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Dynamic Energy Management and Low THD Operation of a 19-Level Cascaded H-Bridge Multilevel Inverter

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Abstract
As the globe puts more and more importance on clean and efficient energy, the usage of Renewable Energy Conversion Systems (RECS), such as solar photovoltaic and wind power technologies, is growing quickly. To connect these sources to the electricity grid, we need to create more sophisticated inverter technologies. This study looks at the modular multilevel inverter (MMI), a novel kind of architecture made for renewable energy applications that work at medium and high voltages. The MMI has a modular architecture that improves the quality of the voltage and makes it easier to scale. This architecture gives you more control, less harmonic distortion, and higher fault tolerance. Using state-space analysis, we create a whole mathematical model that shows how the MMI works on the inside. This approach comprises balancing the voltage of the capacitor and controlling the current that flows through it. This presentation talks about a complete control system that actively controls direct current regulation, balances voltage, and has ways to stop circulating current that work well. MATLAB/Simulink simulations show that the MMI works well with a solar PV system that is linked to the grid. The findings show that there is very little total harmonic distortion (THD), balanced submodule voltages, and a quick dynamic response to changes in the environment and the grid. The suggested model and control strategy guarantee efficient and dependable power conversion, establishing a foundation for future investigations into real-time control, fault diagnostics, and hardware-in-the-loop implementation within smart grid contexts.
Keywords: *Multilevel Inverter (MLI), Cascaded H-Bridge (CHB), Symmetric and Asymmetric Inverters, Neutral Point Clamped (NPC)*

1. Introduction
The rapid advancement of energy systems has intensified the need for effective, dependable, and adaptable power electronic (PE) solutions, particularly regarding the integration of renewable energy sources with contemporary electrical infrastructures [1]. Power electronics, using semiconductor devices like diodes, insulated-gate bipolar transistors (IGBTs), and metal-oxide-semiconductor field-effect transistors (MOSFETs), provide accurate voltage and current regulation via sophisticated control and conversion methodologies [2]. These systems are essential for converting electrical power among different forms, including AC to DC, DC to AC, and for voltage regulation via buck-boost operations. These conversions are essential in several applications, including renewable energy integration, electric vehicle (EV) charging systems, electric locomotion, industrial drives, High Voltage Direct Current (HVDC) transmission, and Flexible AC Transmission Systems (FACTS) [3]. In many situations, multilevel inverters (MLIs) are vital. They transform voltages and create high-quality waveforms, while also reducing total harmonic distortion (THD) [4]. In this work focus on hard to fix the problems of standard MLI topologies such as the cascaded H Bridge (CHB), flying capacitor (FC), and neutral-point clamped (NPC) inverters

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with new combinations. These new ideas aim to reduce the number of parts, improve voltage balancing, improve control techniques, and make the system more efficient and reliable overall [6]. This study focuses on model and evaluate modern multilayer inverter designs that meet smart grid criteria and work well with renewable energy sources. Aim of the research work to reduce THD, increase switching efficiency, and ensure that performance remains stable even when the load changes. This study focuses on how sophisticated MLI topologies can be used in the real world, such as in solar PV systems, wind power systems, and electric mobility [5]. This work advances the creation of smart and sustainable power conversion systems by combining theoretical modeling with real-world applications.

Renewable Energy Trends and the Role of Wind Power in a Sustainable

Energy drives our modern society, drives economic growth and improves our daily lives [7]. As traditional fossil fuels are depleting and pose environmental threats, there is a growing focus on renewable energy sources around the world. Wind power stands out for its maturity, scalability and cost-effectiveness [8]. Designers have made significant progress in wind turbine innovation, advancing grid integration and storage technologies to increase efficiency and reliability. In countries like India, where electricity demand is growing rapidly, wind power is emerging as a promising alternative to traditional energy sources. This technology provides clean, decentralized energy, which has a huge impact on populations in remote and rural areas [10]. Wind power is unique because it has little impact on the environment. It does not emit greenhouse gases and consumes very little water, making it a good choice for anyone who cares about the environment. More and more people around the world are supporting laws that promote renewable energy. This makes wind power an important aspect of our plans for sustainable energy [9]. New designs of wind turbines, ways of connecting them to the grid, and methods of energy storage have all made them far more efficient and reliable. In countries like India, where the need for electricity is growing rapidly, wind power is a potential alternative to traditional energy sources [10]. This technology provides clean, decentralized energy, which is vital for those living in remote and rural areas. Wind power is unique because it has a very low impact on the environment. It does not emit greenhouse gases and requires very little water, making it a good option for a sustainable future. More and more people around the world are supporting laws that promote renewable energy [11]. Wind power is an important aspect of our sustainable energy plans. To get the most out of energy systems and ensure adequate energy in the future, we need to be open to new ideas, make smart investments and put in place strong support systems [12].

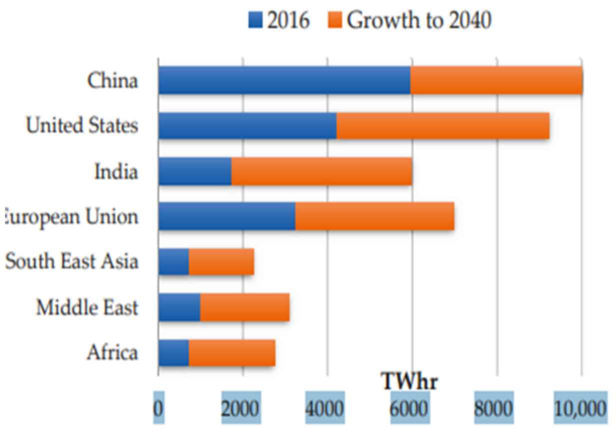

Figure 1 Global Energy Outlook

As shown in Figure 1, India uses the third most energy in the world. In June 2023, its peak consumption will be 223 gigawatts (GW), which is 3.4% more than in 2022. The power industry in the nation employs a mix of conventional fuels like coal, oil, and gas, as well as more ecologically friendly ones including solar, wind, biomass, and industrial waste. India's energy needs are expanding quickly since it has 1.4 billion people and the fastest-growing economy in the world. India has big plans for renewable energy in the short and long term [13]. At the COP26 climate summit in 2021, Prime Minister Modi announced the "Panchamrit." This plan includes reaching 500 GW of non-fossil energy capacity by 2030, meeting 50% of energy needs through renewable

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energy, cutting total projected carbon emissions by one billion tons, cutting the carbon intensity of the economy by 45% by 2030, and reaching net zero emissions by 2070 [14]. Permanent Magnet Synchronous Generators (PMSG) are becoming the go-to choice over Doubly Fed Induction Generators (DFIG). Their brushless design, improved efficiency, and lower maintenance requirements make them especially advantageous for offshore applications. Simulation technologies like the Finite Element Method (FEM) and Computer-Aided Design (CAD) platforms empower us to optimize mechanical, electrical, and aerodynamic factors [15]. Soft computing methodologies like fuzzy logic, neural networks, and evolutionary algorithms have made a significant impact on wind turbine control strategies. They empower us to enhance power forecasting, regulate dynamics effectively, and manage faults more efficiently (Figure 2).

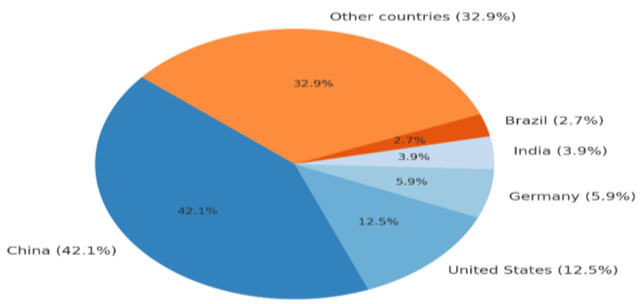

Figure 2 Total Accumulated Capacity of Global Wind Energy

2. Literature Survey

In this section II discuss the different recent research work presented in the last few years in the area of renewable energy.

Reving Masoud Abdulhakeem et.al (2025) This study presents the design and testing of a non-uniform 49-level cascaded inverter tailored for applications in renewable energy. DC power sources organized in a proportional voltage ratio (1:2:7:14), DC batteries with actual voltage values (40:80:280:560 V), along with photovoltaic (PV) panels are utilized to evaluate the performance of the inverter. With minimal harmonic distortion, the inverter produces high-quality sinusoidal output voltage and current waveforms, according to simulations. The inverter per unit exhibits an RMS voltage (VoRMS) of 16.9719V and an RMS current (IoRMS) of 1.0569A, alongside a total harmonic distortion of 0.71216% for voltage and 0.093319% for current. The system delivers actual voltage metrics, showcasing VoRMS at 679.0492V, IoRMS at 4.265A, with THDVo recorded at 0.71227 % and THDIo at 0.16719 %. The inverter reaches VoRMS = 692.7293V and IoRMS = 43.1367A using PV modules, with THD values for output voltage and current recorded at 1.2926 % and 0.33963 %, respectively. The results highlight the inverter's flexibility and effectiveness in generating superior power with minimal harmonic distortion, positioning it as an appropriate option for existing renewable energy systems and industrial uses. [01].

Prasad Kumar Bandahalli Mallappa et.al (2025) Using fewer semiconductor switches, a 25-level architecture and a new asymmetrical 15-level MLI (multilevel inverter) topology are suggested. values provided by alternative topologies suggested in the cited literature, this design seeks to improve the inverter's reliability and efficiency while lowering its size and cost. The MLIs that are being described exhibit low total harmonic distortion (THD) and are capable of producing the necessary output voltage levels with little waste. The cost function and total standing voltage (TSV) were calculated by analyzing setups with different amounts of MLI. The results indicate that the reduced TSV value of the proposed MLI enhances its affordability, efficiency, and market position. Based on experimental evaluations, the design generates energy featuring minimal harmonic content that meets IEEE standards., making it ideal for grid-connected applications and dynamic voltage restorer (DVR) technologies [02].

Rabail Memon et.al (2024) Multilevel inverters (MLIs) excel in medium- and high-power applications, like solar systems, thanks to their ability to deliver improved power quality. However, the many switches and the high voltage stress they endure increase the overall costs of the system. The proposed 17-level asymmetrical MLI showcases reduced components and minimal voltage stress, tackling these challenges in the solar system head-on. This MLI configuration includes four direct current sources and ten switches. The proposed configuration utilizes solar panels paired with boost converters and fuzzy logic controllers as direct current sources, derived from the trinary sequence. The suggested structure is modeled in MATLAB/Simulink®. The proposed configuration ensures an even distribution of stress among the switches, featuring CC/L values of 1.23, 5, and CF/L values of 4.58 and 5.76, respectively, along with weight coefficients of 0.5 and 1.5. These values exceed the performance of MLI configurations. Models indicate that the proposed configuration functions dependably across a range of loads and modulation indices with fuzzy logic controllers, delivering stable output under varying irradiance conditions. [03].

Ahmed Awadelseed et.al (2024) The suggested arrangement consists of an upper section and a lower section. The upper cell features a standard H-bridge, whereas the lower cell incorporates a switching capacitor-driven 5-level inverter. Single-phase isolation transformers link the load to both lower and higher cell outputs. Fewer switches are required for the suggested single-phase isolated inverter to generate a AC output voltage at 15 levels featuring a gain of 7. The switches in the suggested inverter demonstrated lower voltage stress when compared to MLIs found in existing studies. The proposed inverter design is evaluated against existing MLIs found in the literature. The PLECS software models the inverter across various operational conditions, guaranteeing balanced capacitor voltage and satisfactory power quality, even with a low modulation index for the suggested MLI. The effectiveness of the inverter is confirmed through experimental results obtained from a low-power lab prototype. Results from the simulation suggest an asserted efficiency of 97.1% for the inverter. The effectiveness derived from experimental results stands at 96.4% when operating at 700W. [04].

Md. Tariqul Islam et.al (2023) This study suggests a five-level inverter architecture with fewer components to provide reliable AC voltages for grid-integrated solar PV applications. The suggested design generates five-level outputs using seven low-TSV switching devices, three diodes, and two DC-link capacitors. DC capacitor voltages balance naturally with charging and discharging cycles. Thus, no extra sensors or control circuits are needed. It can enhance voltage without an input boost converter. The standalone system uses low-frequency-based half-height (HH) modulation to enhance voltage quality. In MATLAB/Simulink, extensive simulations assess the performance of the suggested topology, yielding 17.58% THDs in phase voltages. With a tiny inductor in series or an For an inductive load, the total harmonic distortion of the current decreases to 8.23%. Enhanced dynamic performance is observed across different loading conditions [05].

Fatima Z. Khemili et.al (2023) This project aims to provide an effective control system for a three-phase H-bridge multilevel inverter driven by photovoltaics. PV modules produce electricity for the system, acting as DC inputs for the cascaded H-bridge multilevel inverter. The authors strive for a nearly sinusoidal voltage signal and minimize total harmonic distortion (THD) to the lowest achievable amount. Thus, an advanced N-level SVM is created to provide proper control for the cascaded inverter. The goal is to create a control strategy that optimizes inverter efficiency and output quality. Furthermore, a robust MPPT strategy is created using an adaptive perturb and observe (P&O) algorithm to enhance MPP tracking. The technique reduces power curve size by 90% and preserves just 10% of the MPP area in the search space process. Each PV system has better MPPT control [06].

Md. Halim Mondol et.al (2022) This article introduces a novel compact cascaded module three-phase MLI architecture with a broader configuration. The system schematic design, switching scheme, operating principle, loss calculation, and thermal analysis of the proposed MLI are thoroughly explained. We investigated the performance of the proposed inverter in both solo and grid-tied modes using a typical PI control technique. The simulation findings demonstrate

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that the inverter works well with the PI control scheme and can reduce grid imbalances with little settling time. Also, it handles rapid load variance well. Experiments evaluate the steady performance of the proposed MLI against sudden load and pf fluctuations. Hence, the suggested inverter offers various advantages over current topologies, including: 1) Reduced circuit elements needed for output level, 2) Moderate TSV with lower equipment costs, 3) Improved current harmonic profile and high-quality AC power, and 4) Low losses and increased conversion efficiency (approximately 95.23%) [07].

Sajjad Ahmed et.al (2022) the suggested architecture with an electric power grid, inverter design equations and feedback controller equations are constructed to determine parameters like voltage levels and DC power sources. The control system for the proposed topology is modeled using a synchronously rotating reference frame for single-phase systems. The suggested inverter system uses the binary search closest level technique for effective PWM generation, tracking grid voltage signals. The suggested system merges the grid and inverter without an output filter. An efficiency study indicates that the suggested system provides active and reactive electricity to the grid with a 90% efficiency and a THD of 1.04%. The voltage and current waveforms show that the proposed system has excellent transient and steady-state performance for dynamic active and reactive power flow (Table 1). Simulate the system in MATLAB/Simulink and verify findings using a hardware prototype circuit implementation [08].

Table 1 Comparison of Previous Different Methods

Ref	Authors & Year	MLI Type / Topology	Key Features	Applicatio n	Simulation /Prototype	Efficiency / THD / Output
[01]	Reving Masoud Abdulhakee m et al. (2025)	49-level asymmetric al cascaded inverter	Per-unit ratio (1:2:7:14); PV and batteries; sinusoidal output	Renewable energy systems, industrial	MATLAB simulation	VoRMS: 692.73V, IoRMS: 43.14A, THDVo: 1.29%, THDIo: 0.34%
[02]	Prasad Kumar Bandahalli Mallappa et al. (2025)	Asymmetri cal 15- and 25-level MLIs	Fewer switches; reduced TSV and cost; grid-compliant	Grid-tied, DVR	Experiment al validation	Low THD, high reliability, improved cost-competitiveness

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[03]	Rabail Memon et al. (2024)	17-level asymmetric al MLI	4 DC sources, 10 switches; trinary logic; fuzzy controller	Solar PV systems	MATLAB/ Simulink	Better CC/L & CF/L values; stable under varying irradiance
[04]	Ahmed Awadelseed et al. (2024)	15-level hybrid inverter (switching capacitor + H-bridge)	Transformer-isolated; reduced stress; gain of 7	Single-phase isolated inverter	PLECS + hardware prototype	Sim: 97.1%, Exp: 96.4% efficiency
[05]	Md. Tariqul Islam et al. (2023)	5-level inverter	7 switches, 3 diodes; no extra sensors; natural voltage balancing	Grid-integrated solar PV	MATLAB + hardware proto	THD voltage: 17.58%, THD current: 8.23%
[06]	Fatima Z. Khemili et al. (2023)	3-phase cascaded H-bridge MLI	Advanced SVM; MPPT with adaptive P&O	PV-powered systems	Simulation	Reduced THD; better MPPT efficiency and tracking speed
[07]	Md. Halim Mondol et al. (2022)	Compact 3-phase cascaded module MLI	Loss and thermal analysis; PI control	Grid-connected + standalone	Sim + Experiment	~95.23% efficiency, low settling time, harmonic reduction
[08]	Sajjad Ahmed et al. (2022)	Modified W-type 81-level single-phase inverter	Grid-tied; binary search PWM; no output filter	Renewable energy grid-integration	MATLAB + Hardware	Efficiency: 90%, THD: 1.04%, reactive/active power control

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3. Proposed Methodology

This research advances multilevel inverter (MLI) technology by modeling and analyzing CHB, NPC, FC, and hybrid topologies under symmetric and asymmetric configurations. Using MATLAB/Simulink and PSIM, the study evaluates performance under solar PV and wind conditions, focusing on reducing THD via advanced modulation techniques like SHE and PSPWM. It addresses dynamic energy inputs, voltage stress, thermal behavior, MPPT integration, and real-time control. Fault tolerance, capacitor balancing, and EMI/EMC impacts are also examined. Hardware prototypes validate performance in grid/off-grid modes. The study proposes scalable MLI architectures for hybrid systems with economic and IEEE-519-compliant performance assessments (Figure 3 and Table 2).

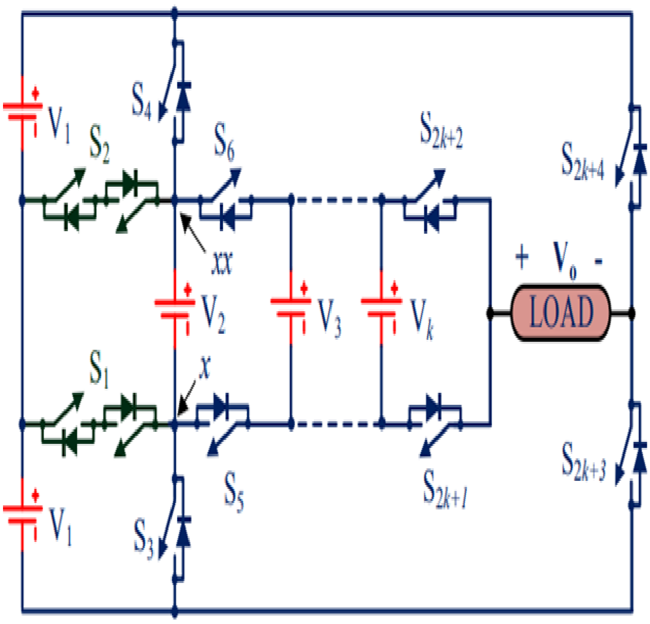

Figure 3 Generalized Structure of the Proposed MLI

Table 2 Switching Table for the Basic Module (13-Level MLI)

S1	S2	S3	S4	S5	S6	S7	S8	Output Voltage (Vo)
0	0	1	0	1	0	1	0	Zero Positive Level
1	0	0	0	1	0	1	0	V_1
0	0	1	0	0	1	1	0	V_2
0	0	0	1	0	1	1	0	$2V_1$
0	1	0	0	1	0	1	0	$V_1 - V_2$
1	0	0	0	0	1	1	0	$V_1 + V_2$
0	0	0	1	1	0	1	0	$2V_1 - V_2$
0	0	0	1	0	1	0	1	Zero Negative Level
0	1	0	0	0	1	0	1	$-V_1$
0	0	0	1	1	0	0	1	$-V_2$
0	0	1	0	1	0	0	1	$-2V_1$

The proposed MLI achieves a Total Harmonic Distortion (THD) of 3.89%, closely matching topologies in [45] and [46], which report 3.72% and 3.78% respectively, but with fewer switches and sources. It complies with IEEE 519 standards, ensuring suitability for grid integration. The inverter also demonstrates high efficiency at 93.67%, outperforming [45] (93.49%) and significantly surpassing [43], which records only 87.72% efficiency (Figures 4-6).

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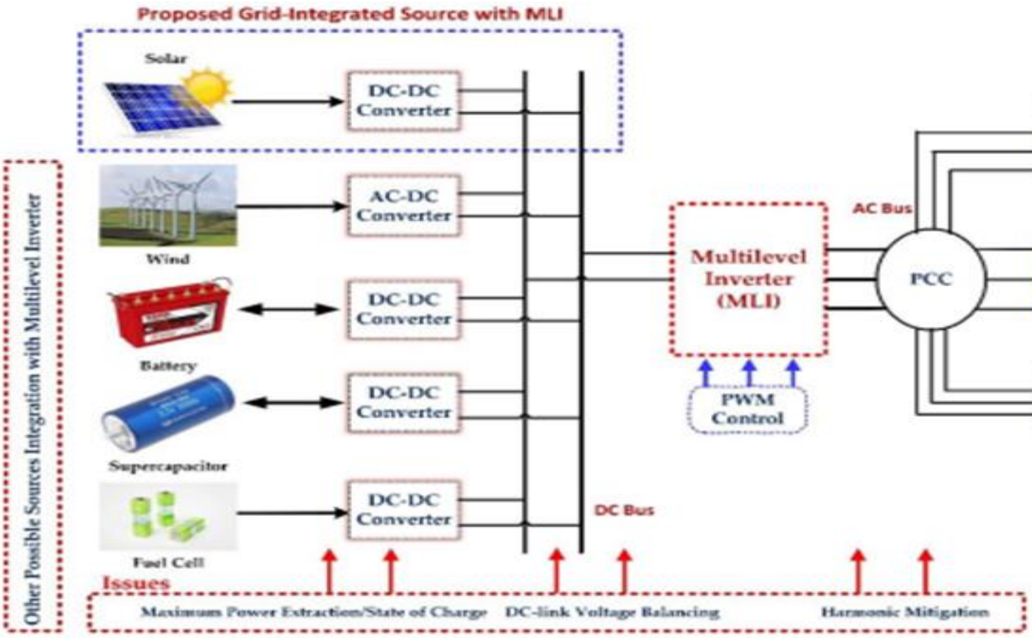

Figure 4 **MLI-Based System Integration of Renewable Energy Sources**

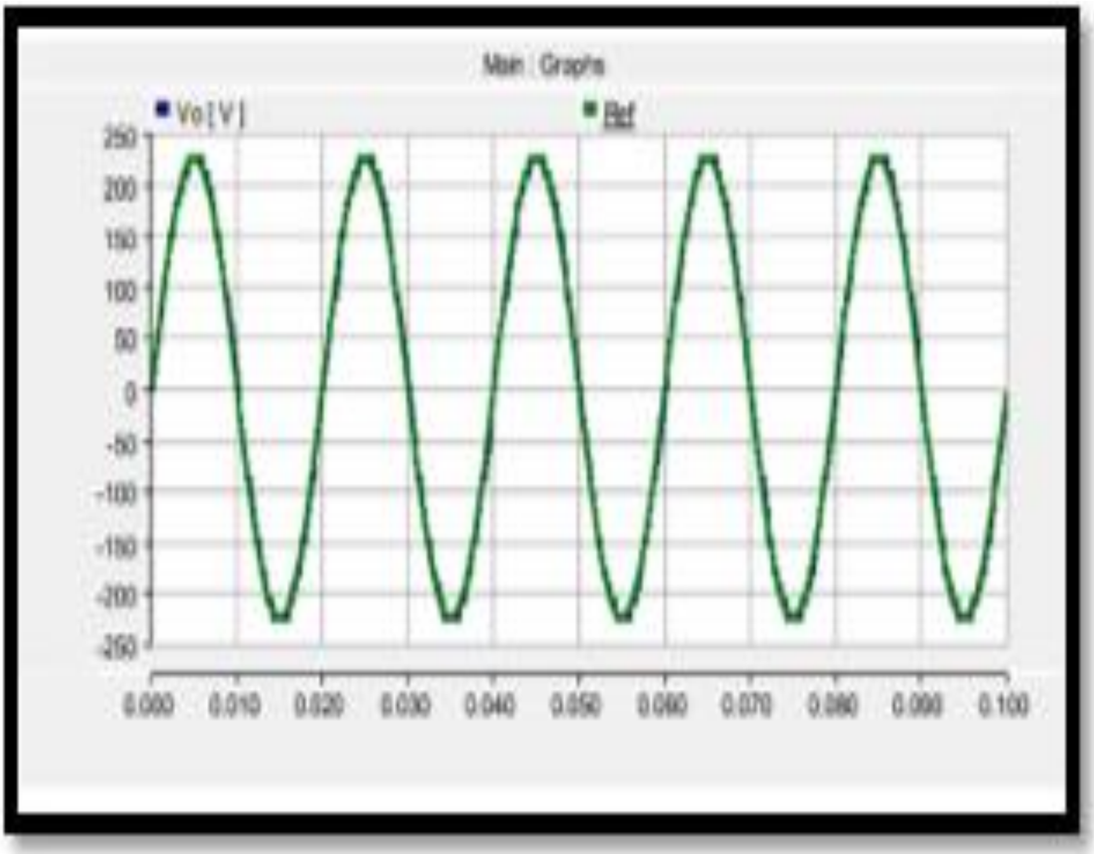

Figure 5 **Load voltage and reference voltage waveforms**

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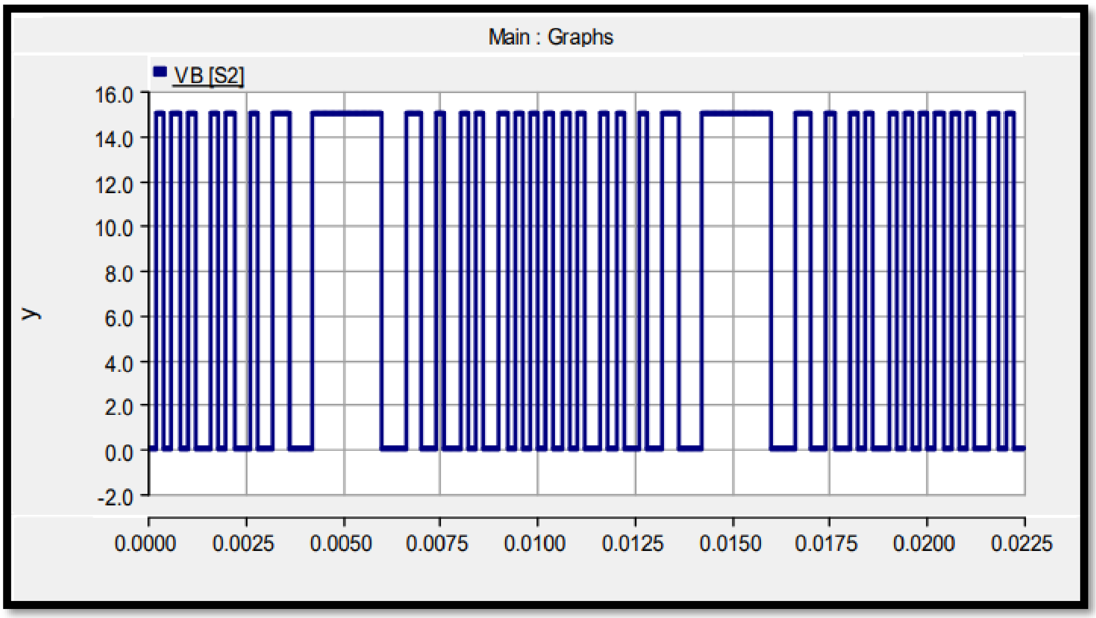

Figure 6 **Load current waveform in multiple micro range**

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Conclusion

This article presents a significant advancement in multilevel inverter (MLI) technology through the design and validation of a novel single-phase 31-level inverter topology. By combining two sub-multilevel stages with an H-bridge, the proposed structure achieves high-resolution output using only 4 DC sources and 12 switches, offering reduced hardware complexity and lower power losses. A systematic comparison of symmetric and asymmetric configurations confirmed the superior performance of trinary asymmetric topologies in generating more voltage levels with the same component count. Operated under fundamental frequency control, the proposed inverter demonstrated excellent waveform quality, with low THD and efficient power delivery, validated through both analytical models and PSCAD/EMTDC simulations. Additionally, switch blocking voltages and loss calculations closely aligned with theoretical predictions. The simplified structure, high efficiency, and grid compatibility make this topology highly suitable for renewable energy integration and space-constrained applications. Overall, this work contributes a practical, cost-effective, and high-performance solution to modern power electronic systems.

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