Volume 7 Nomor 1 Januari 2025 JJEEE e-ISSN : 2715-0887
p-ISSN : 2654-7813

Jambura Journal of Electrical and Electronics Engineering

Performance Analysis of Three Phase Cascaded H-Bridge Multilevel Inverter Design for Solar Power Plant Optimization

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Accepted: October 2024
Approved: January 2025
Published: January 2025

***Abstract*—An inverter is an electrical device that converts direct current (DC) into alternating current (AC). Typically, a standard inverter operates at three voltage levels: +Vdc, -Vdc, and 0. However, a multilevel inverter consists of several smaller inverters connected in a series to produce multiple voltage levels at the output. The primary advantage of this type of inverter lies in its ability to produce a much lower harmonic distortion compared to traditional, non-multilevel inverters. Additionally, the switching components of a multilevel inverter operate at lower frequencies, which makes it more suitable for high-power applications. This research focuses on a three-phase cascaded multilevel inverter, specifically generating output waveforms with up to seven levels. The study involves conducting experiments using RL loads, to observe how these variations affect the output waveforms and their harmonic distortions. The result, THDi values are much lower, with the 3rd harmonic contributing 0.02%, the 5th contributing 0.006%, the 7th contributing 0.004%, the 9th contributing 0.002%, the 11th contributing 0.002%, and the 13th harmonic contributing just 0.001%. These results suggest that the voltage harmonic more significant harmonic distortion than the current, particularly at the 13th harmonic order. This increase highlights the effect of inductive loads on the performance of the inverter, particularly in terms of harmonic content. These findings are crucial for optimizing multilevel inverters in practical applications, ensuring improved performance and efficiency.**

Keywords—Harmonics; Multilevel Inverter; Power Electronics

I. INTRODUCTION

Renewable energy has become an increasingly prominent area of study across the globe. Among the various renewable sources, solar energy stands out due to its abundance, environmental benefits, and ease of implementation. According to the National Energy Council, Indonesia boasts an average solar energy potential of 4.80 kWh/m²/day [1]. This vast potential can be harnessed directly to fulfill electricity demands through the use of photovoltaic (PV) modules [2].

A multilevel inverter is an advanced type of inverter that generates multiple voltage levels, which enhances the quality of the output waveform. The sinusoidal voltage produced by multilevel inverters is superior and does not require high switching frequencies, in contrast to conventional inverters, leading to reduced power losses during switching [3]. These inverters can be classified into various types based on their circuit configurations, commonly referred to as topologies. The most widely used topologies today include the Cascade H-Bridge, Diode Clamps, and Flying Capacitor, each offering distinct advantages and disadvantages [4].

In a previous study [5], a grid-integrated inverter design was developed to observe harmonic waves and evaluate the Total Harmonic Distortion (THD). The research, conducted by Oscar Lopez, Remus Teodorescu, Francisco Freijedo, and Jesus Doval Gandoy, titled "Leakage Current Evaluation of a Single-phase Transformerless PV Inverter Connected to the Grid," focused on assessing both the THD and efficiency of the inverter circuit. The study utilized PV systems with power ratings of 630 WP and 1260 WP. The findings revealed harmonic components up to the 11th harmonic, with the inverter design being a single-phase, single-level inverter connected to the grid.

Generally, on-grid inverters utilize a DC-DC converter to step up the PV voltage to match the required DC link voltage. Among the most commonly used DC-DC converters is the boost converter [6]-[8]. However, in practice, the input voltage required for a three-phase inverter can be quite high, and the output voltage of the boost converter is primarily determined by the duty cycle. As a result, it becomes challenging for a boost converter to supply the necessary voltage for the inverter when the PV voltage significantly deviates from the DC link voltage [9]-[11]. Similar studies have explored inverter type A configurations for large-scale solar power plant applications [12]. For smaller-scale solar power plants, however, a three-phase inverter is generally preferred due to its simpler switching techniques [13]-[15].

The aim of this research is to develop an inverter design utilizing the three-phase H-bridge cascade multilevel inverter method to reduce harmonic distortions. Additionally, this study seeks to investigate the impact of load variations on the harmonic wave output from the inverter, with the goal of minimizing potential damage to electrical equipment caused by these harmonic distortions.

II. METHODS

This study employs harmonic analysis and performance simulation of the multilevel cascaded H-Bridge inverter. Initially, the inverter model is developed, taking into account the topology structure and operating parameters, such as the number of voltage levels and switching frequency. Harmonic analysis is conducted using the Fourier transform method to assess the harmonic spectrum of the inverter's output signal, aiming to identify the contribution of each harmonic to the total distortion. Additionally, performance simulations are carried out using PSIM, considering variations in parameters such as load, switching frequency, and level configuration to optimize inverter performance. This approach is expected to provide valuable insights into the impact of harmonics on inverter performance and their overall contribution to system efficiency.

A. Inverter

An inverter is a power electronics circuit that functions to convert Direct Current (DC) electricity into Alternating Current (AC) electricity. In the inverter circuit, several important components are utilized, such as semiconductor switches, inductors, capacitors, and resistors [16]. The switches used in an inverter must have a fast response to change from an on state to an off state or vice versa; therefore, Metal Oxide Semiconductor Field Effect Transistor (MOSFET) switches are used. Figure 1 illustrates the full-bridge inverter circuit, which uses four MOSFET switches.

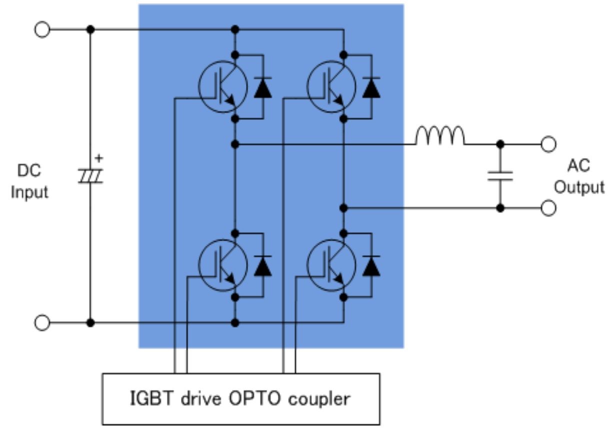


Figure 1. Full-Bridge Inverter

B. Cascade Multilevel Inverter

A cascade multilevel inverter is a type of multilevel inverter that generates output voltage from separate DC sources. The output voltage of this inverter takes the form of a stepped square wave, with voltage levels increasing in steps corresponding to the number of DC sources used in the inverter configuration [17].

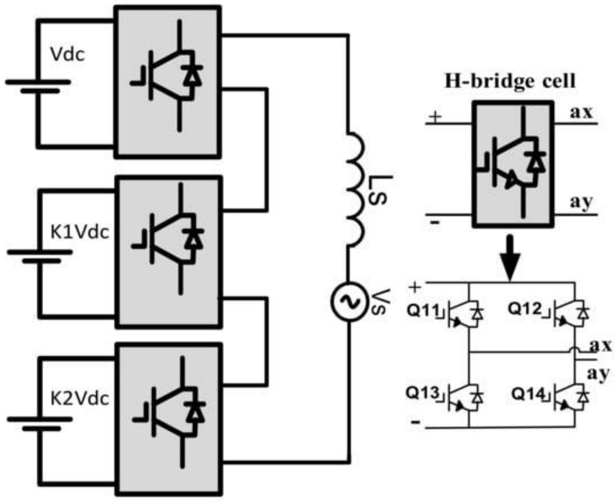


Figure 2. Cascaded Multilevel Inverter

The output voltage of this multilevel inverter is the sum of the output voltages of each individual level inverter [18].

$$V_{out} = \frac{(n-1)V_{dc}}{2} \tag{1}$$

Cascade MLI have the simplest construction and also a simple configuration. They have good output waveforms with a high level of stages. In this multilevel inverter, a high switching frequency is not required to generate a sinusoidal waveform. In a multilevel inverter, whether using its own or separate DC sources, the output voltage corresponds to the number of stages in the inverter. For an inverter with two DC sources, the output voltage (Vo) will consist of five distinct levels: +2Vdc, Vdc, 0, -Vdc, and -2Vdc.

C. Pulse Width Modulation (PWM)

Pulse Width Modulation (PWM) is a technique that compares a reference signal (Vr) with a carrier signal (Vc).

The carrier signal is typically a triangular or sawtooth wave. The fundamental principle of PWM is that when the amplitude of the reference signal (Vr) exceeds that of the carrier signal (Vc), a high or 'on' signal is generated. Conversely, when the amplitude of the reference signal (Vr) is smaller than that of the carrier signal (Vc), a low or 'off' signal is produced [19].

The process of comparing the reference signal with the carrier signal is illustrated in Figure 3, where the comparison of the two waveforms determines the duty cycle value for the PWM. Pulse Width Modulation (PWM) is an effective method for reducing the Total Harmonic Distortion (THD) in load current. The output of a PWM inverter, when using a filter, generally reduces the THD of the square wave (rectangular wave) switching [20].

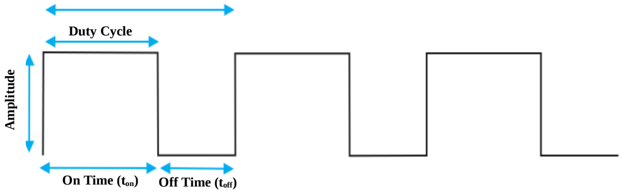


Figure 3. Pulse Width Modulation (PWM)

Ton in the Figure 2 indicates the duration of the output voltage being in the high or 'on' position, while Toff represents the duration of the output voltage being in the low or 'off' position. The sum of the durations of Ton and Toff is called Ttotal, which is commonly known as one period of the waveform [21].

$$T_{total} = T_{on} + T_{off} \quad (2)$$

From the values of T_{on} and T_{off}, the duty cycle can be determined, which is the ratio of the time when the waveform is in the 'on' state to the total time when the waveform is in the 'on' and 'off' states. Thus, the duty cycle can be expressed as shown in the equation below [22].

$$Duty\ Cycle = \frac{T_{on}}{T_{total}} \times 100\% \quad (3)$$

This duty cycle determines the operating time of the semiconductor switch components, creating pulse signals that control the 'on' and 'off' states of the switch. Therefore, the principle of PWM operation for controlling the function of the semiconductor switch is that when "$V_{control}/V_{reff}$" has an amplitude greater than the triangular wave, PWM will output a high condition, causing the switch to be in the 'on' state, thus closing the switch. Conversely, when "$V_{control}/V_{reff}$" has an amplitude smaller than the triangular wave, PWM will output a low condition, causing the switch to be in the 'off' state, thus opening the switch.

D. Harmonics

Harmonics are periodic distortions that occur in the sinusoidal waveforms of voltage, current, or power within electrical energy systems, including Solar Power Plants. These distortions can significantly affect the performance and efficiency of the entire electrical system. The waveform of harmonics consists of waves whose frequencies are multiples of a fundamental frequency, typically 50 Hz or 60 Hz, depending on the region and the type of electrical system in use. In the context of PLTS, harmonics can arise from the use of inverters, which convert direct current (DC) generated by solar panels into alternating current (AC). These inverters often serve as a primary source of harmonics due to their nonlinear operation. When inverters are in operation, they create harmonic waves whose frequencies are multiples of the fundamental frequency. For instance, if the fundamental frequency of the system is 50 Hz, the second harmonic will be at 100 Hz (2f), the third harmonic at 150 Hz (3f), and so on. The resulting distorted waveform can be expressed as the sum of the fundamental wave and the harmonic waves.

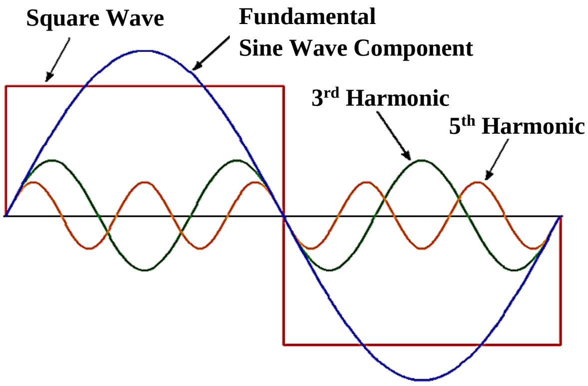


Figure 4. Harmonic Waveform

The relationship between harmonic frequency and fundamental frequency can be expressed as follows [23]:

$$f_h = n \times f_i \quad (4)$$

The harmonic waves will overlay the fundamental wave, resulting in a distorted waveform. This occurs due to the summation effect of the harmonic waves with the fundamental wave. The influence of harmonics in power systems is significant, as these harmonics can cause several effects, such as excessive heating in generators and transformers because harmonics tend to flow to equipment with lower impedance. The magnitude of harmonics in electrical power systems is expressed in Total Harmonic Distortion (THD) with the following equation.

Total Harmonic Distortion (THD) Voltage [24]:

$$THD_v = \frac{\sqrt{{V_2}^2+{V_3}^2+{V_4}^2+\cdots+{V_n}^2}}{{V_1}^2} \times 100\% \quad (5)$$

Total Harmonic Distortion (THD) Current [25]:

$$THD_i = \frac{\sqrt{{I_2}^2+{I_3}^2+{I_4}^2+\cdots+{I_n}^2}}{{I_1}^2} \times 100\% \quad (6)$$

The cause of harmonic waves is the use of nonlinear loads in power systems, which create distortions in the sinusoidal waveform. Nonlinear loads can act as current sources that inject harmonic currents into the power system. As more electronic devices are used, such as televisions, computers, and power-saving devices, the harmonic currents in the electrical system will increase, resulting in a higher Total Harmonic Distortion (THD).

Nonlinear loads will produce an output waveform that is not proportional to the voltage during each half-cycle, resulting in the output waveforms of current and voltage not matching the input waveforms (experiencing distortion). The disturbances in the wave caused by the distortion of current and voltage waveforms are referred to as harmonics.

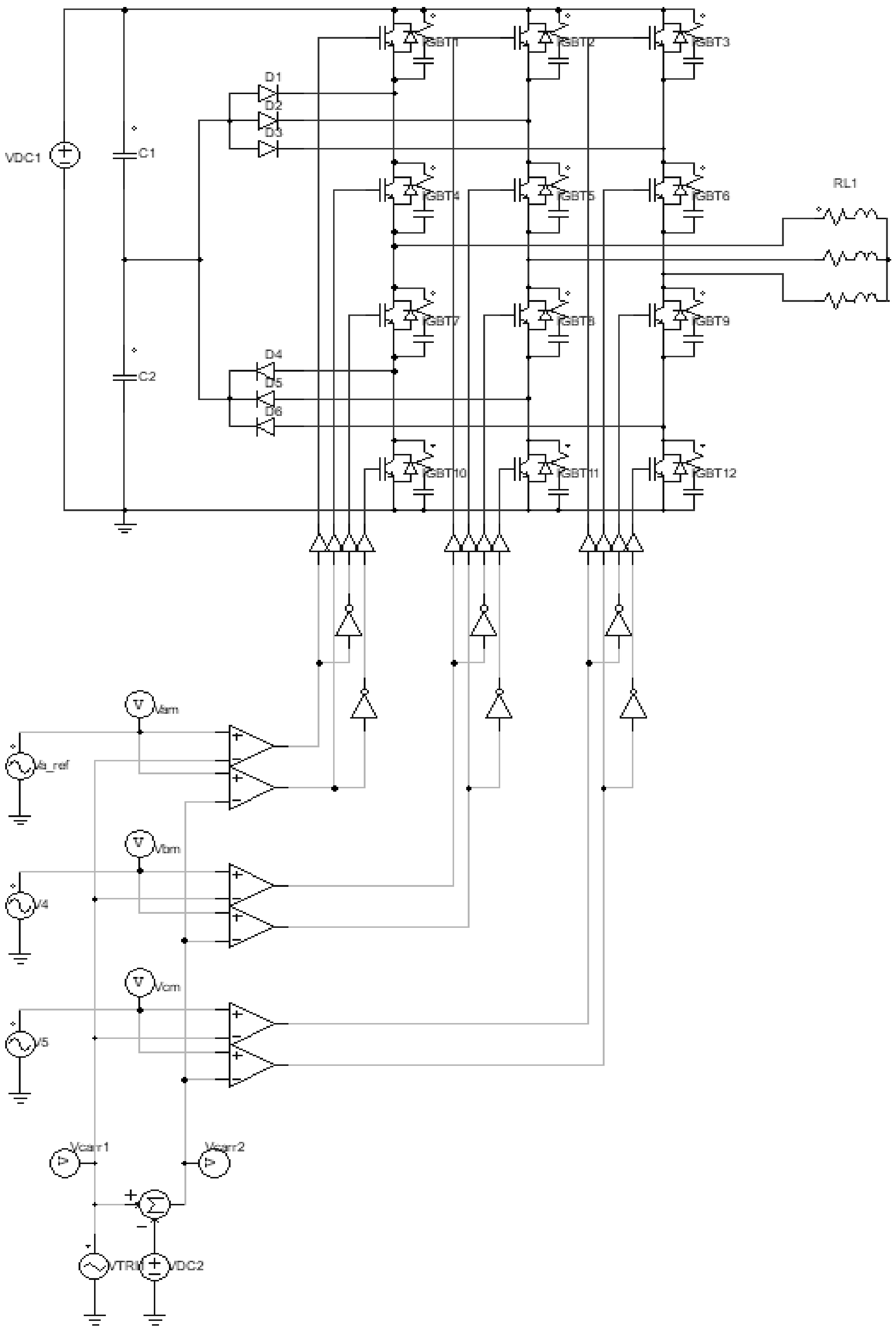


Figure 5. Modeling of Three Phase Cascaded H-Bridge Multilevel Inverter using PSIM

III. Result and Analysis

In this section, we present and discuss the results of the performance analysis of the three-phase cascaded H-Bridge multilevel inverter design for optimizing solar power plants. The analysis was conducted through a series of simulations and tests to evaluate various performance parameters, including power conversion efficiency, harmonics, and dynamic response of the inverter. The obtained results will be compared with industry standards and previous research findings, providing a clear understanding of the advantages and potential improvements of the proposed design. This discussion will also encompass the practical implications of these findings in the context of more efficient and sustainable solar power system applications.

A. *Multilevel Inverter Output Performance*

Multilevel inverters have gained increasing popularity in various applications, particularly in solar power systems, due to their ability to produce output voltages with lower harmonic distortion compared to conventional inverters. In solar power systems, multilevel inverters are essential for converting the DC power generated by solar panels into AC power, which can be used by the load or fed into the grid. Evaluating the performance of multilevel inverters involves assessing key parameters such as power quality, conversion efficiency, total harmonic distortion (THD), and voltage regulation. A comprehensive understanding of these performance aspects is critical for ensuring the optimal efficiency and reliability of the system, especially as the demand for renewable energy solutions continues to grow.

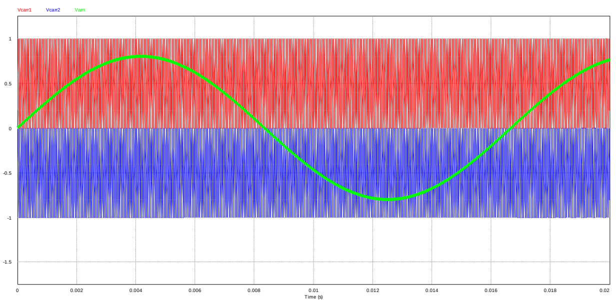
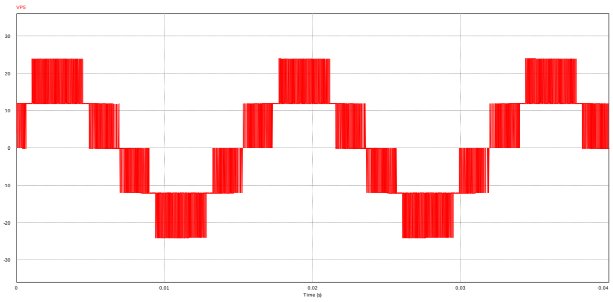
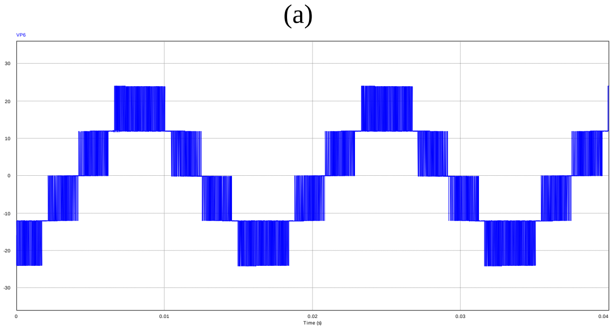


Figure 6. Sinusoidal and Square Wave as Comparator

Figure 6 illustrates the AC output from a multilevel inverter with the corresponding switching events superimposed. The sinusoidal shape of the output voltage reflects the inverter's role in creating an AC output from a DC source, with switching pulses regulating the inverter's performance. The red and blue regions may represent different operational states, such as positive and negative voltage levels or current flow in an alternating current (AC) system. The green waveform exhibits a smooth sinusoidal pattern, which is characteristic of AC power. The sharp white vertical lines scattered across the red and blue areas suggest the presence of switching events, which are typical in inverter circuits. These switching points could indicate the transitions of power electronic devices like transistors or thyristors, used to convert direct current (DC) to AC. The consistent distribution of switching pulses in the red and blue regions suggests a pulse-width modulation (PWM) strategy. PWM is often used in inverters to control the output voltage and current, enabling efficient conversion in renewable energy systems such as solar power plants.



(a)



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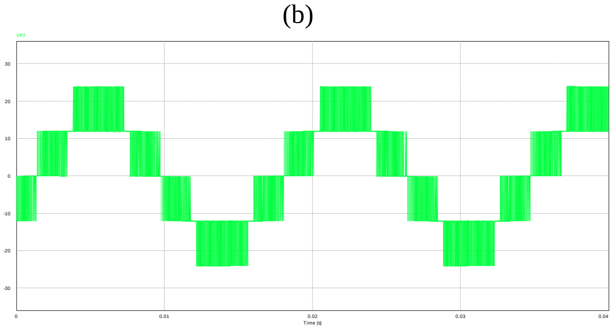


(c)

Figure 7. Output Voltage (a) R-Phase, (b) S-Phase, (c) T-Phase

Figure 7 illustrates three waveforms, each representing a different level of voltage approximation in a multilevel inverter. As the number of voltage levels increases, the waveforms of the three phases become smoother and more sinusoidal. This progression helps to reduce harmonic distortion and enhances the quality of the AC output. The R-phase, with fewer voltage levels, produces a rougher waveform, while the T-phase, with the most voltage levels, offers the closest approximation to a pure sine wave, making it ideal for efficient power conversion in applications such as solar energy systems. Multilevel inverters also enhance power conversion efficiency, especially in renewable energy systems like solar plants. Moreover, the smoother waveforms alleviate stress on the grid and connected devices, improving the overall reliability of the system.

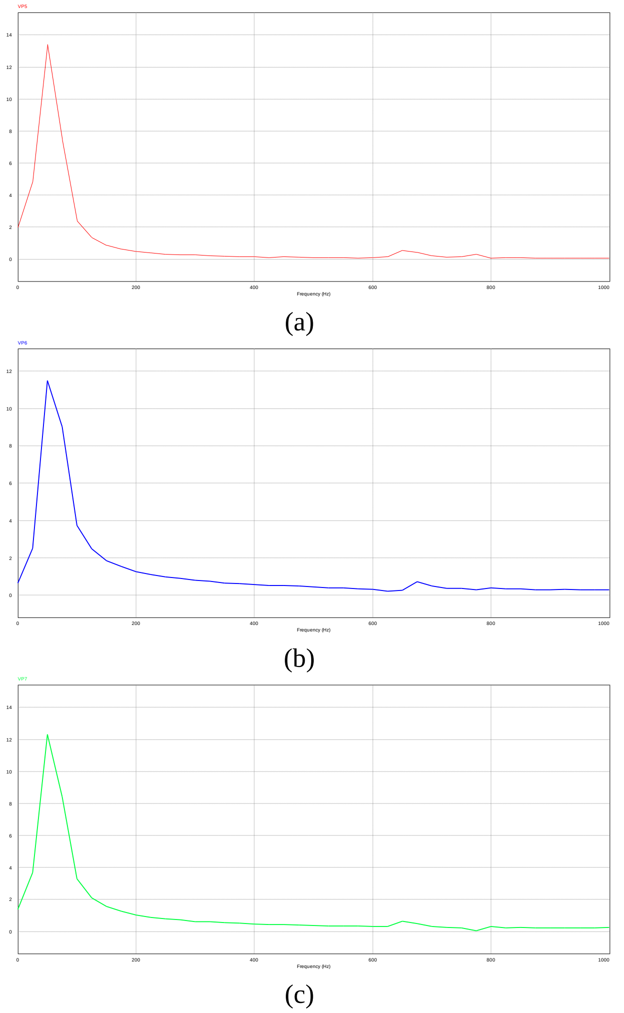


Figure 8. FFT Analysis for Output Voltage (a) R-Phase; (b) S-Phase; (c) T-Phase

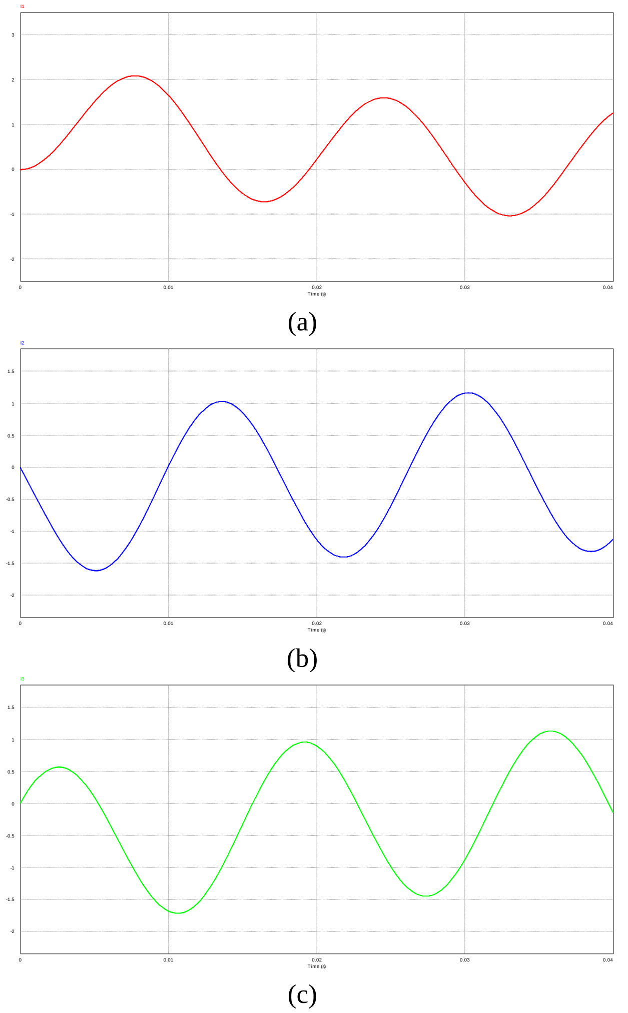


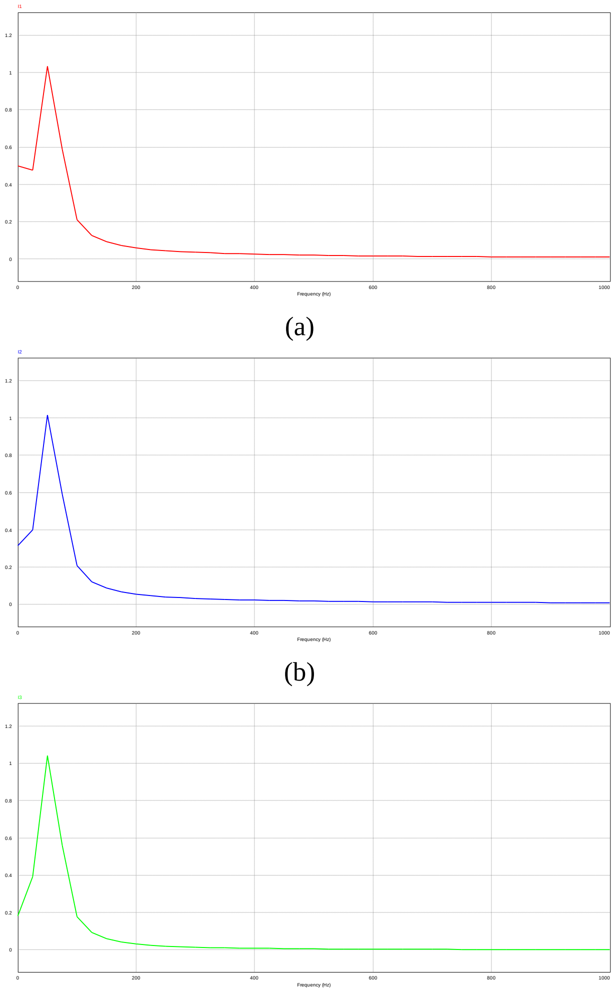
Figure 9. Output Current (a) R-Phase; (b) S-Phase; (c) T-Phase

Figure 8 presents three graphs depicting the Fast Fourier Transform (FFT) analysis of the output voltage across different phases: (a) R-Phase, (b) S-Phase, and (c) T-Phase. In each graph, the vertical axis represents the amplitude of the harmonic components, while the horizontal axis indicates the frequency spectrum. The prominent peaks near the lower frequencies correspond to the fundamental harmonics, which are expected in the output of an inverter. As the frequency increases, the amplitude of the higher-order harmonics diminishes, demonstrating the reduction in harmonic distortion.

In all three phases, the FFT reveals a steep drop-off after the initial peak, suggesting that most of the energy is concentrated at the fundamental frequency. The gradual decrease in amplitude for higher frequencies indicates that the inverter is effectively minimizing harmonic distortion. However, slight variations in harmonic content between the phases are observed, suggesting that each phase may exhibit slightly different levels of distortion. Overall, the inverter appears to maintain good harmonic performance across all three phases, which is essential for ensuring efficient and reliable power delivery in applications such as three-phase solar power systems.

Figure 9 illustrates the output current waveforms for a three-phase system, showing the R-phase (a), S-phase (b), and T-phase (c). Each graph represents the sinusoidal nature of the current in its respective phase, with the y-axis indicating the current magnitude and the x-axis representing time. All three waveforms exhibit a smooth sinusoidal shape, suggesting balanced and stable output currents in each phase. The R-phase (a) waveform is shown in red, the S-phase (b) in blue, and the T-phase (c) in green. The waveforms are shifted by 120 degrees relative to each other, as expected in a typical three-phase system.

These sinusoidal waveforms indicate that the system is operating under normal conditions with minimal distortion, as no irregularities or sharp transitions are visible in the waveforms. This suggests excellent power quality, with consistent and balanced current output across all three phases. The clear phase shifts between the currents ensure proper operation of the three-phase system, minimizing the risk of unbalanced currents or harmonics. Overall, this demonstrates stable and reliable power output, contributing to optimal performance in electrical systems.



(a)

(b)

(c)

Figure 10. FFT Analysis for Output Current (a) R-Phase; (b) S-Phase; (c) T-Phase

Figure 10 displays a series of graphs showing the FFT (Fast Fourier Transform) analysis of the output current for three phases: R-phase (a), S-phase (b), and T-phase (c). In each graph, the y-axis represents the magnitude of the harmonic content of the current, while the x-axis indicates the frequency spectrum. For all three phases, the FFT results reveal a prominent peak at the fundamental frequency, followed by a rapid decline in the magnitudes of higher-order harmonics. This suggests that the output currents in each phase are predominantly influenced by their fundamental frequency, with relatively low harmonic distortion.

The harmonic content is most concentrated near the base frequency, with a gradual tapering off in the higher-order harmonics, a common characteristic of well-regulated electrical systems. The R-phase (a) shows the highest peak, followed by the S-phase (b) and T-phase (c), which exhibit similar patterns but slightly lower peak magnitudes. This analysis provides valuable insight into the quality of the current waveform, aiding in the identification of potential sources of distortion.

Table 1. Harmonic Analysis

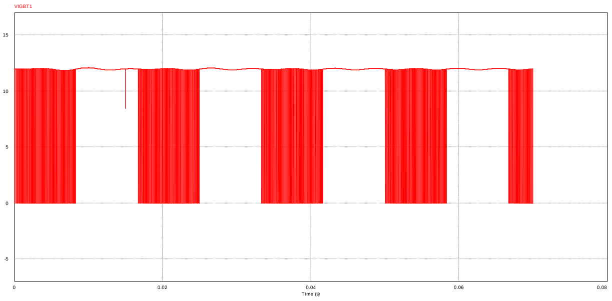
THD Voltage	
Harmonics Orde	**Value**
3rd Orde	0,4%
5th Orde	0,1%
7th Orde	0,1%
9th Orde	0,08%
11th Orde	0,09%
13th Orde	0,7%
THD Current	
Harmonics Orde	**Value**
3rd Orde	0,02%
5th Orde	0,006%
7th Orde	0,004%
9th Orde	0,002%
11th Orde	0,002%
13th Orde	0,001%

Table 1 presents the Total Harmonic Distortion values for both voltage and current across various harmonic orders. For voltage, the 3rd harmonic contributes 0.4%, the 5th and 7th harmonics each contribute 0.1%, the 9th harmonic contributes 0.08%, the 11th harmonic contributes 0.09%, and the 13th harmonic contributes the highest, at 0.7%.

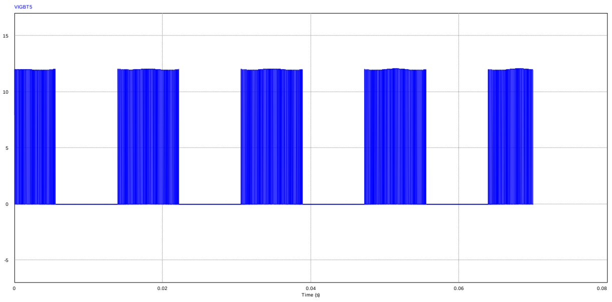
In contrast, the current THD values are much lower, with the 3rd harmonic contributing 0.02%, the 5th contributing 0.006%, the 7th contributing 0.004%, the 9th contributing 0.002%, the 11th contributing 0.002%, and the 13th harmonic contributing just 0.001%. These results suggest that the voltage harmonic more significant harmonic distortion than the current, particularly at the 13th harmonic order. However, the overall current harmonic distortion is minimal, indicating a higher quality current waveform compared to the voltage.

B. Stress Voltage on IGBT Component

In modern electrical technology, Insulated Gate Bipolar Transistors (IGBTs) have become essential components in a wide range of applications, including motor control and power conversion for renewable energy systems. However, one of the key challenges in using IGBTs is managing the stress voltage these components endure. Excessive stress voltage can lead to permanent damage, reduce component lifespan, and degrade overall system efficiency. Therefore, understanding the underlying mechanisms of stress voltage in IGBTs is crucial for ensuring optimal performance and reliability in both industrial and commercial applications. This article will explore the factors influencing stress voltage in IGBTs, as well as strategies to mitigate risks and enhance the reliability of these components.



(a)



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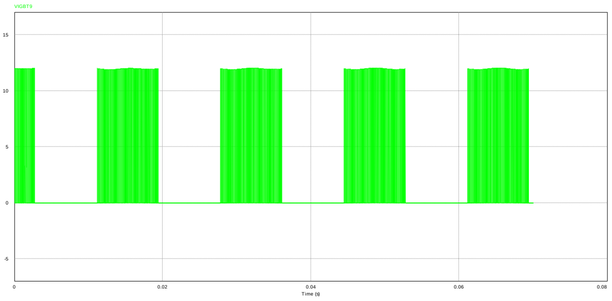

(c)

Figure 11. Voltage Stress on IGBT 1, IGBT 5, IGBT 9 through Drain-Source Section Observation

Figure 11 illustrates the voltage stress observed on IGBT 1, IGBT 5, and IGBT 9 through the drain-source section in three different conditions. In figure (a), represented by red bars, the voltage stress appears to be relatively high and somewhat inconsistent, indicating significant strain on these components, possibly due to higher switching frequencies or load variations. In figure (b), shown with blue bars, the voltage stress levels are lower and more uniform compared to figure (a), suggesting an improvement in the circuit, potentially due to optimized operating conditions or better control mechanisms. Lastly, figure (c), depicted with green bars, shows the lowest and most consistent voltage stress among the three, which could imply that further optimizations, such as the implementation of RC snubber circuits, have been applied to effectively mitigate voltage spikes. Overall, the decreasing voltage levels across the figures indicate progressive efforts to reduce stress on the IGBTs, likely improving their performance and lifespan in the system. This reduction in voltage stress not only enhances the reliability of the IGBTs but also contributes to the overall efficiency of the multilevel inverter system.

IV. Conclusion

The results of the study indicate that the Fast Fourier Transform (FFT) analysis of the inverter output voltage and current across the three phases (R, S, T) demonstrates good harmonic performance, with the majority of the energy concentrated at the fundamental frequency. In the voltage analysis, the primary harmonic peak is observed at the fundamental frequency, while higher-order harmonics exhibit a rapid decrease in amplitude. Although slight differences in harmonic content are noted between phases, the overall harmonic performance of the inverter remains excellent, which is crucial for maintaining the efficiency and reliability of the three-phase solar power system. The current analysis also shows the dominance of the fundamental frequency with low harmonic distortion. The highest current harmonic peak is found in the R-phase, while the S and T phases exhibit similar patterns with slightly lower amplitudes. Based on the Total Harmonic Distortion (THD) data, the harmonic distortion in voltage is more pronounced than in current, particularly at the 13th order harmonic. However, the overall harmonic distortion in current is minimal, indicating a higher quality current waveform compared to the voltage waveform.

Refference

[1] Widagdo, R. S., Andriawan, A. H., Slamet, P., Budiono, G., Wardah, I. A., & Hartayu, R. (2023, November). Harmonic Mitigation Using Passive Filters in 3-Phase Inverters to Improve Power Quality on Microgrid. In *2023 International Conference on Advanced Mechatronics, Intelligent Manufacture and Industrial Automation (ICAMIMIA)* (pp. 295-300). IEEE.

[2] El Hammoumi, A., Chtita, S., Motahhir, S., & El Ghzizal, A. (2022). Solar PV energy: From material to use, and the most commonly used techniques to maximize the power output of PV systems: A focus on solar trackers and floating solar panels. *Energy Reports*, *8*, 11992-12010.

[3] Srinivasan, G. K., Rivera, M., Loganathan, V., Ravikumar, D., & Mohan, B. (2021). Trends and challenges in multi-level inverter with reduced switches. *Electronics*, *10*(4), 368.

[4] Balal, A., Dinkhah, S., Shahabi, F., Herrera, M., & Chuang, Y. L. (2022). A review on multilevel inverter topologies. *Emerging Science Journal*, *6*(1), 185-200.

[5] Lopez, O., Teodorescu, R., Freijedo, F., & DovalGandoy, J. (2007, February). Leakage current evaluation of a singlephase transformerless PV inverter connected to the grid. In *APEC 07-Twenty-Second Annual IEEE Applied Power Electronics Conference and Exposition* (pp. 907-912). IEEE.

[6] Merai, M., Naouar, M. W., Slama-Belkhodja, I., & Monmasson, E. (2021). A systematic design methodology for DC-link voltage control of single phase grid-tied PV systems. *Mathematics and Computers in Simulation*, *183*, 158-170.

[7] Ali Khan, M. Y., Liu, H., Yang, Z., & Yuan, X. (2020). A comprehensive review on grid connected photovoltaic inverters, their modulation techniques, and control strategies. *Energies*, *13*(16), 4185.

[8] Boscaino, V., Ditta, V., Marsala, G., Panzavecchia, N., Tine, G., Cosentino, V., ... & Di Cara, D. (2024). Grid-connected photovoltaic inverters: Grid codes, topologies and control techniques. *Renewable and Sustainable Energy Reviews*, *189*, 113903.

[9] Goyal, V. K., & Shukla, A. (2020). Isolated DC–DC boost converter for wide input voltage range and wide load range applications. *IEEE Transactions on Industrial Electronics*, *68*(10), 9527-9539.

[10] Jamal, I., Elmorshedy, M. F., Dabour, S. M., Rashad, E. M., Xu, W., & Almakhles, D. J. (2022). A comprehensive review of grid-connected PV systems based on impedance source inverter. *IEEE Access*, *10*, 89101-89123.

[11] Callegari, J. M. S., Cupertino, A. F., de Nazareth Ferreira, V., & Pereira, H. A. (2020). Minimum DC-link voltage control for efficiency and reliability improvement in PV inverters. *IEEE Transactions on Power Electronics*, *36*(5), 5512-5520.

[12] Zidane, T. E. K., Aziz, A. S., Zahraoui, Y., Kotb, H., Aboras, K. M., & Jember, Y. B. (2023). Grid-connected Solar PV power plants optimization: A review. *IEEE Access*.

[13] Elsanabary, A. I., Konstantinou, G., Mekhilef, S., Townsend, C. D., Seyedmahmoudian, M., & Stojcevski, A. (2020). Medium voltage large-scale grid-connected photovoltaic systems using cascaded H-bridge and modular multilevel converters: A review. *IEEE Access*, *8*, 223686-223699.

[14] Alotaibi, S., & Darwish, A. (2021). Modular multilevel converters for large-scale grid-connected photovoltaic systems: A review. *Energies*, *14*(19), 6213.

[15] Blaabjerg, F., Yang, Y., Kim, K. A., & Rodriguez, J. (2023). Power electronics technology for large-scale renewable energy generation. *Proceedings of the IEEE*, *111*(4), 335-355.

[16] Khodaparast, A., Hassani, M. J., Azimi, E., Adabi, M. E., Adabi, J., & Pouresmaeil, E. (2020). Circuit configuration and modulation of a seven-level switched-capacitor inverter. *IEEE Transactions on Power Electronics*, *36*(6), 7087-7096.

[17] Siddique, M. D., Rawa, M., Mekhilef, S., & Shah, N. M. (2021). A new cascaded asymmetrical multilevel inverter based on switched dc voltage sources. *International Journal of Electrical Power & Energy Systems*, *128*, 106730.

[18] Majumdar, S., Mahato, B., & Jana, K. C. (2020). Analysis and implementation of a generalised switched-capacitor multi-level inverter having the lower total standing voltage. *IET Power Electronics*, *13*(17), 4031-4042.

[19] Biswas, S. P., Anower, M. S., Haq, S., Islam, M. R., Rahman, M. A., & Muttaqi, K. M. (2023). A new level shifted carrier based PWM technique for a cascaded multilevel inverter based induction motor drive. *IEEE Transactions on Industry Applications*, *59*(5), 5659-5671.

[20] Mondol, M. H., Biswas, S. P., Rahman, M. A., Islam, M. R., Mahfuz-Ur-Rahman, A. M., & Muttaqi, K. M. (2022). A new hybrid multilevel inverter topology with level shifted multicarrier PWM technique for harvesting renewable energy. *IEEE Transactions on Industry Applications*, *58*(2), 2574-2585.

[21] Zhang, G., & Yu, J. (2021). Open-circuit fault diagnosis for cascaded H-bridge multilevel inverter based on LS-PWM technique. *CPSS Transactions on Power Electronics and Applications*, *6*(3), 201-208.

[22] Saleh, A. A., Antar, R. K., & Al-Badrani, H. A. (2021). Design of new structure of multilevel inverter based on modified absolute sinusoidal PWM technique. *International Journal of Power Electronics and Drive Systems*, *12*(4), 2314.

[23] Widagdo, R. S. W., Budiono, G., & Novianto, M. I. (2023). Analysis of Capasitor Bank Installation for Power Quality Improvement at PT. Sunrise Steel. *Wahana*, *75*(2), 60-72.

[24] Widagdo, R. S., Setyadjit, K., & Wardah, I. A. (2023). Analysis and Mitigation of Harmonics Distortion with Optimization Capacitor Banks and Single-Tuned Passive Filters. *Jambura Journal of Electrical and Electronics Engineering*, *5*(2), 204-209.

[25] Widagdo, R. S., Andriawan, A. H., & Tauladan, I. S. (2023). Harmonic Mitigation with Active Filter in Coal Boiler Plant PT. Salim Ivomas Pratama. *Jurnal ELEMENTER (Elektro dan Mesin Terapan)*, *9*(2), 235-245.