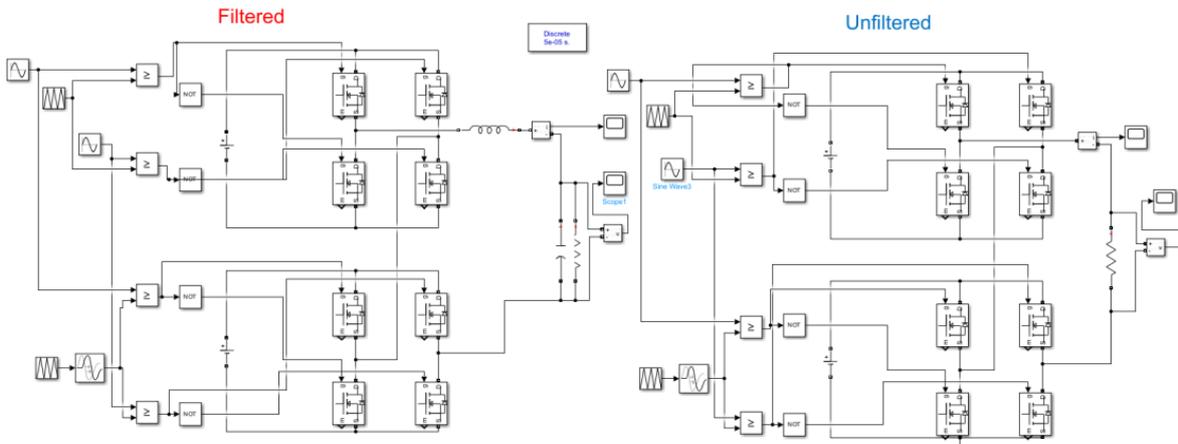


Fig. 4 Phase shift multi-level inverter design

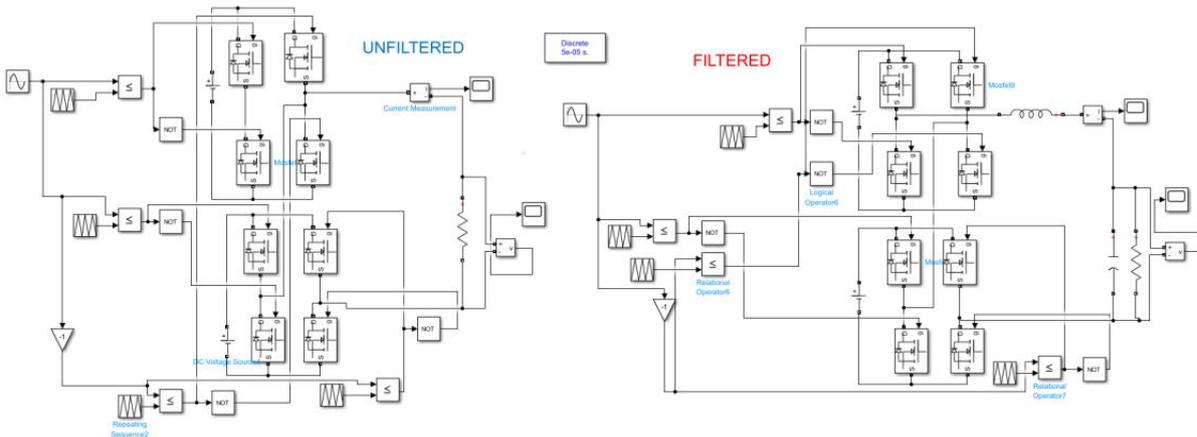


Fig. 5 SPWM multi-level inverter design

4.2 Total Harmonic Distortion Results and Analysis

In this section focuses on the simulation results of various multilevel inverter configurations, including square wave, phase shift, and sinusoidal pulse width modulation (SPWM) designs. The simulations analyze the total harmonic distortion (THD) for both unfiltered and filtered output voltages and currents. Results demonstrate that filtering significantly reduces THD, improving the quality of the output waveform. Among the configurations, SPWM provides the best performance with the lowest THD values, highlighting its suitability for applications requiring high power quality. The findings validate the effectiveness of multilevel inverters in producing high-quality AC outputs while emphasizing the importance of filtering techniques for enhancing system efficiency and reliability. In Figure 6 to Figure 8 show the result of the simulated THD result from FFT analysis in MATLAB software. Table 5 shows the collected data.

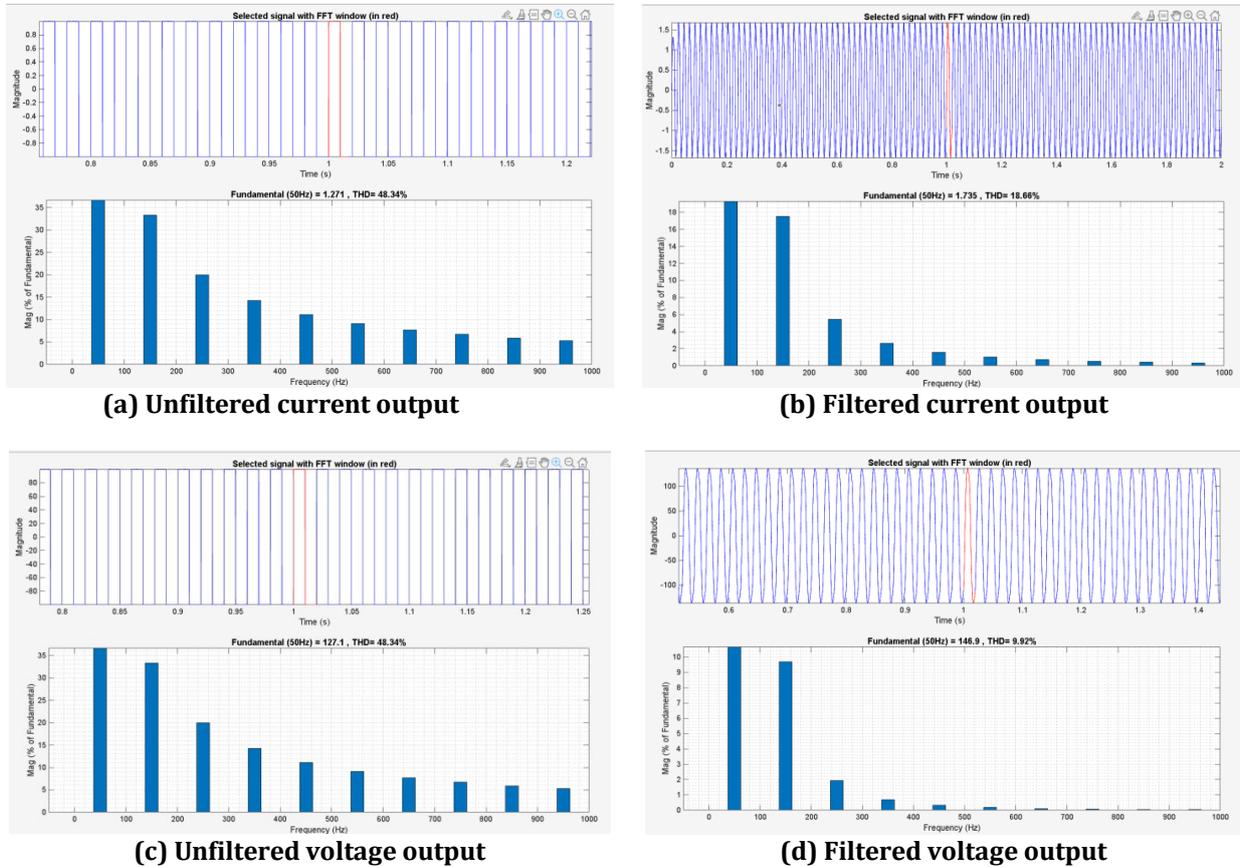
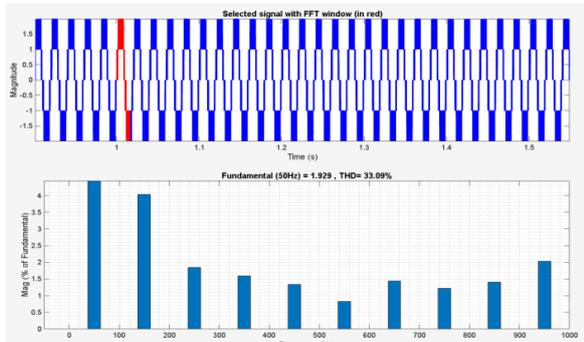
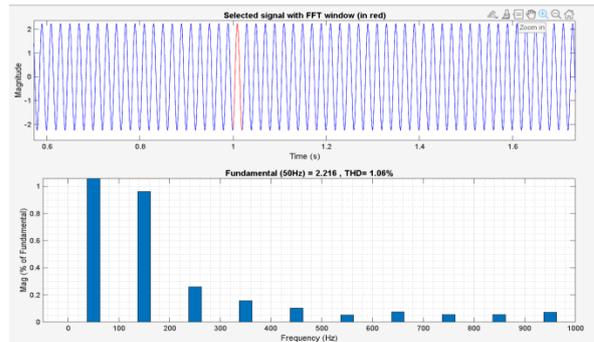


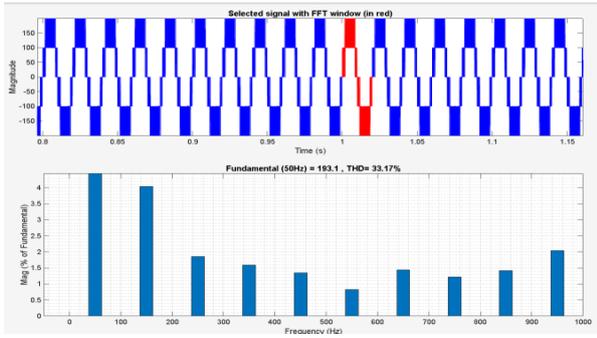
Fig. 6 (a)(b) Current output THD analysis for square wave; (c) (d) Voltage Output THD analysis for Square Wave



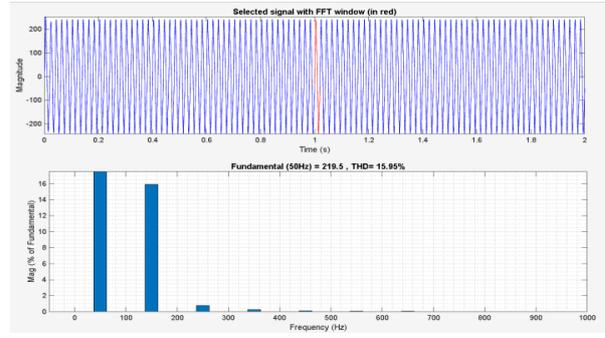
(a) Unfiltered current output



(b) Filtered current output

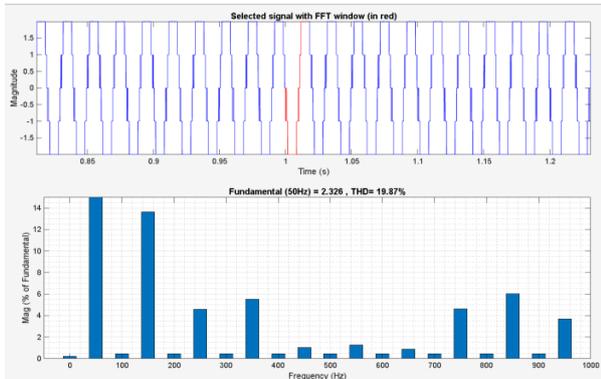


(c) Unfiltered voltage output

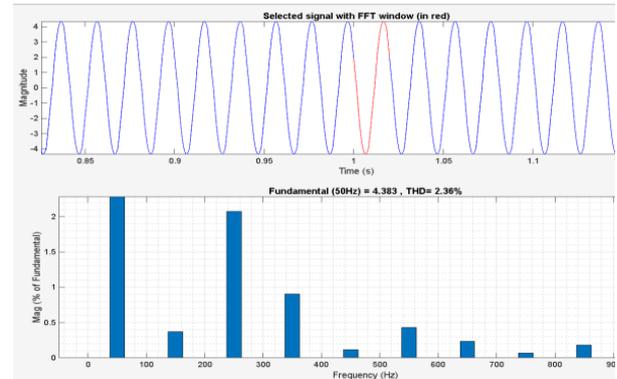


(d) Filtered voltage output

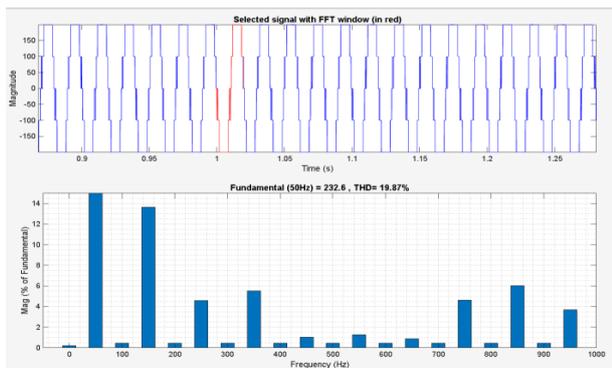
Fig. 7 (a)(b) Current output THD analysis for square wave; (c) (d) Voltage Output THD analysis for phase shift



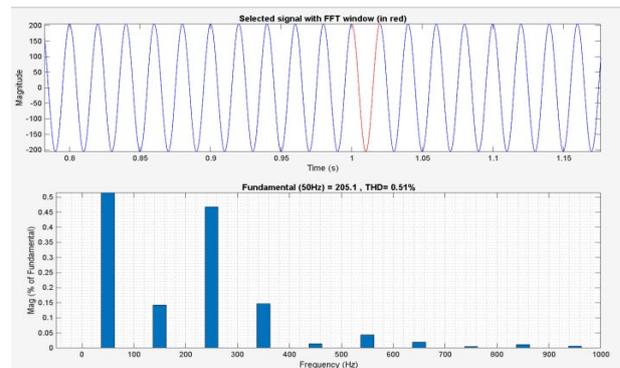
(a) Unfiltered current output



(b) Filtered current output



(c) Unfiltered voltage output



(d) Filtered voltage output

Fig. 8 (a)(b) Current output THD analysis for square wave; (c) (d) Voltage output THD analysis for SPWM

Table 5 Data of THD analysis

Type of modulation	Total Harmonic Distortion							
	Unfiltered Voltage output		Filtered Voltage output		Unfiltered Current output		Filtered Current output	
	Calculate	Simulate	Calculate	Simulate	Calculate	simulate	Calculate	Simulate
Square Wave	42.8%	48.3%	6.2%	9.2%	42.8%	48.3%	20.3%	18.7%
Phase Shift	27.5%	33.1%	25.6%	17%	27.5%	33.1%	2%	1.06%
SPWM	23.3%	19.9%	9.8%	0.5%	23.3%	19.9%	9.8%	2.4%

From the result of the simulation, confirm that the THD performance reduce significantly after apply LC filter to the circuit design. The manual calculation vary with the simulation result because of the assumption on the harmonic and the simulation result were more accurate because its data came from the simulated circuit.

4.3 Simulation Output Result

This section presents the simulation output results for the multilevel inverter configurations analyzed in the study. The results include both unfiltered and filtered output voltage and current waveforms, demonstrating the effectiveness of different modulation techniques such as square wave, phase shift, and sinusoidal pulse width modulation (SPWM). The analysis reveals that filtering significantly enhances output quality by reducing total harmonic distortion (THD), with SPWM yielding the best performance among the configurations tested. The section also discusses the implications of these results for practical applications, emphasizing the importance of selecting appropriate filtering methods to ensure reliable inverter operation. Overall, the findings underscore the potential of multilevel inverters to deliver high-quality AC outputs while minimizing harmonic distortion, contributing to improved power quality in various applications. Figure 9 to Figure 11 show the output waveform from three different modulations.

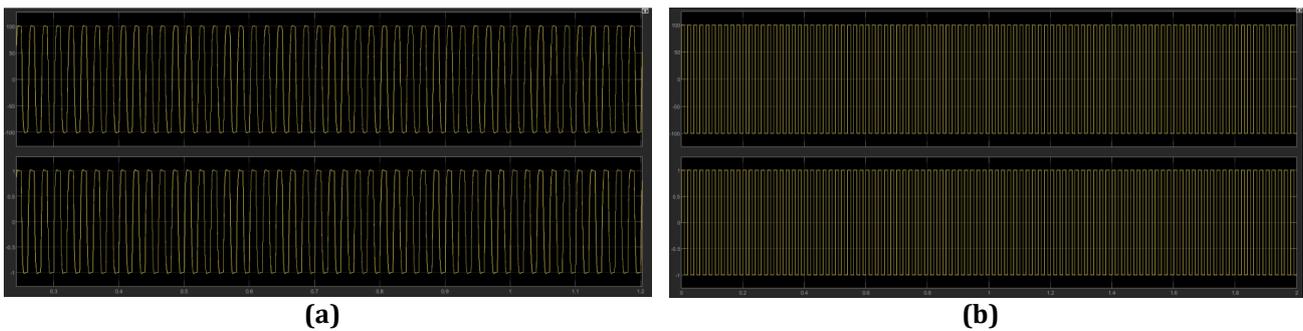


Fig. 9 (a) Filtered and (b) Unfiltered output voltage and current for square wave

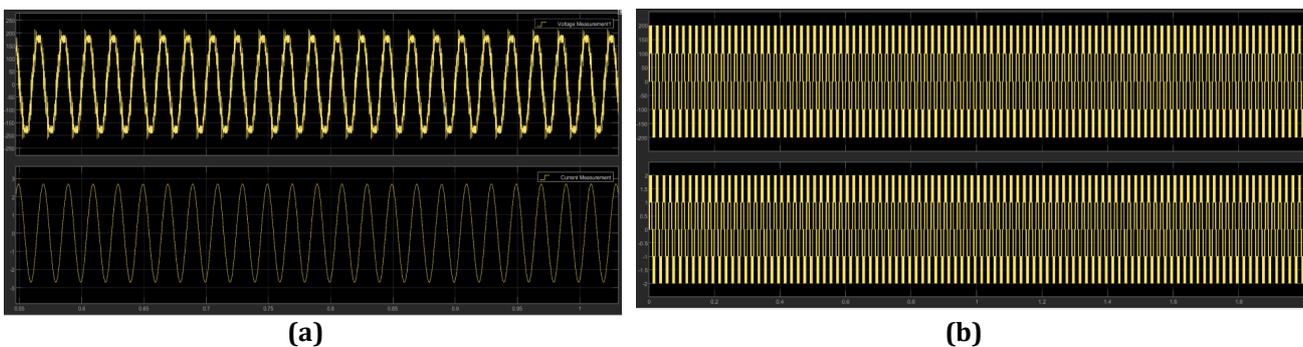


Fig. 10 (a) Filtered; and (b) Unfiltered output voltage and current for phase shift

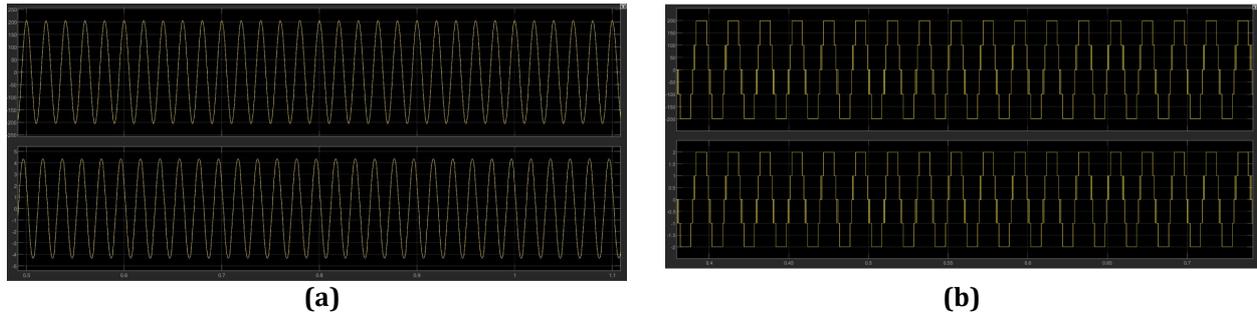


Fig. 11 (a) Filtered; (b) Unfiltered output voltage and current for SPWM

Table 6 shows the simulated output result of voltage and current as well as input voltage and input current of the simulation from MATLAB/Simulink. Table 7 shows the result of the calculated version of the output current and voltage manually.

Table 6 Simulation result of output voltage and current

Type of Modulation	Input Voltage (V)	Input Current (A)		Simulation Output Voltage (V)		Simulation Output Current (A)	
		Filter	Unfiltered	Filter	Unfiltered	Filter	Unfiltered
Square Wave	100	1.025	1	102.2	99.8	1.023	0.9989
Phase Shift	100	3.117	1.994	221.8	199.2	2.702	1.992
SPWM	100	2	1.994	205.1	199.2	4.338	1.992

Table 7 Result of calculated output voltage and current

Type of Modulation	Input Voltage (V)	Input Current (A)		Calculated Output Voltage (V)		Calculated Output Current (A)	
		Filter	Unfiltered	Filter	Unfiltered	Filter	Unfiltered
Square Wave	100	1	1	100	100	1.414	1
Phase Shift	100	3	2	200	199.97	2.45	1.997
SPWM	100	2	2	200	199.97	2	1.997

Table 7 compares the performance of a multi-level inverter using different modulation techniques, showing that the square wave technique produces the lowest output voltage, followed by SPWM, while the phase shift modulation achieves the highest output. A slight difference is observed between the calculated results in Table 7 and the simulation results, which may be attributed to resonance at specific frequencies or incompatibility of the LC filter with the multi-level inverter.

5. Conclusion

The project successfully achieved its main objectives, including developing a fully functional simulation to analyze THD performance and the output voltage of the proposed multi-level inverter. Slight differences between calculation and simulation results were noted, primarily due to assumptions made during manual calculations, which rely on idealized models. The project also met the objective of analyzing filtered and unfiltered signals. Throughout the process, various electrical and electronic theories were studied and applied, providing valuable learning opportunities. While there is room for further improvement, the project is a fully functional and complete foundation for future enhancements by other students.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the paper's publication.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Mohamed Faizal bin Othman, Afarulrazi Bin Abu Bakar; **data collection:** Mohamed Faizal Bin Othman; **analysis and interpretation of results:** Mohamed Faizal Bin Othman, Afarulrazi Bin Abu Bakar; **draft manuscript preparation:** Mohamed Faizal Bin Othman, Afarulrazi Bin Abu Bakar. All authors reviewed the results and approved the final version of the manuscript.

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