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Renewable Energy based Multilevel Inverter to Enhance Resilience in Distribution Network through Domestic Load Reduction



Abstract: - As the demand for electricity grows, the distribution network faces numerous challenges, making the need for reliable energy solutions increasingly important. This paper proposes a method to integrate renewable energy sources through a novel Multilevel Inverter (MLI) configuration. The multilevel inverter has attracted significant interest in the industry due to its ability to improve power quality by reducing harmonic distortion. A new inverter design with fewer switching components for photovoltaic (PV) systems is introduced. The inclusion of a boosting circuit in this inverter configuration allows the achievement of an output voltage having seven-level with enhanced gain. To achieve this, proposed design employs three balanced voltage sources and ten semiconductor switches. To optimize energy extraction from the available low value input, the Perturb and Observe (P&O) method is utilized for maximum power point tracking (MPPT). This method helps to regulate the voltage and improves the capability to deliver power under varying conditions to the load. The boosting circuit connects the solar input to the inverter having H-bridge, and the system is modulated using a modulation called sinusoidal PWM. The working principle, along with simulation and laboratory prototype, is thoroughly examined to confirm the performance and practicality of this system, demonstrating its potential to improve the resilience of the power distribution network by reducing domestic energy demand.

Keywords: Photovoltaic system, multilevel inverter, maximum power point tracker, sinusoidal pulse width modulation, and perturb & observe algorithm.

I. INTRODUCTION

Recently, renewable energy sources have gained significant attention. The initiatives aimed at boosting their production capacity. Clean and environment-friendly energy harvesting has emerged as a critical component. It is particularly compelled to transition away from fossil fuels, a major contributor to global warming. The solar energy gained more attention due to its more availability and environmentally friendly nature [1]. Solar energy has become a promising solution for developing nations, including India, to meet their escalating energy demands, offering a sustainable departure from conventional electricity generation. The competitiveness of solar systems has made them an attractive choice for residential, commercial, and industrial users, whether for standalone or grid-connected operations [2]. Remote off-grid communities have embraced hybrid renewable energy-based micro-grids, but designing optimal systems poses challenges due to unpredictable resource availability, fluctuating load demands, and high component costs, prompting the development of advanced optimization algorithms. The output of photovoltaic (PV) panels fluctuates due to solar irradiation and temperature variations, but implementing Maximum Power Point Tracking (MPPT) algorithms optimizes energy harvesting [3].

Given the essential role of inverters in PV systems, Multilevel Inverters (MLIs) have become the preferred choice over traditional Voltage Source Inverters (VSIs) due to their superior power quality output by reducing the harmonics. The multilevel inverters are generally divided into three, Cascaded H-Bridge (CHB) type MLI, Switched Diode (SD) type MLI, and Flying Capacitor (FC) type MLI [4]. Multilevel inverters (MLIs) are categorized into symmetrical and asymmetrical configurations, determined by the magnitude of the voltage sources utilized. Identical voltage sources are used in symmetrical configuration, whereas asymmetrical MLI's employ unequal magnitudes of voltage sources. The symmetrical configuration offers enhanced performance due to increased redundant states, facilitating improved voltage balancing and enhanced fault tolerance across the capacitors. In

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contrast, asymmetrical MLIs can produce an output having greater number of levels at voltage sources while utilizing the same quantity of switching components as their symmetrical counterparts [5], [6].

The effectiveness of MLIs is largely depends on the choice of techniques used for modulation. Maximizing the performance of MLIs requires careful optimization. For that, different Pulse Width Modulations (PWMs) are employed sinusoidal PWM and space vector PWM reduce harmonic distortion and switching losses, improving DC-link utilization. Selective Harmonic Elimination PWM (SHE-PWM) eliminates specific harmonics, and Nearest Level Modulation (NLM) reduces switching losses. Hybrid PWM combines techniques to leverage advantages. Optimization technique based on Particle Swarm and optimization algorithm based on Genetics are used to refine PWM patterns, minimizing distortion caused by the harmonics and switching losses.

Traditional Multilevel Inverters (MLIs) have significant drawbacks, including high component counts, complex voltage balancing, limited scalability, and high losses. They also suffer from bulky designs. The increased count only cause complexity of the traditional MLIs and it increases power losses. To rectify the disadvantage of traditional MLI, new reduced component count topologies are proposed. The validation of Reduced Switch Count (RSC) MLIs were reviewed in several papers. Researchers propose an innovative asymmetrical MLI topology with component count reduction, suitable for a wide range of applications [7]. A novel of transformer-less single-phase MLI is developed in paper [8]. A triple boost inverter of single phase setup is proposed for the grid-tied applications in paper [9]. The authors did a survey on the different reduced component topologies explained in paper [10]. A triple voltage boost gain-based seven-level inverter is introduced in [11]. A reduced switch CHB topology is introduced and explained in [12]. The paper [13] proposes an inverter design that incorporates inherent self-balancing capabilities and mitigates voltage stress. Improved PUC inverter topology is proposed in [14]. However, all the topologies considered for the study uses more number of components than the proposed topology. A seven level RSC MLI topology with booster capability proposed in this paper focuses on maximizing the levels of output and minimizing the number of semiconductor switches. The organization of this paper is outlined as: Section II represents the renewable energy based MLI modelling, Section III provides a detailed analysis of various simulation results and compares them with the other topologies. Section IV includes hardware results and lastly, Section V provides a summary of the paper

II. PROPOSED SYSTEM MODELLING

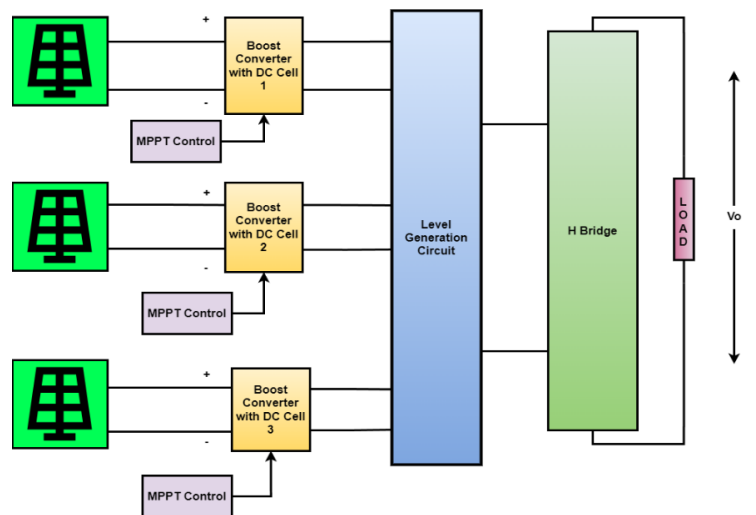


Fig. 1. Structural model of the topology proposed

Fig.1 Presents a block diagram illustrating the structural model of the topology proposed and detailed representation of its main components and their interconnections. The topology proposed for the multilevel inverter focuses on achieving high-quality AC output with a significantly reduced switch count, addressing some of the primary challenges in traditional multilevel inverter designs [15]. As a result, it provides a compact, cost-effective solution that is well-suited for applications requiring reliable power conversion in constrained spaces or budgets.

A. *Circuit topology of a 7-Level Inverter*

Comparing this with the traditional CHB MLI topology, the switch count is reduced. In this proposed topology, three voltage sources, four switches on the inverter side and six switches on the booster circuit are used. The number of switches was reduced here to reduce the complexity and the cost. Fig. 2 depicts the complete circuit diagram of the renewable energy based MLI configuration.

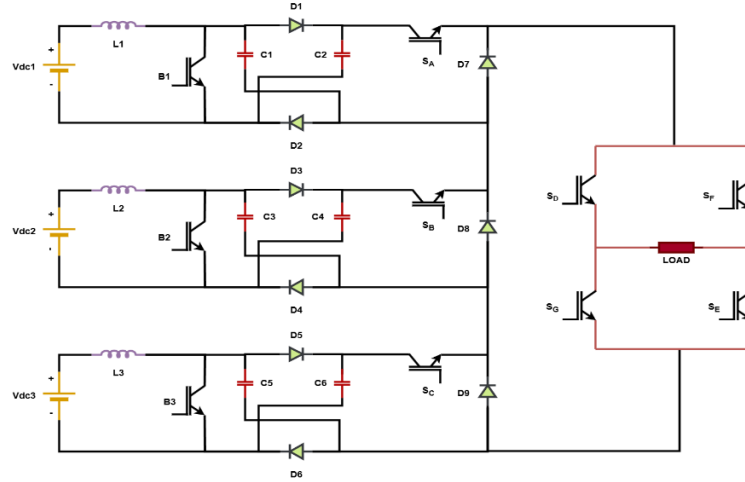


Fig. 2. Topology depicting the proposed renewable based MLI configuration

TABLE I SWITCHING STATES FOR VOLTAGE LEVELS IN A RENEWABLE ENERGY-BASED MLI

Level of Voltage obtained	S _A	S _B	S _C	S _D	S _E	S _F	S _G
Peak Positive Voltage	1	1	1	1	1	0	0
Upper Mid Positive Voltage	1	1	0	1	1	0	0
Lower Mid Positive Voltage	1	0	0	1	1	0	0
Zero Voltage	0	0	0	0	0	0	0
Lower Mid Negative Voltage	1	0	0	0	0	1	1
Upper Mid Negative Voltage	1	1	0	0	0	1	1
Peak Negative Voltage	1	1	1	0	0	1	1

The switch scheme for the suggested topology is provided in Table I. The electrical configuration consists of three voltage sources. The voltage sources represented as Vdc1, Vdc2, & Vdc3. The circuit is divided into three circuit sections: booster circuit, voltage generation circuit, and H-bridge circuit. DC-DC converters effectively boost DC voltage with low input from sources such as photovoltaic systems. A booster circuit made up of a capacitor, a diode, an inductor, and a switch. A boost converter’s output can be enhanced by connecting a parallel capacitor-diode configuration to the booster circuit. The booster circuit consists of three switches, B1, B2, & B3. S_A, S_B, S_C are the level generation switches, and S_D, S_E, S_F & S_G are the inverter circuit semiconductor switches. This topology generates 7 levels of output voltage. For the modulation of switches, SPWM strategy is used.

B. *PV Module*

A photovoltaic module is commonly known as a solar panel, converts the sunlight into electricity through photovoltaic effect. The module's efficiency depends on factors like the material used, the amount of sunlight

received, the angle of installation, and temperature conditions [4]. MPPT is used in this system to get maximum efficient output. It continuously adjusts the electrical operating point of the module PV to ensure that it produces the maximum possible power under varying conditions, such as changes in sunlight intensity, temperature, and shading [7]. The flowchart depicting the P&O based strategy used for controlling tracking of maximum power is shown in Fig. 3. The following notations are used to represent various terms in the given flowchart of P&O algorithm.

- $V_{pv}(t)$ = Voltage of the PV module
- $I_{pv}(t)$ = Array current of the PV module
- $P_{pv}(t)$ = Power of the PV module
- V_{err} = Difference between V_{ref} and V_{dc}
- V_{ref} = Reference voltage
- V_{dc} = DC voltage
- D = Duty cycle
- Delta D = Increment value used to increase/decrease the duty cycle D
- $D(t-1)$ = Old pulse duration ratio.
- $V_{pv}(t-1)$ = Old PV voltage.

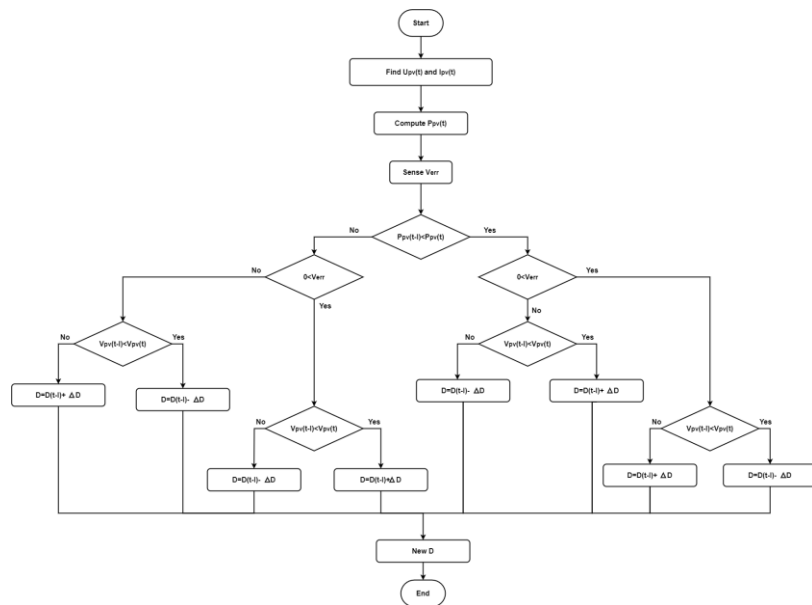


Fig. 3. P&O algorithm flowchart

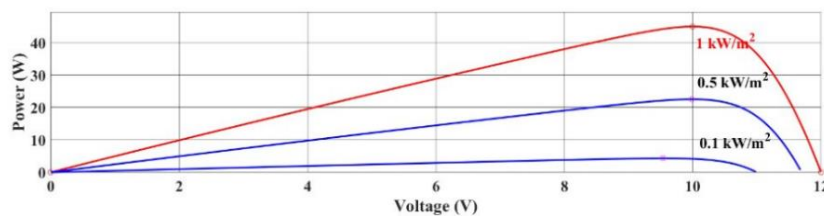


Fig. 4. P-V Curve plot of MPPT

In the peak range of sunlight, maximum power is delivered to the load using this algorithm. Variations in sunlight affect the energy delivered to the load, which is scrutinized using Simulink and illustrated in Fig. 4. The graphical representation shows the variation of power with different levels of sun irradiation.

C. Boost Converter

For step up the low voltages from the PV systems to higher voltage levels booster circuits are capable. The boosting circuit's output can be enhanced by connecting a capacitor and diode in parallel, creating a voltage doubling or peak holding circuit. This configuration captures peak output ripple, charging the capacitor through the diode, which then blocks reverse discharge, maintaining a higher voltage. As a result, output ripple is reduced, and voltage stability is improved. Additionally, this setup smooths peak fluctuations, providing a consistent voltage level, and acts as an extra filter to complement the main output capacitor. Moreover, it preserves peak voltage even during brief output drops or interruptions, ensuring a reliable output.

D. PWM Technique

To ensure the efficient and optimal performance of power electronic systems, modulation strategies play a vital role. In this topology, the system operates using a modulation method known as sinusoidal PWM. The reference signal which is sinusoidal having low frequency is compared with a triangular signal having higher frequency. Sinusoidal PWM works by this comparison and it produce a sine-like AC voltage waveform. The simulation model of sinusoidal PWM given below in Fig. 5.

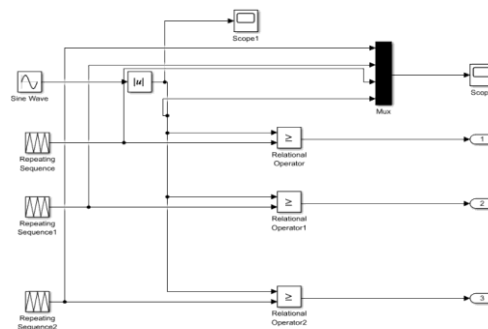


Fig. 5. SPWM synthesis circuit

E. Simulink-based Model of the Suggested Renewable Energy based MLI System

The Simulink model shown in Fig. 6 of the proposed topology consists of PV modules and MPPT controllers. Three MPPT controllers are employed to harvest maximum power from the solar panels.

To ensure the PV module produces the maximum possible output power under varying conditions, such as changes in sunlight intensity, temperature, and shading the electrical operating point of the PV module is continuously adjusted. The MPPT's are modulated by P&O algorithm. Also determined the THD by applying different scenarios in the proposed system.

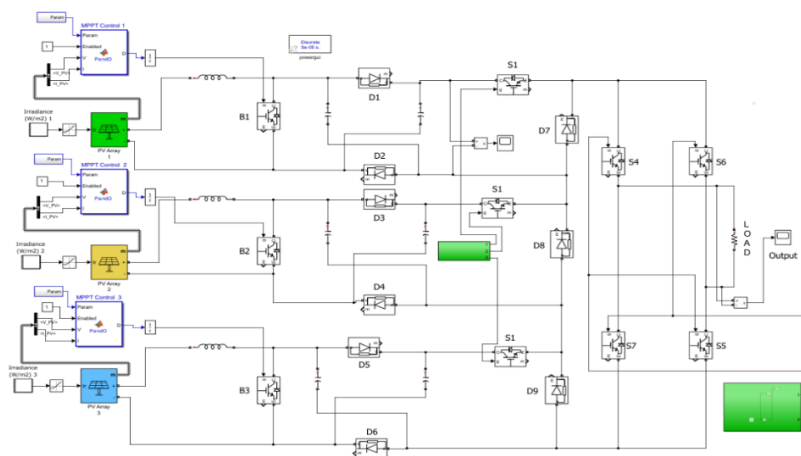


Fig. 6. Simulink circuit of the seven-level inverter system

III. SIMULATION RESULTS

Under various scenarios, the seven-level proposed topology was tested using the MATLAB Simulink platform. The specifications of the Simulink model are outlined below on the Table II.

TABLE II PARAMETERS USED FOR THE SIMULINK-BASED MODEL

Parameter	Value
Fundamental frequency	50 Hz
DC Source Voltage	12 V each
Capacitor C1, C2, & C3	100e-6 F
Inductor L1, L2, & L3	1e-6 H

The specifications under the standard operation conditions of the PV model are given below.

- Maximum Power $P_{mpp} = 45$ Watts
- Voltage at MPP $V_{mpp} = 10$ Volts
- Current at MPP $I_{mpp} = 4.5$ Amps
- Voltage at open circuit $V_{occ} = 12$ Volts
- Current at short circuit $I_{sc} = 5$ Amps
- Temperature coefficient of V_{occ} (% deg. C) = -0.2727

The total distortion caused by harmonics in EMF measured across the terminals and current is determined under different scenarios. In Fig. 7, the waveform of the potential difference across the R load is illustrated. These scenarios are determined under the equal input and the fixed load of resistive type.

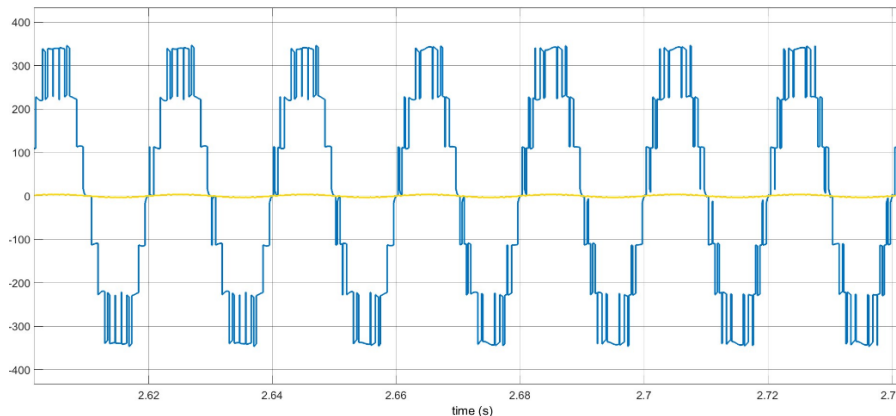


Fig. 7. Voltage and current waveform of Renewable Energy based MLI on R Load

The total distortion caused by harmonics in the flow of current in the system with a RL load and in the potential difference across the RL load configuration is illustrated below in Figs. 8 to 10. The inverter's potential difference between the output terminals and the flow of current through the load is evaluated for total distortions caused by harmonics under unequal conditions of inputs.

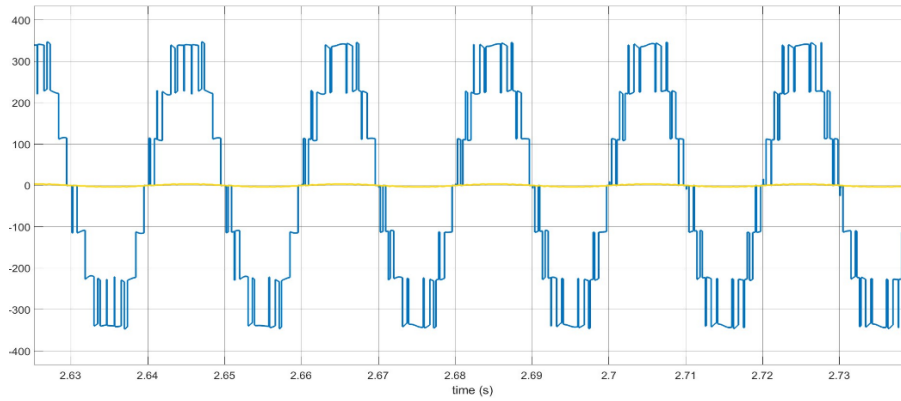


Fig. 8. Voltage and current waveform of Renewable Energy based MLI on RL Load

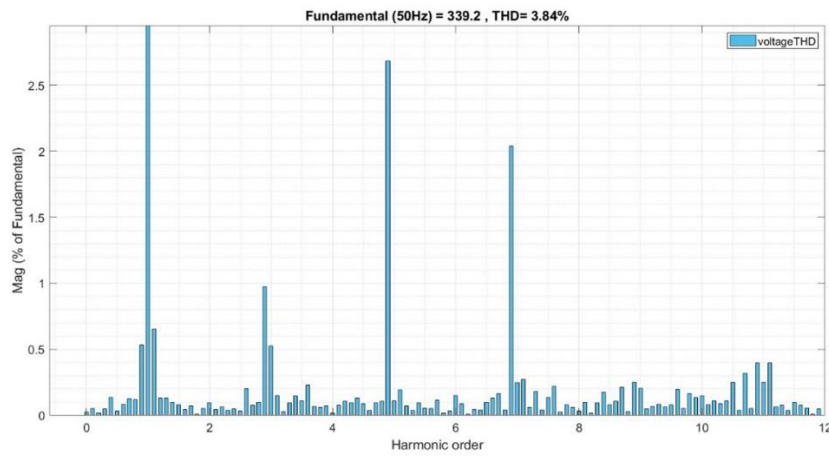


Fig. 9. Voltage THD via FFT in Renewable Energy-Integrated MLI for RL Load

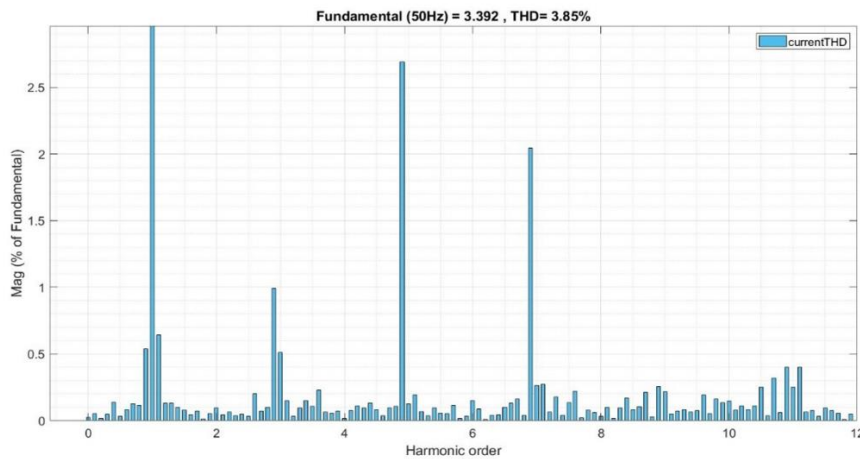


Fig. 10. Current THD via FFT in Renewable Energy-Integrated MLI for RL Load

The FFT assessment of the suggested system in different scenarios, makes clear that the proposed system have low THD as compared with the other topologies presented in papers [12]-[14] & [16]-[18]. The switch count of the system is also reduced.

The reduction of switch count decreases the complexity of the entire system configuration. Also, the results pertaining to the simulation-based models of other different topologies are given below in Table III. The scenarios are, changes in R load, changes in RL load and different amplitude ratings.

TABLE III MAJOR OBSERVATIONS

Scenarios	THD in Voltage
R load (R=100 Ohm)	3.88%
R load changes from 100 Ohm to 1 k Ohm	3.87%
RL load (R= 100 Ohm & 1mH)	3.84%
RL load (R=1 k Ohm & L=10mH)	3.84%
Amplitude of the Reference wave = 3	3.88%
Amplitude of the Reference wave = 2.8	4.20%
Amplitude of the Reference wave = 2.6	4.84%

The proposed 7-level inverter's performance is validated through simulation. Table III provides the simulation results, highlighting the THD in voltage for various load conditions and amplitude values. It demonstrates the effect of these factors on power quality. For a load consisting solely of a 100-ohm resistor, the THD is 3.88%. As the resistive load changes from 100 Ohms to 1 Kilo Ohm, the THD slightly decreases to 3.87%, indicating that the variation in load resistance has a little effect on harmonic distortion. For an RL load with a resistive value of 100 Ohms and an inductive value of 1 milli Henry, the THD reduces slightly to 3.84%, indicating that the inductive component improves the voltage quality marginally. Similarly, for an RL load with a resistance of 1 Kilo Ohm and an inductance of 10 milli Henry, the THD remains at 3.84%, showing that these parameters do not significantly affect harmonic distortion. When the amplitude value is set to 3, the THD is 3.88%, reflecting relatively low distortion at higher amplitude levels. However, as the amplitude value is reduced to 2.8, the THD increases to 4.20%, and further reduction to 2.6 results in a THD of 4.84%, highlighting the inverse relationship between amplitude and voltage quality.

The simulation results clearly demonstrate that the proposed multilevel inverter topology is well-suited for photovoltaic (PV) applications. It reduces the total harmonic reduction and the components count. A comparison of the suggested renewable energy based MLI having 7-level with various other 7-level inverter topologies is provided in Table IV.

TABLE IV BENCHMARKING THE PROPOSED INVERTER TOPOLOGY AGAINST OTHER DESIGNS

Topologies	THD %
[12]	23.34%
[13]	23.86%
[14]	25.12%
[16]	12.15%
[17]	4.5%
[18]	18.69%
Proposed topology	3.84%

The RE based MLI has less THD when compared with different topologies. The THD's of the different topologies are very high as compared with the proposed topology. That is evident from Table IV. The papers referenced present various inverter topologies with differing Total Harmonic Distortion (THD) rates, reflecting their effectiveness in reducing harmonic content. Papers [12] (THD: 23.34%), [13] (THD: 23.86%), and [14] (THD: 25.12%) discuss conventional or early-stage inverter designs with relatively high THD, indicating room for improvement. Paper [16] achieves a better THD of 12.15%, suggesting more advanced optimization. Paper [17]

reports a significantly lower THD of 4.5%, demonstrating improved efficiency. Paper [18] shows a moderate THD of 18.69%, still lower than the first group but with room for further enhancement. In comparison, the proposed topology achieves the best performance with a THD of 3.84%, highlighting its superior capability in reducing harmonic distortion and improving voltage quality. The proposed topology has the ability to increase the voltage gain, since it incorporates booster circuits. The boosting of the voltage makes it more suitable for renewable energy applications or high-power medium voltage applications.

IV. LABORATORY PROTOTYPE RESULTS

The general model of the hardware framework is shown in the Fig.11. The breakdown of experimental results from the prototype developed is illustrated in Fig. 12 and Fig. 13. The input 12V given to the inverter circuit is boosted with the help of the booster circuit. Using a microcontroller, gate pulses are generated and amplified to the required level by the gate driver circuit. The gate pulse from the controller is too weak to modulate the switches of the booster circuit which is a portion of multilevel inverter topology. The gate driver circuit works with the rectified step-down AC voltage. MPPT controller determines the maximum power point to analyse the strength of the sunlight and give maximum output from the solar panels. Using the DSO, the potential difference across the load as well as the current flow through the load of the suggested topology were observed.

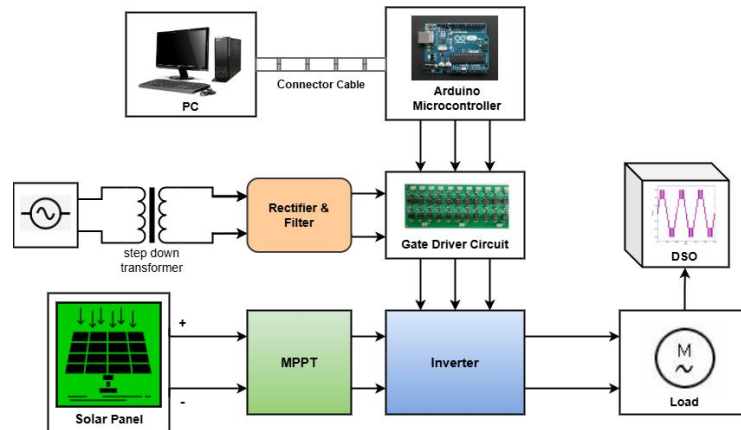


Fig. 11. Architectural diagram of the hardware setup

Fig. 12 shows the output signals for voltage and current in the developed system for resistive load with 100 Ohms resistance



Fig. 12. R load (100 Ohms) hardware waveform of renewable energy based MLI

The voltage and current waveforms generated by the suggested system for a resistive load with 1 Kilo Ohms resistance are analyzed and presented in Fig. 13.

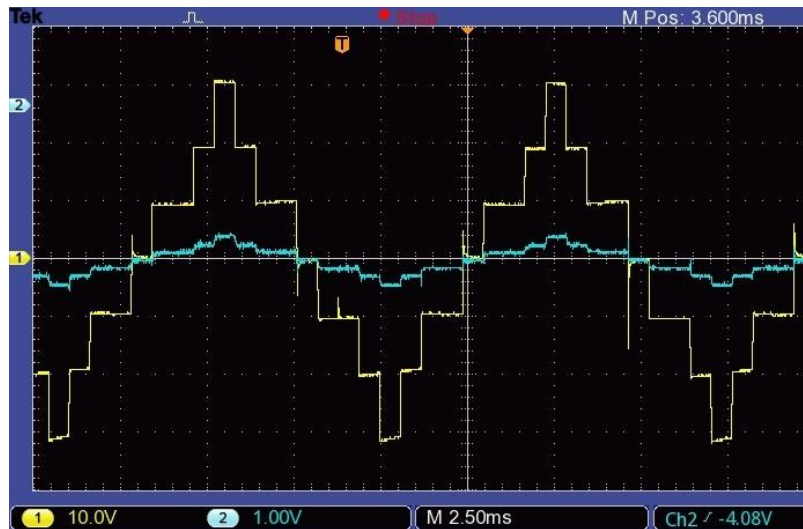


Fig. 13. R load (1 Kilo Ohms) hardware waveform of renewable energy based MLI

As illustrated in Fig. 13, the current output decreases when the resistance is high. Conversely, as depicted in Fig. 12, the current output increases when the resistance is low

V. CONCLUSION

It is concluded with a thorough analysis of multilevel inverter topologies, starting with an overview of their significance in contemporary power electronics and renewable energy applications. A thorough review of the literature outlined the benefits and drawbacks of the current inverter designs, providing the groundwork for creating an ideal solution. It became clear from the research that traditional inverter topologies frequently suffer from significant switching losses, higher complexity, and decreased energy efficiency, which highlights the need for a more efficient design methodology. A new system was proposed, and the Simulink model is simulated in different scenarios to determine the THD's. By using fewer switches and a booster circuit to stabilize the input DC voltage, this novel topology lowers switching losses and guarantees steady power delivery to the inverter. The harmonic profile from the computer simulation is verified, and the findings are compared with the experimental results. The suggested configuration has a lower THD rating than the other topologies. For the high-power applications and the renewable energy applications, the developed multilevel inverter topology is a good solution. The proposed system can enhance the resilience in the distribution network through domestic load reduction by operating as a standalone system.

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