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Three-Level Inverter: Advancing Voltage Control in Power Systems for Sustainable Energy Management

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Abstract: This study delves into the Three-Level Inverter, a notable innovation in power systems known for its enhanced voltage management features in comparison to conventional two-level inverters. By providing more voltage levels, it improves waveform control, which is essential for maintaining stability in the changing global energy environment. The inverter effectively tackles voltage instability concerns by using sophisticated modulation techniques, as shown by oscilloscope analysis and simulation results. The study's implications have a wide range of applications, including solar power systems and electronic device power supply, highlighting its social influence and potential for practical use in energy conversion.

Keywords: Three-Level Inverter, Voltage Control in Power Systems, Modulation Techniques for Voltage Stability, Renewable Energy Systems, Power Electronics Design and Technology.

1. INTRODUCTION

Within the domain of power systems, the precise control of voltage is a crucial aspect that supports the stability and reliability of electrical networks. The need for skilled energy management has significantly increased in recent years, driven by advancements in technology and the growing complexity of power distribution networks. Within this context, the deployment of sophisticated inverter technologies assumes a vital role in preserving ideal voltage levels and wrestling with the issues given by the undulations in power supply. A major breakthrough in this arena is represented by the Three-Level Inverter, a technical

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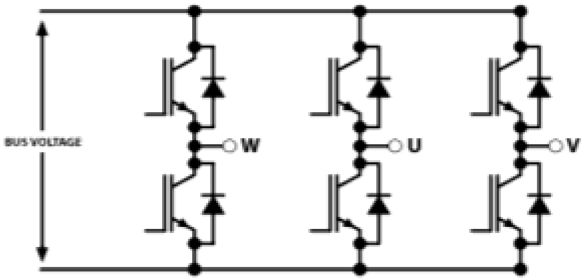
advancement that has received accolades for its prowess in boosting voltage management inside power systems [1]. Diverging from standard two-level inverters, the Three-Level Inverter offers additional voltage levels, so endowing a heightened degree of control over the output waveform. This improved granularity facilitates superior regulation of voltage, curbing aberrations and fluctuations that could potentially compromise the stability of the electrical system. Against the backdrop of a rapidly expanding global energy market, typified by an amplified focus on the integration of renewable energy and the deployment of smart grid technologies, the issue of voltage control assumes heightened significance. The Three-Level Inverter, armed with its enhanced modulation techniques and augmented capabilities, appears as a salient option in facing the present difficulties related with voltage instability in power systems. This scientific research offers a detailed examination of voltage regulation subtleties, exposing the vital significance of Three-Level Inverters in gaining exact control and bolstering the durability of contemporary power infrastructures [2], [3], [4].



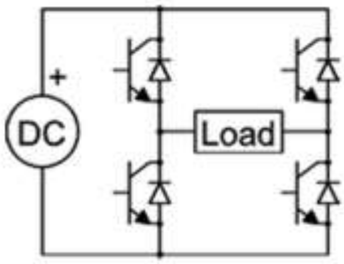


Figure 1: Multi Level and Three level inverter circuit.

2. LITERATURE REVIEW

A. Bendre, G. Venkataramanan, D. Rosene, and V. Srinivasan, “Modeling and design of a neutral-point voltage regulator for a three-level diode-clamped inverter using multiple-carrier modulation,” IEEE Trans. Ind. Electron., vol. 53, no. 3, pp. 718–726, Jun. 2006. This paper introduces a neutral-point voltage regulator for a three-level diode-clamped multilevel inverter, employing a multiple-carrier sine-triangle modulator and closed-loop control. The proposed approach minimizes voltage distortion and reduces the dc bus capacitance, validated through analytical, simulation, and experimental assessments [5]. D. G, N. R. Varma, A. Spandana, P. A. Kumar, B. Venumadhav, and B. P. Kumar, “Design and Implementation of Three-phase Three Level NPC Inverter,” in 2023 7th International Conference on Trends in Electronics and Informatics (ICOEI), Tirunelveli, India: IEEE, Apr. 2023, pp. 106–110. The three-level Neutral-Point-Clamped (NPC) PWM inverter, deployed in renewable energy systems such as wind turbines and PV installations, transforms DC power to AC with superior waveform quality than conventional two-level inverters. Renowned for its high power capacity and enhanced efficiency, the NPC PWM inverter emerges as a preferred choice for power electronic conversion in renewable energy applications [6]. N. Kishore, K. Shukla, and N. Gupta, “A Novel Three-Phase Multilevel Inverter Cascaded by Three-Phase Two-Level Inverter and Two Single-Phase Boosted H-

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Bridge Inverters," in 2022 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia), Singapore, Singapore: IEEE, Nov. 2022, pp. 330–334. This paper introduces a novel three-phase 9-level inverter topology, integrating two H-bridge inverters and a two-level three-phase inverter with PWM voltage boosting, leveraging three symmetrical DC sources and four switched capacitors for enhanced performance, reduced power electronics components, and simplified gate-driver circuits [7]. R. Davoodnezhad, D. G. Holmes, and B. P. McGrath, "A Novel Three-Level Hysteresis Current Regulation Strategy for Three-Phase Three-Level Inverters," IEEE Trans. Power Electron., vol. 29, no. 11, pp. 6100–6109, Nov. 2014. This paper proposes an innovative hysteresis current regulation strategy for three-level inverters, utilizing the measured average of the switched phase leg output voltage to dynamically adjust the controller's hysteresis band, ensuring a consistent phase leg switching frequency [8]. P. Chaturvedi, S. Jain, and P. Agarwal, "Carrier-Based Neutral Point Potential Regulator With Reduced Switching Losses for Three-Level Diode-Clamped Inverter," IEEE Trans. Ind. Electron., vol. 61, no. 2, pp. 613–624, Feb. 2014. This paper introduces a novel Neutral Point Potential (NPP) regulator for a three-level diode-clamped inverter, incorporating a sine-triangle regulator and closed-loop controller to minimize switching losses and enhance dc-bus voltage balance, leading to reduced voltage distortion and lower required capacitance. Experimental, analytical, and simulation results validate the proposed approach across varying load power factor angles [9]. Y. Hoon, M. Mohd Radzi, M. Hassan, and N. Mailah, "DC-Link Capacitor Voltage Regulation for Three-Phase Three-Level Inverter-Based Shunt Active Power Filter with Inverted Error Deviation Control," Energies, vol. 9, no. 7, p. 533, Jul. 2016. This article introduces an innovative inverted error deviation (IED) control technique integrated into the DC-link capacitor voltage regulation algorithm of a three-level neutral-point diode-clamped inverter-based shunt active power filter (SAPF). The proposed method demonstrates enhanced performance in mitigating harmonics by effectively addressing severe DC-link voltage deviations during dynamic-state conditions, as validated through MATLAB-Simulink simulations and experimental implementation on a TMS320F28335 Digital Signal Processor, outperforming conventional proportional-integral and fuzzy logic control algorithms [10]. O. Mikram, A. Abouloifa, I. Lachkar, M. Aourir, and H. Katir, "Flatness-Based-Control of Three-phase shunt active power filters based on five-level NPC inverter," in 2020 International Conference on Electrical and Information Technologies (ICEIT), Rabat, Morocco: IEEE, Mar. 2020, pp. 1–5. This paper presents a novel flatness control strategy for a three-phase shunt active power filter utilizing a five-level neutral-point-clamped inverter, aiming to simultaneously mitigate current harmonics and reactive power associated with nonlinear loads, while regulating the DC capacitor voltage through cascaded loops, validated through Matlab/Simulink simulations [11]. L. Vancini, M. Mengoni, G. Rizzoli, L. Zarri, and A. Tani, "Fault-Tolerant and Voltage Balancing Control for Five-Phase Three-Level T-type Inverters under Open-Switch Faults," in 2023 IEEE 14th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), Chania, Greece: IEEE, Aug. 2023, pp. 465–471. This paper presents a fault-tolerant technique for enhancing the reliability of five-phase three-level T-type inverters during Open Switch Faults (OSF), focusing on voltage balancing of dc-bus capacitors and demonstrating feasibility through simulation results[12]. C. Qin and X. Li, "Improved Virtual Space Vector Modulation Scheme for the Reduced Switch Count Three-Level Inverter with

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Unbalanced Neutral-Point Voltage Conditions," in 2022 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA: IEEE, Oct. 2022, pp. 1–6. This article introduces an Improved Virtual Space Vector Modulation (IVSVM) for a Reduced Switch Count (RSC) three-level inverter under unbalanced neutral-point voltage conditions, utilizing a revised space vector diagram and non-orthogonal coordinate system for duty cycle calculation, resulting in controlled voltages across dc-link capacitors and validated through experimental verification [13]. Y. Hoon, M. A. M. Radzi, M. K. Hassan, and N. F. Mailah, "Operation of Three-Level Inverter-Based Shunt Active Power Filter Under Nonideal Grid Voltage Conditions With Dual Fundamental Component Extraction," IEEE Trans. Power Electron., vol. 33, no. 9, pp. 7558–7570, Sep. 2018. This paper introduces a novel dual fundamental component extraction algorithm for three-level neutral-point diode clamped inverter-based shunt active power filters, ensuring harmonics mitigation and reactive power compensation under nonideal grid voltage conditions, without reliance on phase-locked loop elements, validated through MATLAB–Simulink simulations and TMS320F28335 DSP-based laboratory prototype experiments [14].

Background

The inverter design is based on the H-bridge topology, employing MOSFETs for efficient DC-to-AC conversion [15], [16]. The theoretical foundation includes capacitors for voltage stability, a voltage regulator for constant DC supply, and control elements like resistors and switches. The project aims to bridge the theoretical framework with practical implementation, emphasizing the importance of different components in achieving a reliable inverter system [17], [18].

Motivation

The quest of creative solutions in power electronics has been a driving factor in modern academic and industry research, reflecting the continual desire for better energy efficiency and sustainable technology. The inspiration for the project derives from the requirement to overcome issues inherent in AC power generating. The project's financial basis, backed by a prudent utilization of resources totaling 1191 Tk, displays a dedication to thrift while securing the procurement of critical components. The theoretical background of the research gravitates towards the creation and modeling of a Three-Level Inverter, a vital component in the conversion of DC to AC electricity. Embracing a careful approach, the project combines crucial parts such as capacitors, MOSFETs, resistors, and switches to maximize voltage control. The simulation phase, done in Proteus and controlled by an Arduino UNO, illustrates the project's commitment to precision and dependability in producing AC signals by MOSFET modulation. The hardware implementation of the inverter further highlights the project's practical aspect. Construction of a specialized enclosure, integration of MOSFET driving circuits, and the usage of an Arduino Nano board display a thorough balance of theoretical understanding and hands-on application. Safety precautions, societal issues, and ethical factors have been delicately knitted into the fabric of the project, assuring a responsible development approach. The socioeconomic impact of the Three-Level Inverter extends beyond simply technological achievement. With applications in renewable energy, motor drives, and industrial automation, the initiative connects with the global imperative of

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sustainable development. Ethical issues, shown in the implementation of ethical pricing schemes and a determination to prohibit illegitimate applications, emphasize the project's conscientious approach.

Objective

The objective of this research paper is to present a comprehensive investigation into the design and simulation of a Three-Level Inverter for voltage regulation in AC power generation. The study focuses on the meticulous integration of key components such as capacitors, voltage regulators, MOSFETs, diodes, resistors, switches, and LEDs to achieve stable and regulated AC output. The paper delves into the operational details of the inverter circuit implemented in Proteus, controlled through an Arduino UNO. The hardware prototype's complex assembly process, including the construction of an inverter box, banana sockets, MOSFET driver circuits, and Arduino Nano board, is detailed [19]. Operational parameters and user safety precautions are emphasized to ensure reliable performance and prevent mishaps. Societal considerations highlight the potential applications in renewable energy systems, motor drives, and industrial automation, contributing to improved energy efficiency and sustainable development. Ethical considerations underscore responsible pricing, application, and distribution practices, emphasizing the importance of avoiding harmful or unauthorized uses. The paper concludes with reflections on life-long learning, acknowledging the foundational concepts and outlining future plans for real-world applications, industrialization, and continuous skill development in the field of power electronics [20].

3. METHODOLOGY

In this research, we attempted to construct and simulate a Three-Level Inverter to handle voltage control difficulties in AC power generation. Our focus was on generating steady and regulated AC output through rigorous component selection and circuitry design. Firstly, capacitors (22µF, 0.1µF, 0.22µF) were strategically incorporated to provide voltage stability and eliminate undesired noise in the output waveform. The voltage regulator (7805) acted as the cornerstone of the control circuitry, delivering a consistent and controlled DC voltage supply. Key to successful DC-to-AC conversion were the IRLZ44N MOSFETs, chosen for their quick switching characteristics leading to better performance. Diodes were introduced to regulate current flow and avoid reverse voltage, ensuring circuit integrity. Resistors played a significant part in voltage division and current limiting, affecting the behavior of the control circuit. Switches (3 pins, 2 pins) permitted manual control and testing throughout the design process, while LEDs served as visual indicators delivering real-time input on the inverter's operating condition. The inverter's main purpose, converting DC to AC, was vital for different applications such as solar power consumption and powering electrical gadgets. We used the basic H-bridge architecture and examined two essential control strategies: basic frequency-variable bridge converter and PWM control [21]. Our simulation uses an oscilloscope to observe and evaluate the AC output, using Channel A as the output signal, Channel B as High output, Channel C as SD signal, and Channel D for Low output. Comparing the output signals, we noticed the formation of positive and negative AC waves

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through the regulated on-off states of switches. The shutdown signal was properly established between the off and on states of the high and low sides. This strategy resulted in a three-level inverter design. The simulation successfully proved the creation of AC output from a DC input, signifying the end of the inverter design process. In performing the design and modeling of a Three-Level Inverter to solve issues in AC power production, our methodology was careful and complete. The foundational components, including capacitors (22µF, 0.1µF, 0.22µF), were intelligently inserted to assure not only voltage stability but also the elimination of undesirable noise in the output waveform. This thorough consideration targeted at creating a high-quality AC output. The voltage regulator (7805) played a vital role as the cornerstone of the control circuitry, delivering a consistent and controlled DC voltage supply. This reliable DC supply was important for the later DC-to-AC conversion procedure. The choice of IRLZ44N MOSFETs was purposeful, using their quick switching characteristics to increase the overall performance of the inverter in effectively converting DC power to AC. To ensure the integrity of the circuit, diodes were included to regulate current flow and avoid reverse voltage. The role of resistors (10k, 1k) was multifarious, involving voltage division and current limiting, influencing the behavior of the control circuit [22], [23].

The presence of switches (3 pins, 2 pins) offered not only a way for human control but also permitted testing throughout the design phase, helping to the iterative development process. Visual indications in the form of LEDs were strategically positioned to deliver real-time input on the operating state of the inverter, ensuring that any difficulties or irregularities could be rapidly addressed. The ultimate purpose was to design a strong and dependable inverter that could be employed in numerous contexts, from solar power systems to powering electronic gadgets. Building upon the basic H-bridge architecture, we studied two essential control strategies: the basic frequency-variable bridge converter and PWM control. These tactics allowed us to alter the AC magnitude and phase, remove particular harmonics, and generate notches or 0-state areas in the output waveform. The variety of these tactics brought a layer of adaptability to our inverter design, making it appropriate for varied applications. The simulation approach required the use of an oscilloscope to see and evaluate the AC output. By designating distinct channels for output, high output, shutdown (SD) signal, and low output, we acquired significant information into the inverter's performance. The comparison of output signals demonstrated the successful synthesis of positive and negative AC waves through the regulated on-off states of switches, verifying the three-level inverter structure. A deeper analysis of the shutdown signal indicated our planned directive to turn on the shutdown signal between the off and on states of the high and low sides. This subtle approach contributed to the overall success of the simulation, displaying the meticulous attention to detail throughout the design and implementation phases. In summary, the research involved a systematic and extensive investigation of inverter design principles, component selection, and simulation analysis. The process includes a step-by-step integration of major components, strategic control tactics, and a special focus on obtaining steady and controlled AC output. The simulation results proved the effectiveness of our design, signifying the successful completion of the three-level inverter project [24].

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Simulation

A thorough simulation utilizing Proteus software was performed before implementing the circuit physically. The simulated prototype was extensively scrutinized within the software environment. The following diagram represents the whole circuit that has been carefully constructed and validated using simulation methods. Using Proteus as the simulation platform was an important initial step to ensure that the suggested circuit design would work properly and perform as expected before being implemented in the physical hardware prototype.

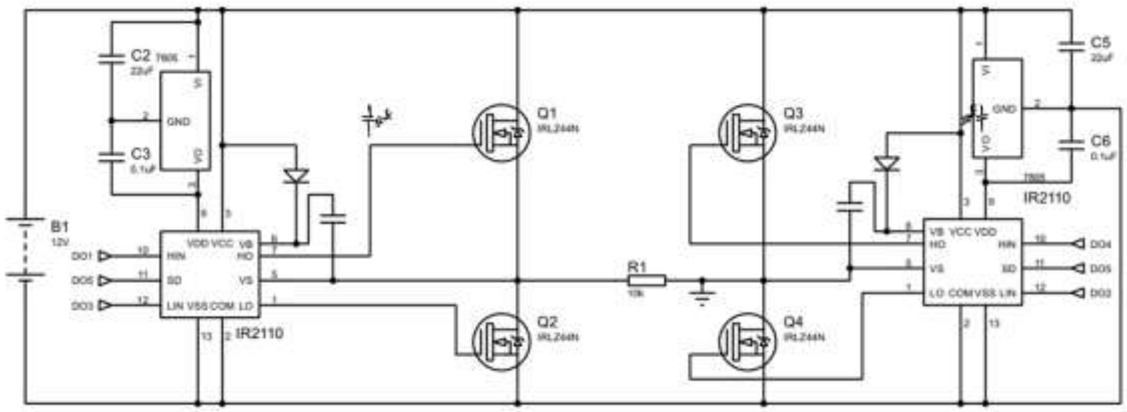

Figure 2: Diagram Layout

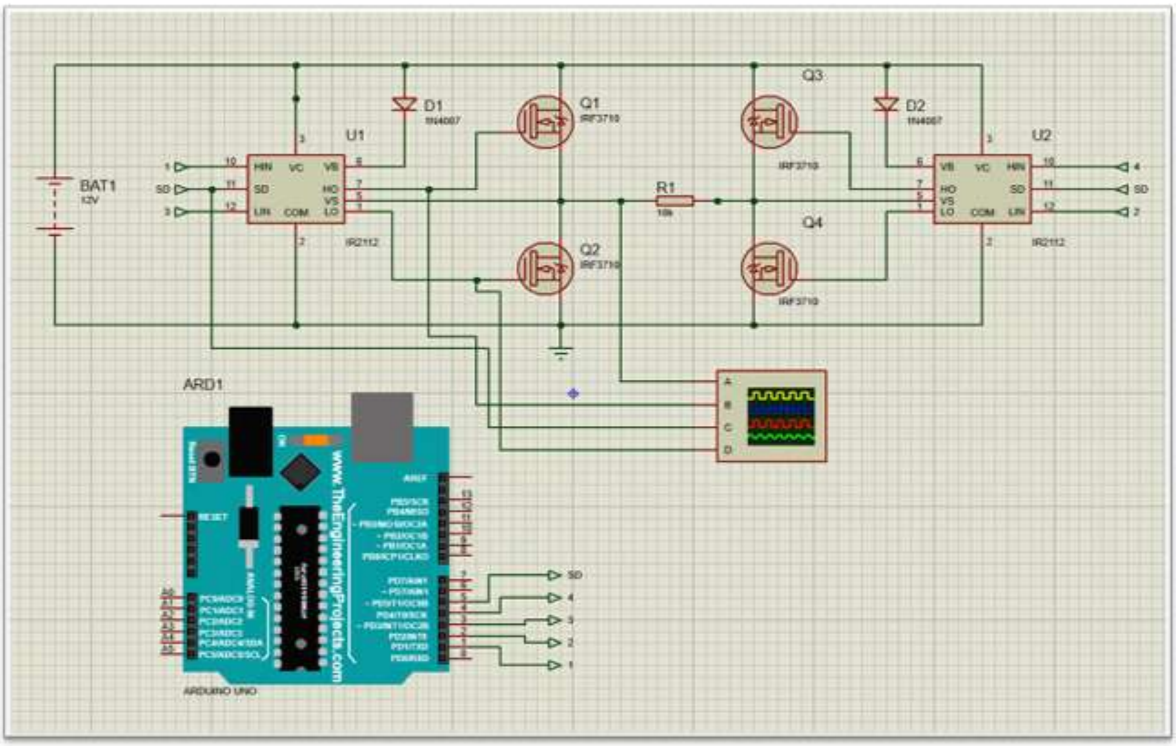

Figure 3: Simulation Diagram

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Hardware

In the pursuit of developing a meticulously designed and simulated Three-Level Inverter, our focus remains steadfast on achieving stable and regulated AC output. Our foundational components are strategically chosen to ensure optimal performance and reliability:

- Capacitors (22µF, 0.1µF, 0.22µF): Integrated with precision to promote voltage stability and minimize unwanted noise in the output waveform.
- Voltage Regulator (7805): Serving as the linchpin of the control circuitry, the voltage regulator guarantees a constant and regulated DC voltage supply.
- MOSFET (IRLZ44N): Leveraging the IRLZ44N MOSFETs for efficient DC-to-AC conversion, their fast switching characteristics contribute significantly to enhanced overall performance.
- Diode: Safeguarding the integrity of the circuit by controlling current flow and preventing reverse voltage.
- Resistors (10k, 1k): Employed for crucial tasks such as voltage division and current limiting, these resistors play a pivotal role in shaping the behavior of the control circuit.
- Switch (3 pins, 2 pins): Providing a manual control mechanism and facilitating testing during the design phase.
- LED: Serving as visual indicators, these LEDs offer real-time feedback on the operational status of the inverter.

  Through the meticulous integration of these components, we aim to achieve a Three-Level Inverter that not only meets but exceeds the stringent requirements of stable and regulated AC output, marking a significant advancement in power electronics design and technology. The intricacies of the task necessitated the creation of various components, encompassing:

- Construction of a dedicated enclosure for the inverter to ensure structural integrity and safety.
- Installation and connection of Banana Sockets, meticulously integrated to facilitate external connections and testing procedures.
- Development of two MOSFET Driver Circuits, a crucial element for the efficient operation of the inverter.
- Precise soldering of MOSFETs onto their designated locations within the circuit, ensuring proper connectivity and functionality.
- Completion of all additional connections within the circuit, emphasizing precision to uphold the integrity of the designed system.
- Integration of an Arduino Nano board, serving a pivotal role in the control and monitoring aspects of the inverter.
- Implementation of additional customizations tailored to optimize the inverter's performance.

The accompanying visual documentation presents a tangible representation of our hardware prototype, showcasing the meticulous attention to detail and the comprehensive nature of the implemented design and construction processes.

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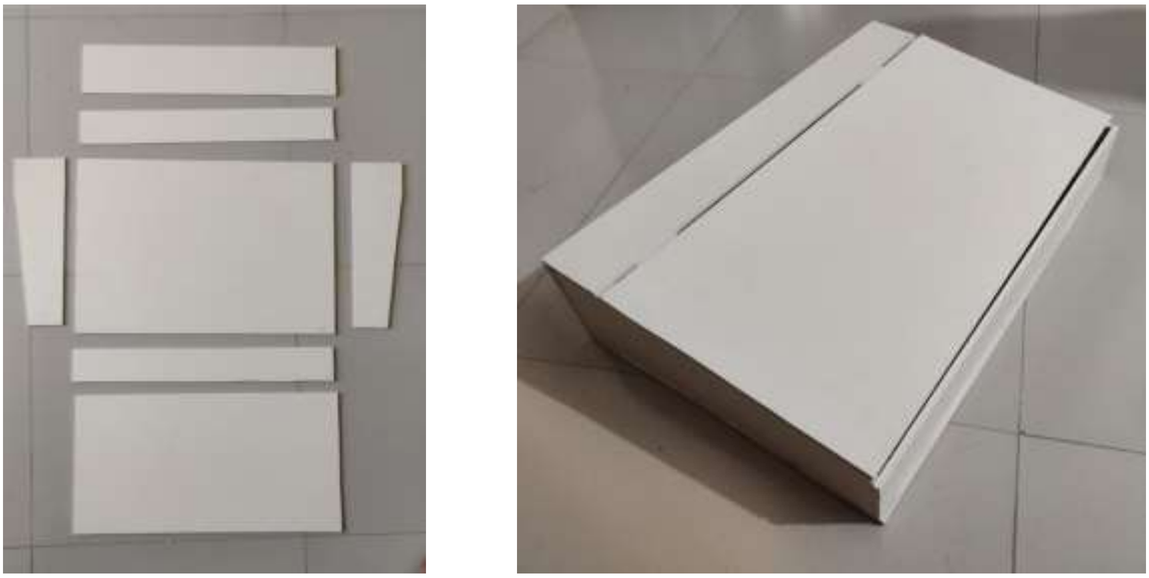

Figure 4: Handmade Cardboard box for the inverter.

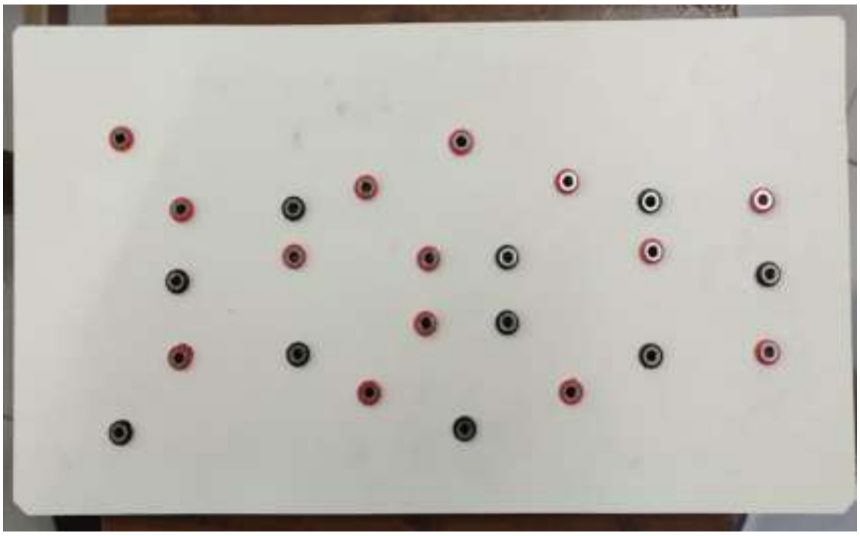

Figure 5: Banana Socket installed in the inverter box

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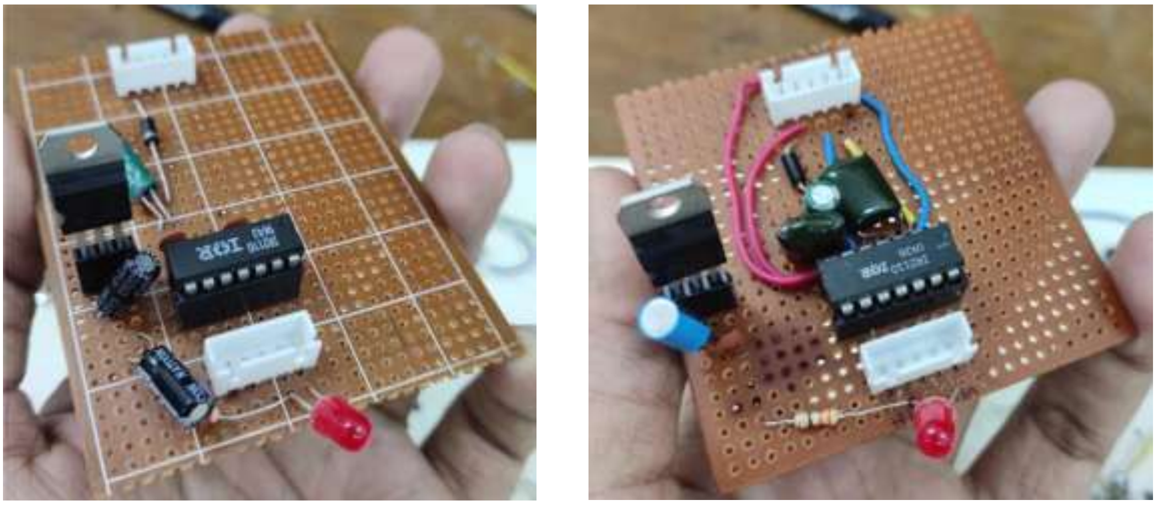

Figure 6: Two MOSFET Driver Circuit

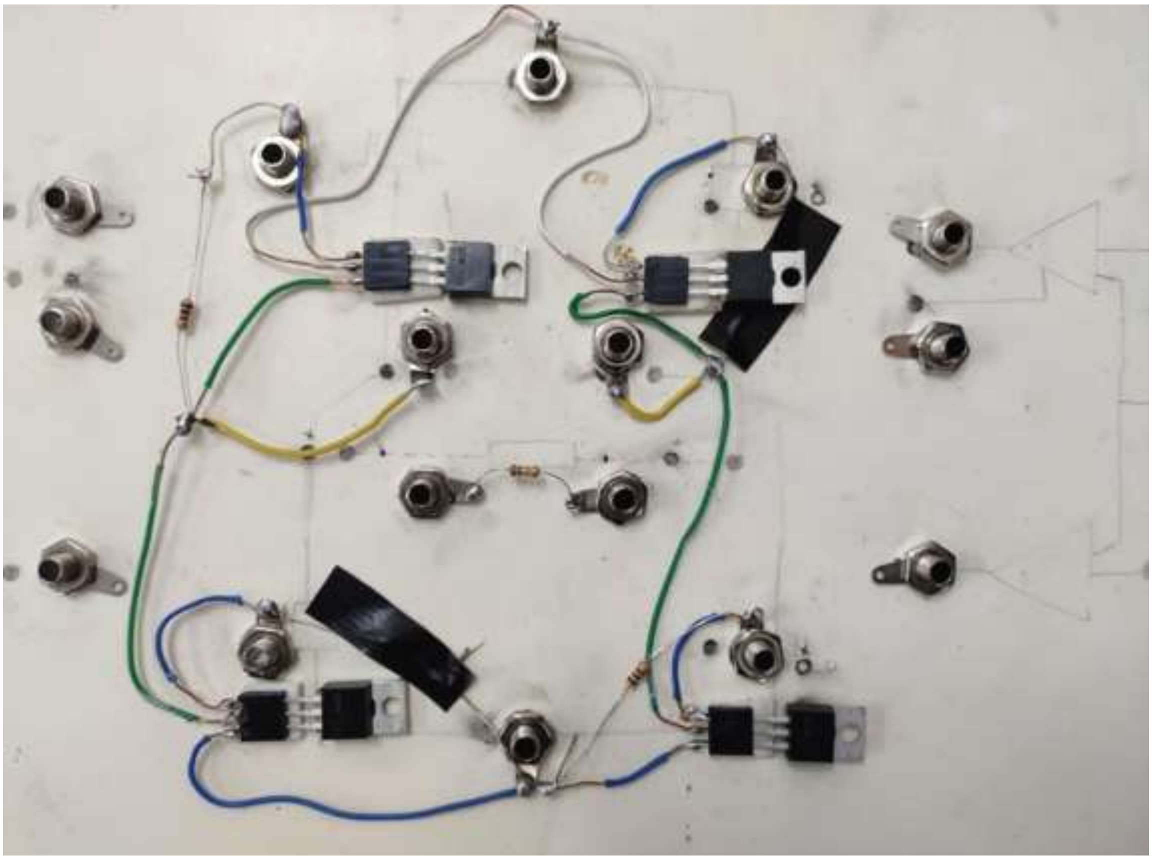

Figure 7: Soldered MOSFET at their place

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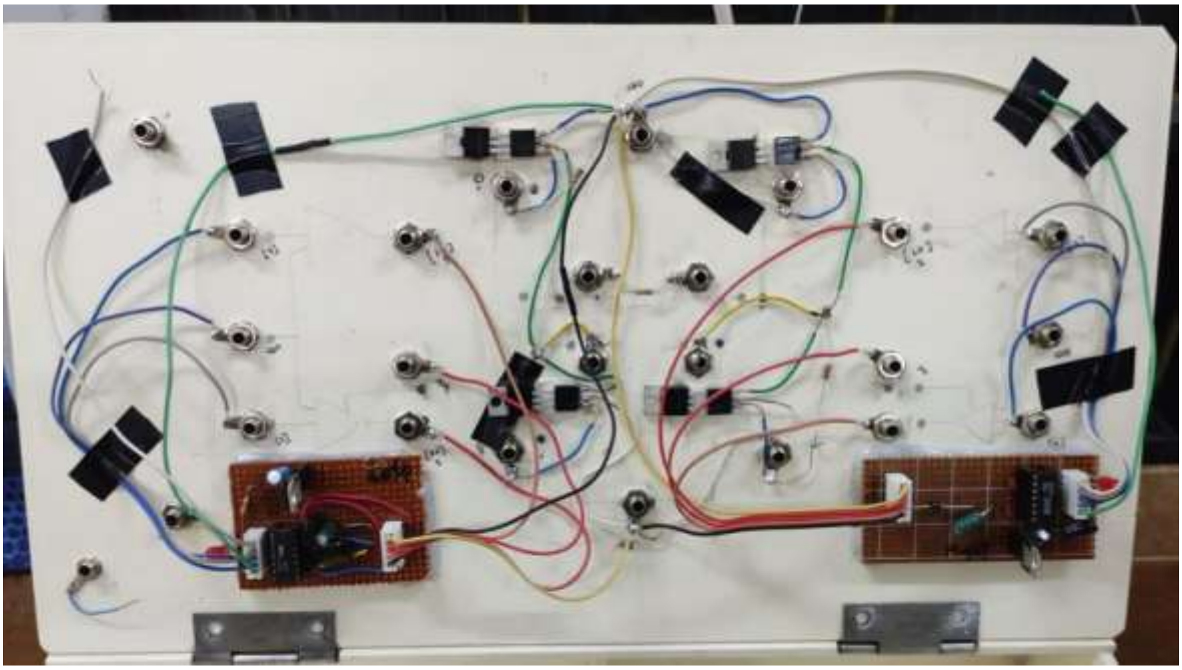

Figure 8: Complete Connection of the circuit

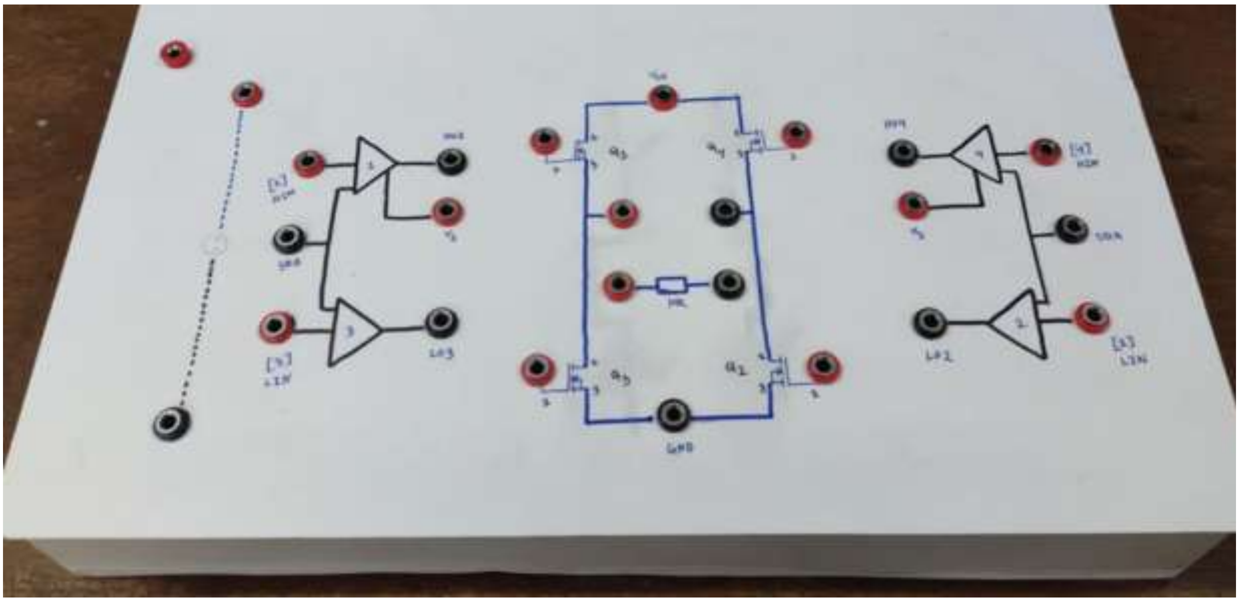

Figure 9: Final Patent Prototype

4. RESULT AND DISCUSSION

The oscilloscope was leveraged to examine and analyze the AC output, with separate channels designated for distinct signals. Channel A represented the Output Signal, Channel B designated the High Output, Channel C indicated the SD (Shutdown) signal, and Channel D

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represented the Low Output. In Figure 10, the simulation results were displayed, demonstrating the variances in these signals.

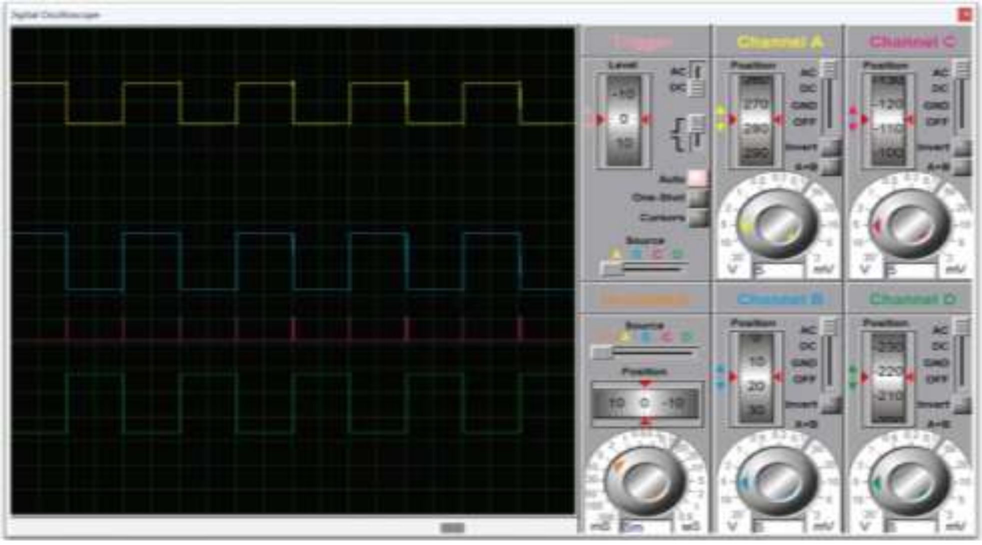

Figure 10: Simulation Result (Output, High O/P, SD, Low O/P)

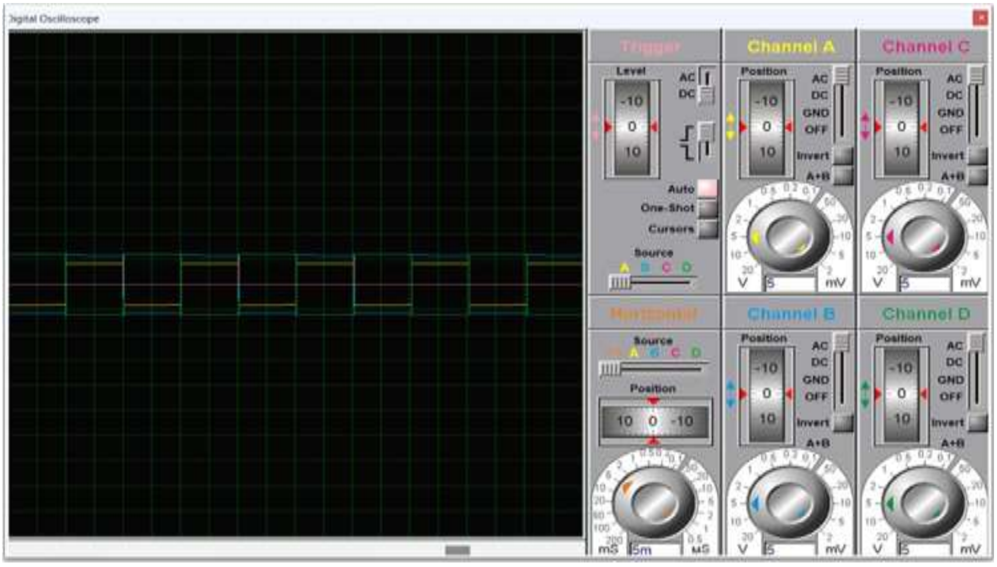

Figure 11: Comparison of Output Signal.

Figure 11 further digs into the comparison of the output signal, whereby all signals were aligned to the zero point for a thorough picture of the output waveform. The graphic depiction in this image elucidates the successful creation of an AC signal. Specifically, the high side and low side signals for switches 1 and 2 contributed to the positive AC wave, whereas the signals for switches 3 and 4 formed the negative AC wave. The presence of a tiny ground signal during the shutdown stage substantiates the implementation of a three-level inverter design. A deeper inspection of the shutdown signal reveals a purposeful

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directive to activate the shutdown signal between the off and on states of the high and low sides. This subtle approach increases the control mechanism and helps to the overall success of the simulation, verifying the three-level inverter design. The simulation findings corroborate the attainment of the stated objective: producing an AC output signal from a DC input. The difficulties of the inverter process have been successfully handled, signifying the conclusion of the inverter design project. This extensive study and visualization give vital insights into the operation and performance of the three-level inverter, establishing the groundwork for its possible use in numerous fields, such as solar power systems and electronic device power supply.

Future Scope

The project opens avenues for future applications in renewable energy systems, motor drives, and industrial automation. The efficient voltage regulation and reduced harmonic distortion contribute to sustainable development goals, aligning with energy efficiency and environmental concerns. Future plans include real-world applications and potential industrialization to meet broader energy conversion needs.

5. CONCLUSION

The meticulous design and simulation of a Three-Level Inverter demonstrate its capability for stable and regulated AC output. The combination of theoretical understanding, simulation, and hardware implementation reflects a comprehensive approach. The project's societal impact, ethical considerations, safety precautions, and lifelong learning aspects further contribute to its holistic significance in the field of power electronics.

Declaration

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.
Competing Interests: The authors declare that they have no competing interests.
Ethics Approval: Not applicable
Consent for Publication: The authors declare that all authors consented to the publication of this research and the included data.
Data Availability: The data used in this study are available from the authors upon reasonable request.

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