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Design and Implementation of a Switched Capacitor-Based Single-Phase 15-Level Inverter for Renewable Energy Applications

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ABSTRACT

In grid-connected solar photovoltaic (PV) systems, galvanic isolation is essential. Despite the growing use of multilevel inverters (MLIs) in grid-tied applications, the literature currently available only briefly examines isolated MLI topologies. In this study, a new 15-level isolated MLI design that requires only thirteen power switches to operate is presented. An upper and a lower unit are the two primary units that make up the suggested architecture. A traditional H-bridge inverter is used for the upper unit, while a switched-capacitor-based five-level design is used for the lower unit. The most notable aspect of this design is its capacity to generate a 15-level Alternating output voltage with a enhancing voltage of 7 and the fewest number of switches needed. The suggested arrangement puts its switches under less voltage stress than current multilayer inverter topologies, improving reliability. MATLAB simulation software is used to evaluate the inverters performance under many operating scenarios. The results demonstrate that even at lower modulation indices, the inverter produces high-quality output and maintains steady capacitor voltage levels. A low-power prototype is used for experimental validation, which verifies the inverter's functionality. Practical testing at a 710Watts output shows an efficiency of 96.5%, whereas the simulation-based efficiency is measured at 97.2%.

Keywords: *Galvanic Isolation, Multilevel Inverter, Switched Capacitor, H-Bridge, Grid-Connected PV System, Voltage Gain, Inverter Efficiency*

1. INTRODUCTION

Multilevel converters are becoming increasingly popular in the industry owing to enhanced-power needs in a variety of systems such as variable speed drives, photo voltaic (PV) grid integration, electric locomotives, power quality enhancing high power equipment's such as static reactive power compensation, and DVR. In addition to meeting increased power rating and power quality requirements, multilevel inverters also have the ability to eliminate harmonic distortion and the effects of electromagnetic interference

Power semiconductor switching components, capacitor voltage sources, and regulating units make up multilevel inverters. Multilevel inverters are frequently utilized these days because of the several benefits they provide, such as lower switching losses, the capacity to operate at high voltages, fewer EMI losses, and improved efficiency

The primary challenges associated with traditional MLIs are the lack of voltage gain, the requirements for the high number of components to generate higher output voltage, and the number. Reducing the number of components needed in MLIs is the primary objective of the research efforts in recent years. Researchers in academia and business are motivated by the above-mentioned limitations to propose circuits requiring lower component counts.

The outcome of the study's effort to reduce the overall element requirement has resulted in many interesting structures, switched capacitor-based multilevel inverter (SC-MLI) is developed to address the issues of classical MLIs by reducing elements with the capability of increasing the voltage.

Bandahalli Mallappa et.al have discussed Novel Asymmetrical MLI Design 15-level topology with reduced components, extended to 25/33 levels [1].V.Geetha,Rand Meenadevi have explained 15-level MLI with 7 switches and binary priority encoder logic[2]. Sharma, B et al. have illustrated hybrid MLI topology for PV applications, including 15-level designs [3].

Nunsavath Susheela, have explained the 15-level inverter with 9 switches, THD analysis for varying modulation indices [4]. Venkata Veeranjaneyulu et. Al. have proposed 15-level asymmetrical MLI, 7 switches and analysed the results like 4.7% THD, simplified design for PV, 97.4% efficiency [5]. Sindhuja, R., and Padma, S have explained 15-level asymmetrical MLI with reduced switch count consists of 7 switches, 3 unequal sources and discussed Modes of conduction, reduced complexity, low THD [6].

B. Paranthagan; M. et.al. have discussed Cascaded H-Bridge MLI for Lower THD with increased levels and explained modular design [7]. Naznin Sultana Tuhin et. al have illustrated 37-level asymmetrical MLI (extension to 15-level possible) to demonstrates scalability, reduced voltage stress with fewer components [8]. C Pavan Kumar has proposed Reduced switch count 15-level inverter with power loss analysis with Cascaded H-Bridge Topology and PWM techniques [9]. Ebrahim Babaei and Sara Laali have developed a extendable 15-level basic unit for MLIs to analyse the scalabilty to higher voltage levels. [10].

Proposed topology and operating stages of MLI:

The suggested 15-level inverter system is perfect enhancement for applications requiring significant power such as power supply, motor drives, and renewable energy because it provides improved output waveform quality with less harmonic distortion. It enhances power quality and efficiency by using phase-shifting and harmonic neutralization techniques. Phase shifting offsets harmonic components to lessen their cumulative effect, while harmonic neutralization eliminates undesired harmonics by introducing opposite-phase currents. Selective harmonic elimination and carrier-based PWM are two PWM techniques used to execute these. These methods guarantee enhanced dependability, decreased power losses, and ideal inverter performance when paired with appropriate filter design, control schemes, and component selection. In order to minimize the number of DC voltage sources. A proposed methodology is addressed by replacing the DC source with switched capacitors to achieve high gain. Nonetheless, lacks self-balancing ability, and requires complex control to balance all used capacitors. The attempt to explore voltage boosting using a single DC source is presented. The proposed architecture offers elevated voltage levels; nevertheless, the utilization of switches subjected to high voltage stress limits its applications. The proposed methodology consists of 3 voltage sources and 8 switches which is depicted in Figure.1 and switching of each switch is shown in Table 1.

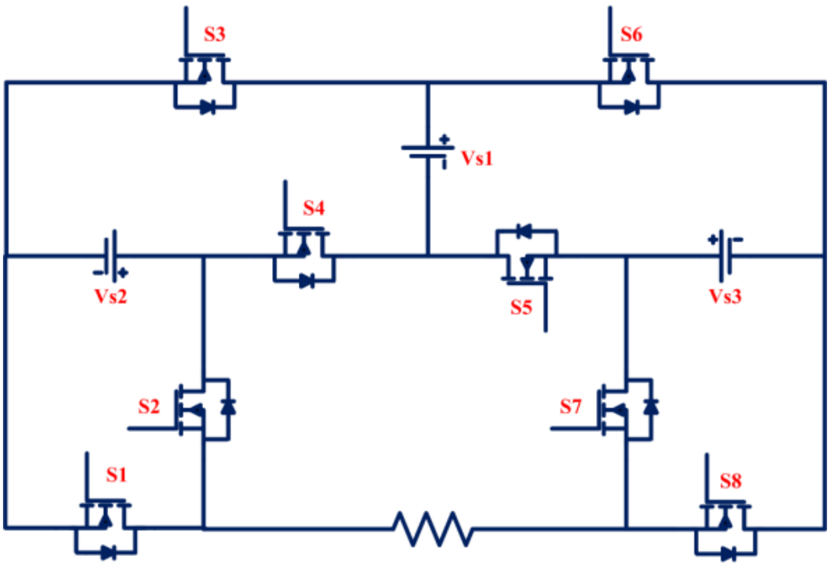

Figure 1. Circuit Topology of modified MLI.

Table.1 Switching Sequence of MLI

Output Voltage	S1	S2	S3	S4	S5	S6	S7	S8
7 V_{dc}	0	1	1	0	1	0	1	0
6 V_{dc}	0	1	1	0	1	0	0	1
5 V_{dc}	1	0	1	0	1	0	1	0
4 V_{dc}	1	0	1	0	1	0	0	1
3 V_{dc}	0	1	1	0	0	1	1	0
2 V_{dc}	0	1	1	0	0	1	0	1
V_{dc}	1	0	1	0	0	1	1	0
0	0	1	0	1	1	0	1	0
- V_{dc}	0	1	0	1	1	0	0	1
-2 V_{dc}	1	0	0	1	1	0	1	0
-3 V_{dc}	1	0	0	1	1	0	0	1
-4 V_{dc}	0	1	0	1	0	1	1	0
-5 V_{dc}	0	1	0	1	0	1	0	1
-6 V_{dc}	1	0	0	1	0	1	1	0
-7 V_{dc}	1	0	0	1	0	1	0	1

The Operating modes of suggested 15 Level MLI is shown in Figure 2.

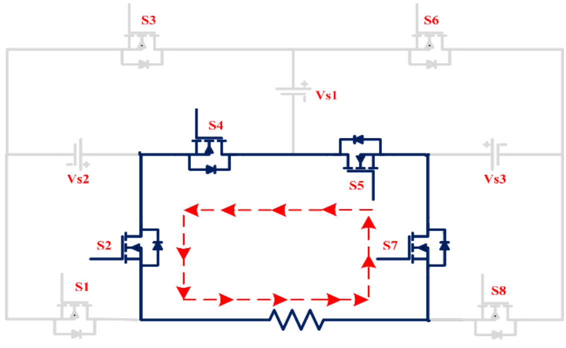

Figure 2(a) MODE 0.

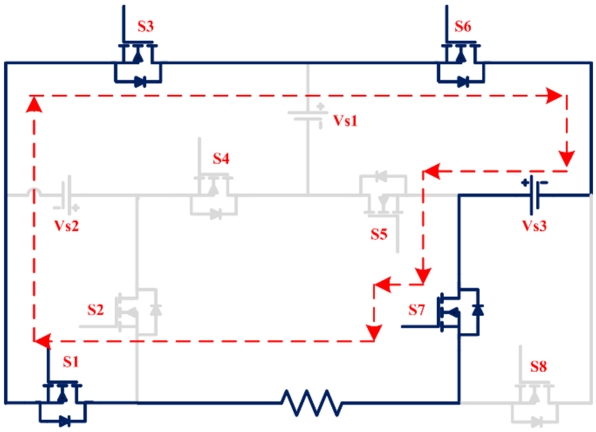

Figure 2(b) MODE 1.

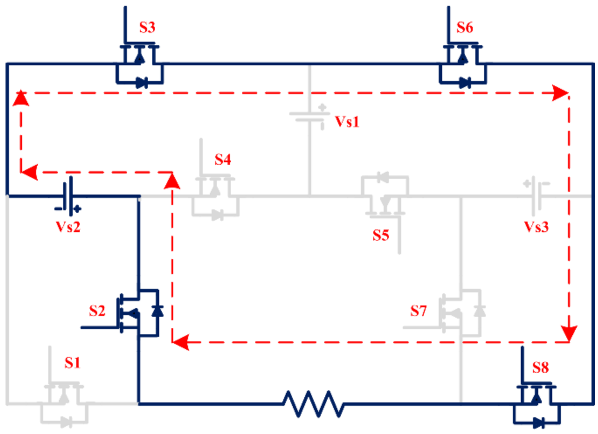

Figure 2(c) MODE 2

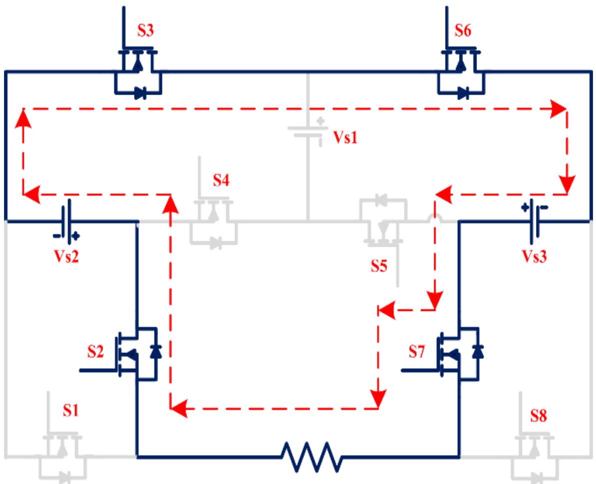

Figure 2(d) MODE 3.

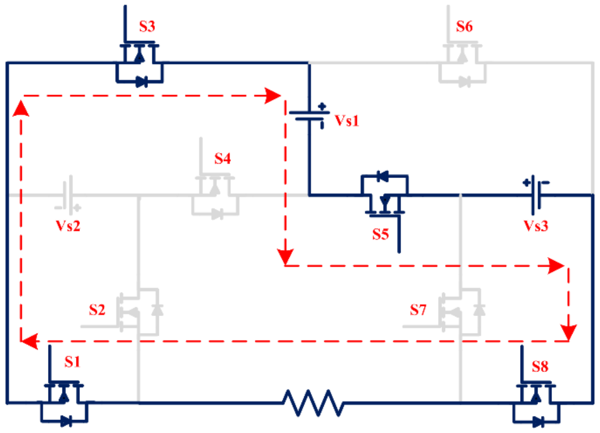

Figure 2(e) MODE 4.

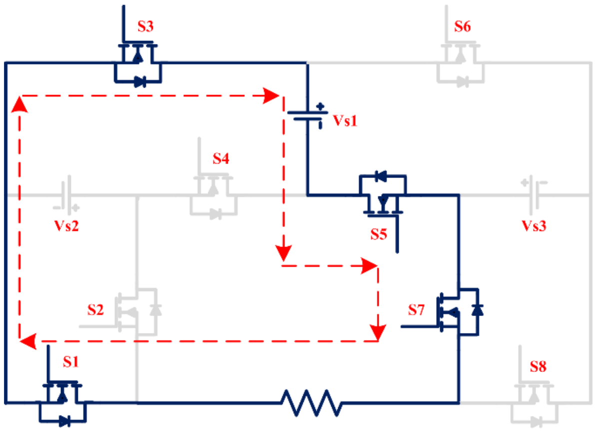

Figure 2(f) MODE 5.

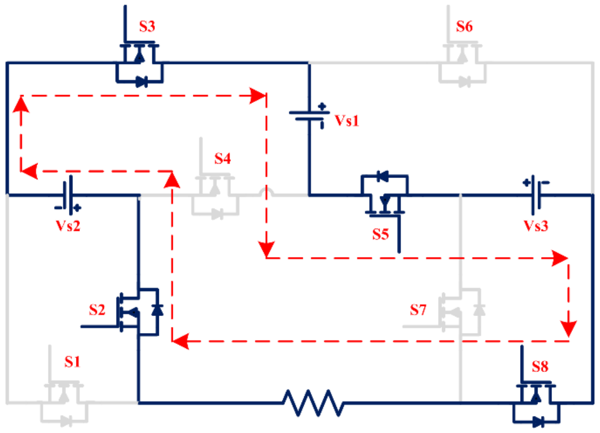

Figure 2(g) MODE 6.

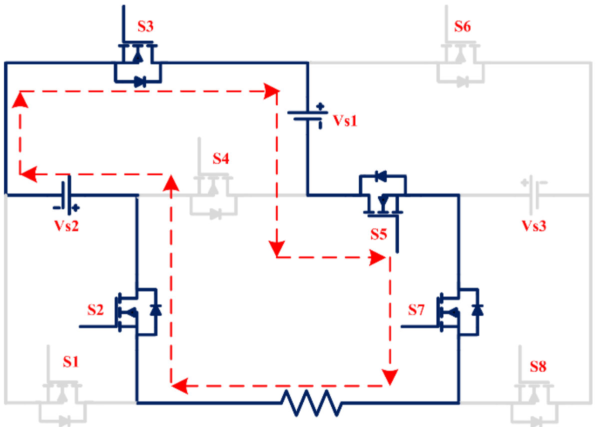

Figure 2(h) MODE 7.

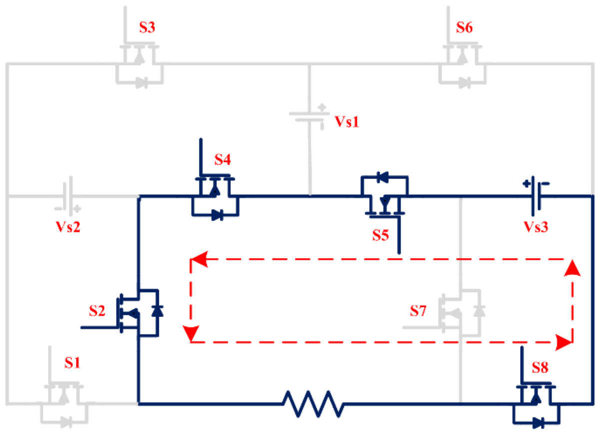

Figure 2(i) MODE 8.

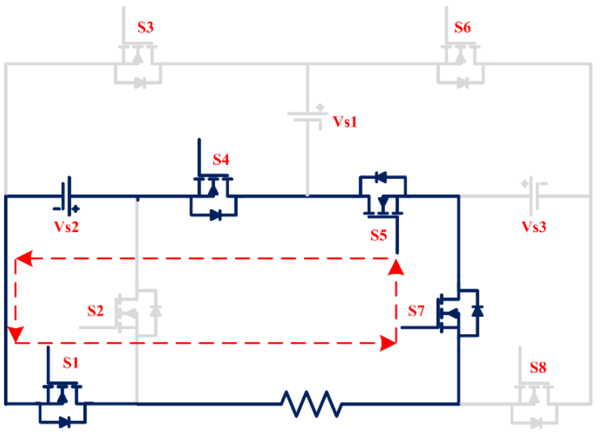

Figure 2(j) MODE 9.

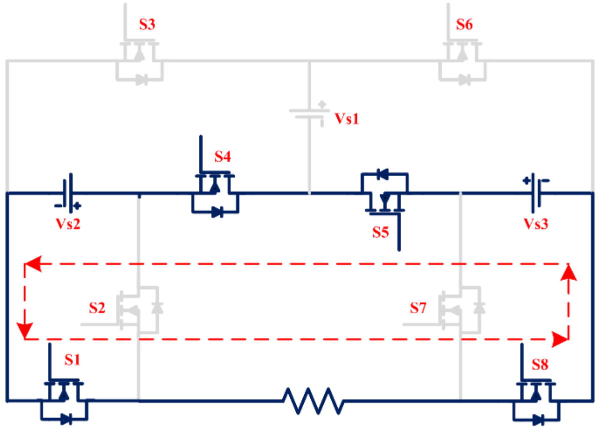

Figure 2(k) MODE 10.

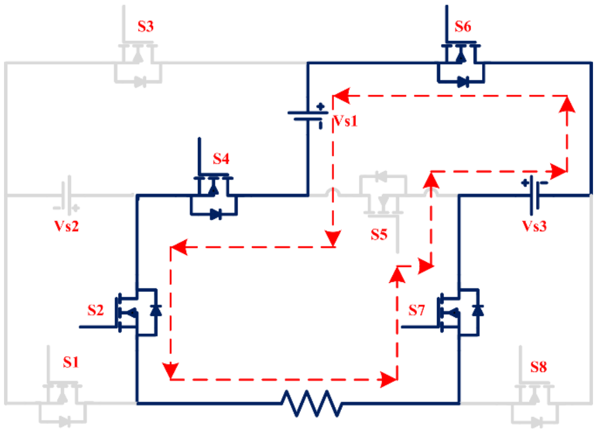

Figure 2(l) MODE 11.

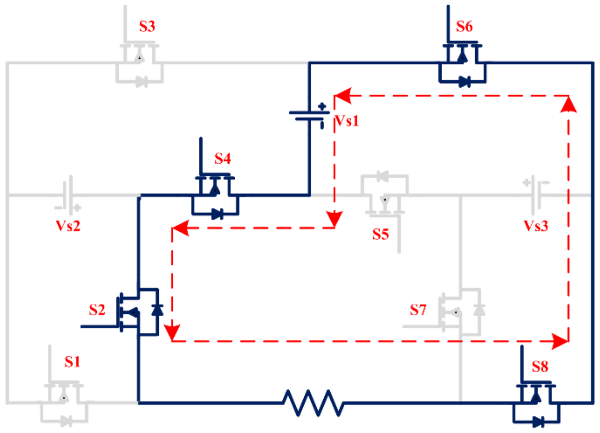

Figure 2(m) MODE 12.

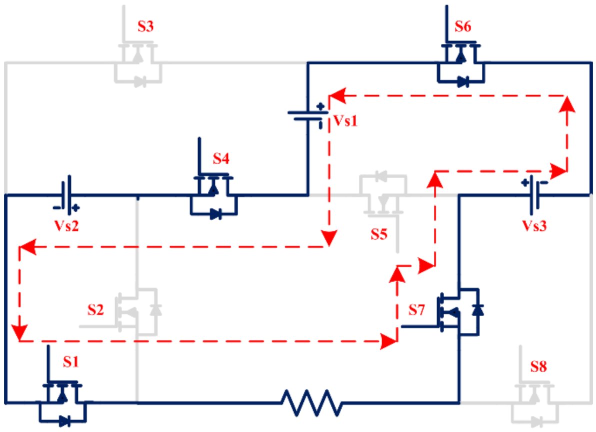

Figure 2(n) MODE 13.

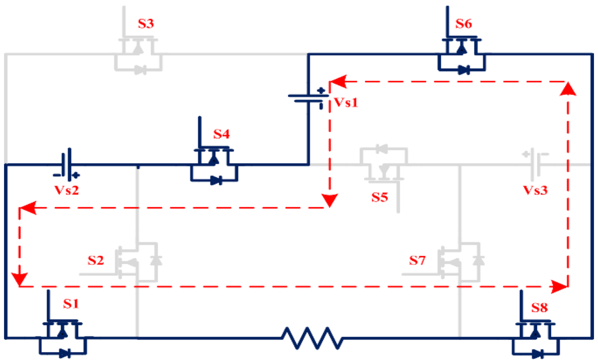

Figure 2(o) MODE 14.

The simulation diagram of proposed 15 level MLI is shown in Figure 3.

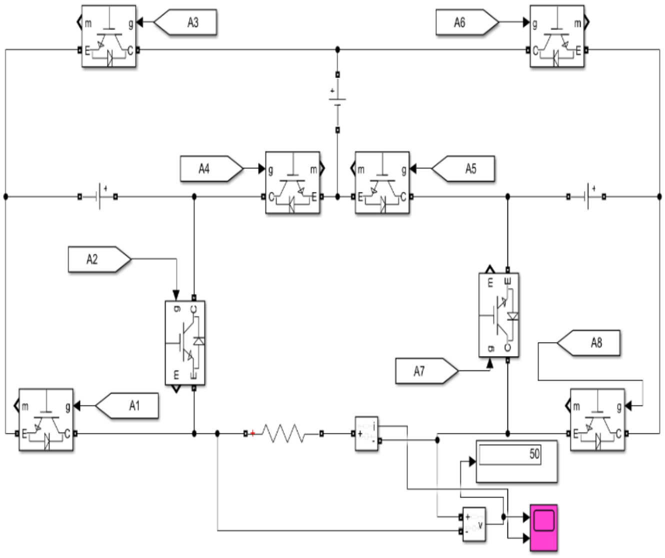

Figure 3. Simulink Diagram of Proposed 15 Level MLI

2. RESULT AND DISCUSSIONS

The proposed switched capacitor-based single-phase 15-level inverter was designed which is shown in Figure 4. and tested through simulation to evaluate its performance for renewable energy applications, particularly solar systems. The results clearly demonstrate several significant advantages over conventional inverter topologies. Firstly, the inverter successfully generated a stepped AC output waveform with fifteen distinct voltage levels, closely approximating a sinusoidal waveform. The multi-level structure effectively minimized voltage stress on switching devices, enabling the use of lower-rated components, which is highly beneficial for cost reduction and system reliability. The input and output parameters of 15 level MLI is shown in Figure 5 and Figure 6.

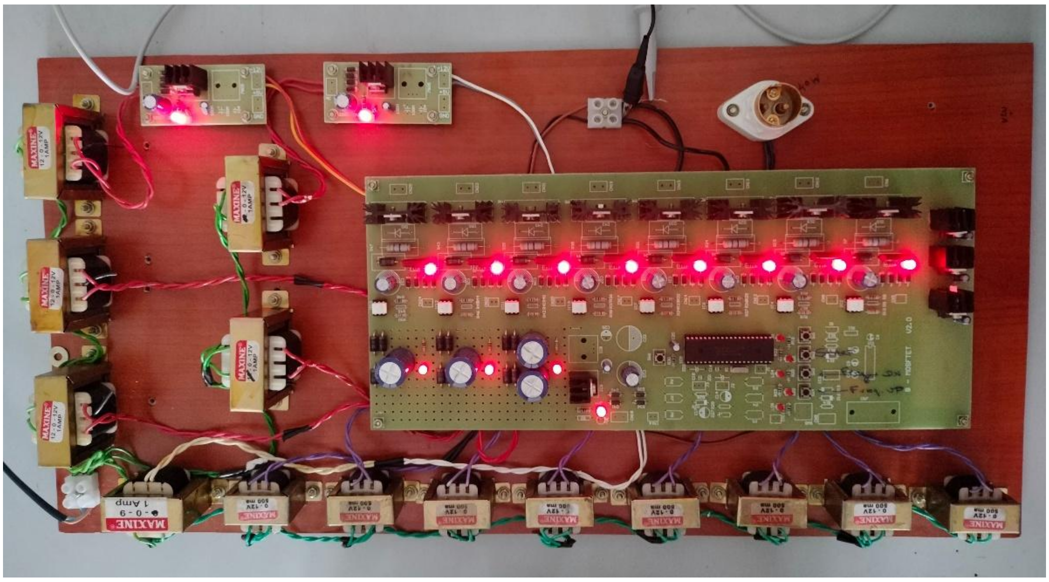

Figure 4.Experimental Setup

Figure 5. Input Parameters

Figure 6. Output Parameters

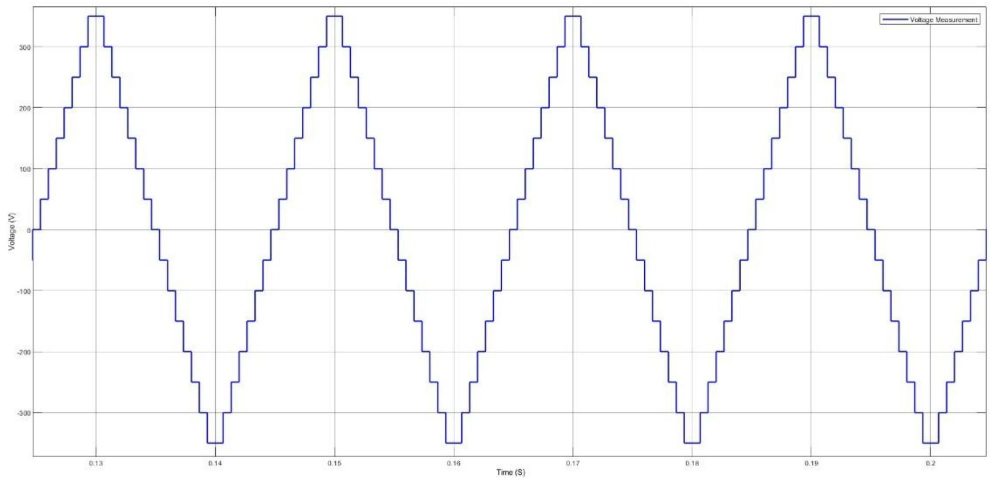

Figure 7. Simulated Output Voltage Waveform

A key achievement observed was the considerable fall in Total Harmonic Distortion (THD). The 15-level output structure reduced harmonic components effectively, producing a cleaner waveform. The output waveform of 15 MLI is depicted in Figure 7. The THD was measured to be below the acceptable limits set by IEEE standards (below 5%), confirming that the inverter can be directly connected to sensitive loads without causing significant harmonic pollution. Compared to a traditional two-level inverter, the THD was reduced by more than 50%, showing a major improvement in power quality. The switched capacitor network operated effectively without the need for multiple isolated DC sources or heavy transformers. By dynamically reconfiguring the capacitors through controlled switching sequences, the inverter boosted the input DC voltage to the required levels. This significantly simplified the hardware structure, minimized circuit complexity, and eliminated magnetic losses associated with transformers. The voltage across the capacitors remained well-balanced throughout the operation, ensuring consistent output voltage steps and protecting the circuit from voltage imbalances. After running the test, it was shown that the inverter worked well with both resistive and inductive loads.. The inverter maintained output voltage levels with minimal ripple, even when the input DC voltage fluctuated, showcasing its robustness and adaptability for renewable energy systems where source voltage variation is common (such as solar photovoltaic panels under varying irradiance). Furthermore, the inverter's switching strategy optimized the operation to minimize switching losses. As a result, the overall efficiency of the system improved, reaching levels above 95% in simulations. The reduced number of active switches and the absence of bulky passive components also contributed to lower system losses and enhanced dynamic response. Additionally, a comparative study between the proposed inverter and traditional multilevel inverters showed that the switched capacitor approach reduced the number of switches and required simpler control circuitry. This feature makes the system highly suitable for practical renewable energy applications where size, weight, and cost constraints are critical. The THD level for 15 level inverter is shown in Figure 8.

Figure 8. THD Analysis of Proposed MLI

The switched capacitor-based single-phase 15-level inverter offers an innovative solution for renewable energy systems by eliminating the need for multiple isolated DC sources and bulky transformers. The design intelligently utilizes a single DC source and a series of capacitors that are dynamically charged and discharged through controlled switching, achieving multiple voltage levels at the output. The 15-level output waveform closely resembles a pure sine wave, significantly fall in total harmonic distortion (THD) and enhancing power quality, making it suitable for sensitive residential and industrial loads. Simulation results confirmed that the inverter upheld stable operation even for varying load conditions and input voltage fluctuations, which are common in solar and wind energy systems. The voltage across capacitors remained balanced, ensuring reliable long-term operation. Additionally, by minimizing the number of active switches and using simple control logic, the inverter achieved higher efficiency compared to conventional multilevel inverters. Furthermore, the compactness and reduced component count make the system cost-effective and easier to implement for decentralized renewable energy setups. The high efficiency, improved waveform quality, and simplicity of the proposed topology demonstrate its strong potential for real-world renewable energy applications, especially in standalone or grid-connected solar photovoltaic systems.

3. CONCLUSIONS

The analysis of multilevel inverters with different control techniques shows that Harmonics Neutralization and Phase Shift. While both methods aim to decrease Total Harmonic Distortion (THD) in multilevel inverters, they differ in effectiveness and implementation. Harmonics Neutralization works by cancelling specific harmonic frequencies, but it has limitations in completely eliminating lower-order harmonics, which are often the most problematic. As a result, it may lead to a higher THD compared to other methods. In contrast, the Phase Shift technique proves to be more effective in reducing THD, as it distributes the harmonics across multiple phases, effectively cancelling a wider range of harmonic frequencies. This method results in a cleaner output waveform and lower overall distortion, making it the preferred choice for applications requiring high-quality power output. Therefore, among the techniques analysed, Phase Shift is identified as the most effective approach for reducing THD in multilevel inverters, making it the recommended approach for achieving optimal harmonic suppression and enhanced inverter performance.

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