ISSN: 2454-9940

INTERNATIONAL JOURNAL OF APPLIED SCIENCE ENGINEERING AND MANAGEMENT

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INTERNATIONAL JOURNAL OF APPLIED SCIENCE ENGINEERING AND MANAGEMENT

ISSN 2454-9940

www.ijasem.org

Vol 19, Issue 1, 2025

Enhanced 13-Level Multilevel Inverter Using Minimal Switched Capacitors

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Abstract

This paper proposes an increasing demand for efficient power conversion systems, driven by the rapid adoption of renewable energy sources, has led to significant advancements in multilevel inverter technologies. Among these, the Reduced Switched Capacitor (RSC) inverter topology has gained attention due to its ability to generate high-quality output waveforms while minimizing harmonic distortion and improving overall efficiency. This study presents an analysis of a simplified 13-level inverter utilizing RSC technology.

Additionally, a Pulse Width Modulation (PWM) control strategy is employed to regulate switching signals, ensuring optimized harmonic suppression and enhanced waveform quality. The proposed inverter topology reduces the number of power switches and capacitors, leading to improved system efficiency, lower cost, and simplified implementation. The system is modelled and simulated using MATLAB/Simulink, and the obtained results demonstrate an efficiency of 98.50%, along with significantly reduced Total Harmonic Distortion (THD). This highly efficient and compact inverter design is well-suited for renewable energy systems, industrial motor drives, and various power electronic applications where high performance and reduced circuit complexity are essential.

Keywords: Pulse width modulation control,Capacitor Voltage Self Balancing,Reduced Switched Capacitor Technology,Harmonic Distortion

1. INTRODUCTION

Multilevel inverters (MLIs) are well-established in power electronics, offering benefits such as high-quality output waveforms, reduced voltage stress on switches, and minimized electromagnetic interference (EMI).A prominent MLI topology is the Switched-Capacitor Multilevel Inverter (SC-MLI), which converts a fixed DC-link voltage into multiple output levels using a series-parallel switching approach involving capacitors, power switches, and diodes. This method enables voltage step-up and self-balancing of capacitor voltages without the need for inductors or complex control mechanisms.

While SC-based circuits are well-explored in DC-DC converters, their integration into multilevel AC voltage generation is still developing. Initial attempts in 1989 combined a Series-Parallel Switched Capacitor (SPSC) network with a full-bridge inverter to produce multiple DC voltage levels. By the late 1990s, advancements in optocouplers and FET driving circuits led to SC-MLIs characterized by improved efficiency, reduced weight, and compact size.

Recent research has focused on optimizing SC-MLI topologies to reduce component count and enhance performance. For instance, a comprehensive review highlights various SC-MLI configurations and their applications in renewable energy systems and electric vehicles.

2. LITERATURE SURVEY

Multilevel inverters (MLIs) are essential in applications like solar energy, battery storage, and motor drives due to their fault tolerance, low total harmonic distortion (THD), and near-sinusoidal output. Traditional MLIs, such as cascaded H-bridge, flying capacitor, and neutral point clamped inverters, are designed for medium-to-high voltage applications like high-voltage direct current (HVDC) transmission. However, these topologies face challenges in low-voltage microgrid applications, especially those incorporating renewable energy sources.

Ruijie Sun *et al* [2022] found that the few parts needed to build a multilayer inverter (MLI). By combining a T-type unit fed by flying capacitors (FCs) with a double-mode switched-capacitor (SC) unit, a hybrid MLI with extra levels and high output voltage quality is produced. The T-type unit is in charge of increasing the number of output levels, while the SC unit is utilized to increase the output voltage's amplitude to double the dc input voltage.

Anh-Tuan Huynh *et al* [2022] briefly claimed that two pulse-width modulation (PWM) techniques, for the proposed ASC-EqZSI design, a single- phase active switched-capacitor embedded quasi-Z-source inverter (ASC-EqZSI) and PWM1 and PWM2 in particular were utilized to improve boost capability and reduce switching loss.

Marcus Vieira Soares *et al* [2022] suggested that various dc-dc topologies with distinct characteristics have been proposed for the integration of renewable sources with electronic loads. These topologies include switched capacitor, hybrid switched capacitor, and medium frequency isolated modular multilevel converter topologies. This work presents a bidirectional hybrid switching capacitor dc-dc converter based on modular multilevel converters.

Pulavarthi Satya Venkata Kishore *et al* [2022] suggested that the switched capacitor technology is the basis for the new decreased switch count seven-level triple boost inverter. The topology balances the voltage across the capacitors and has fewer components. The suggested topology has an extremely straightforward construction that be readily expanded to accommodate more voltage levels.

Zichao Ye *et al* [2022] developed "multi-resonant sc converter" refers to a family of resonant switched-capacitor (SC) converters with numerous operational phases. With fewer switches and capacitors, these converters which are derived from basic two-phase SC topologies like the Series-Parallel and the Doubler achieve the same conversion ratio. Soft-charging and soft-switching operation are made possible by the augmenting inductor, which resonantly charges and discharges all flying capacitors at various resonances.

Yaoqiang Wang *et al* [2022] proposed the switched-capacitor multilevel inverter (SCMLI) is the most widely used type of multilevel inverter. This type of inverter architecture generates multilayer output by controlling the charging and discharging of capacitors using the on/off states of switches. In order for the switches to endure the output voltage peak, the majority of SCMLIs employ an H-bridge structure to alter the output voltage's polarity

Mohammad Amin Rezaei *et al* [2022] developed boosting the maximum output voltage while decreasing the number of switches. The topology that is being given is different from similar topologies, even though there are numerous similarities. When compared to identical structures, certain switches have their direction reversed, which changes the direction of current flow.

Hammad Alnuman *et al* [2023] described a switched-capacitor-based 13-level inverter with minimal switch stress and a high gain. The proposed converter uses a single dc source, 14 switches, 3 capacitors, and 1 diode to generate a 13-level single-phase ac output voltage with a voltage gain of 6. Different loads achieve self-voltage balancing without the need for additional equipment or complex control techniques.

Mohammad Ali Hosseinzadeh *et al* [2023] proposed a due to their high voltage gain, single-phase switched-capacitor multilevel inverters are a great substitute for low-power applications. However, because these topologies are unique, controlling and modulating them is not straightforward. For these inverters, FCS-MPC has thus become a desirable control option.

Sudipto Mondal *et al* [2023] suggested that Due to their single source needs for multilayer output voltage production, switched-capacitor (SC) based multilevel inverter topologies are currently the most popular among several MLIs for PV systems. However, the majority of the present SC-based design requires at least two SCs for power conversion for commonly used single-phase, five- level inverters. A five-level transformerless inverter based on a single SC is recommended; it requires no diode or capacitor and just requires seven switches and a single dc voltage source.

3. SYSTEM DESCRIPTION

A novel 13 level SC-MLI system is designed to produce large number of voltage level with better quality output waveform along with reduced component requirements. The initial working stage of the developed system starts with the input DC supply that is connected to the inverter for generating power quality outputs. In

ISSN 2454-9940
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addition to that, PWM generator is connected to produce PWM pulses for attaining low frequency modulation to achieve enhanced switching operation with stable system performance.

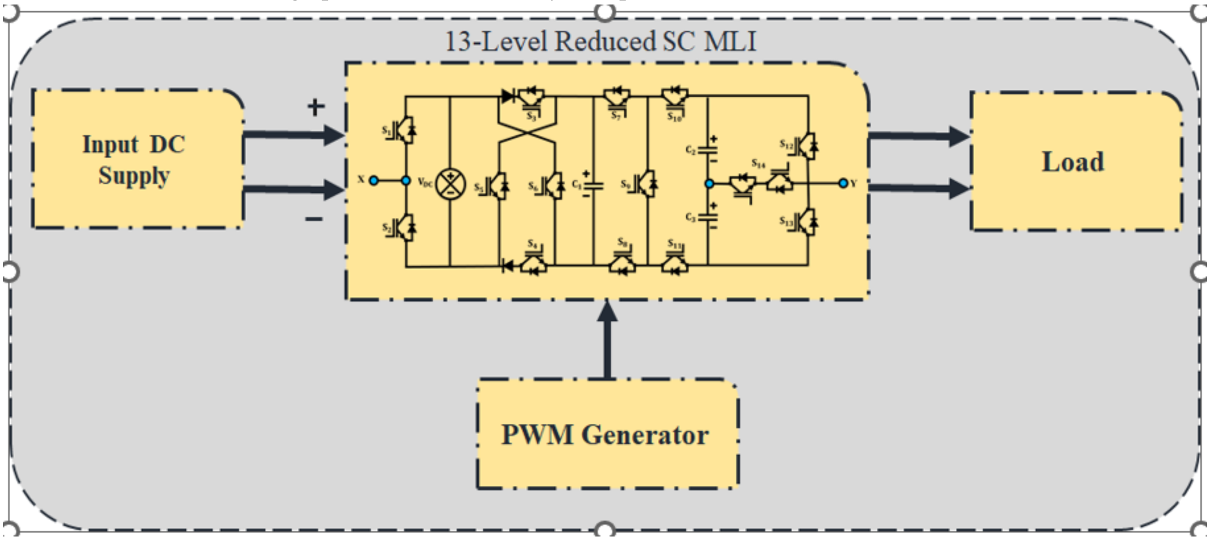

Figure 1 Block Diagram of Proposed System

4. INPUT DC SUPPLY

This system utilizes a multi-level operation to power and control the load through a reduced switched capacitor 13-level inverter. It requires three separate DC power supplies: a primary DC input for the inverter, a 15V DC supply for the driver circuit, and a 5V DC supply for the controller. The inverter converts the primary DC input into an alternating output with 13 voltage levels, ensuring reduced harmonic distortion, improved efficiency, and optimized power delivery.

The 15V DC supply powers the driver circuit, which includes components like the TLP250 optocoupler. This circuit acts as an interface between the controller and the inverter switches, providing electrical isolation and delivering the necessary gate drive voltages for the semiconductor switches. It receives pulse-width modulation (PWM) signals from the DSPIC30F4011 controller and amplifies them for precise control of the inverter.

The 5V DC supply powers the DSPIC30F4011 controller, which generates the PWM signals needed to regulate the inverter's output. The controller processes input signals, implements modulation techniques, and ensures accurate switching timing. By carefully distributing the input DC supplies, the system achieves efficient energy conversion, precise control, and reliable operation of the load.

5.MULTILEVEL VOLTAGE SOURCE INVERTER

Multilevel inverters (MLIs) are widely used for DC to AC conversion, especially in high-voltage and high-power applications. These inverters generate multiple voltage levels to produce smoother AC waveforms, resulting in lower total harmonic distortion (THD) compared to traditional two-level inverters. MLIs are commonly found in motor drives, power grids, renewable energy systems, and high-voltage direct current (HVDC) transmission, where they improve power quality, efficiency, and reduce electromagnetic interference (EMI). This technology, which emerged in the 1970s, addresses the limitations of traditional inverters, particularly in high-power applications.

MLIs work by producing multiple voltage steps from a series of DC sources, which reduces the load on switching devices, minimizes power losses, and enhances the overall waveform quality. By bringing the output waveform closer to a pure sinusoidal signal, MLIs reduce THD. With lower switching frequencies and fewer switching losses, MLIs are more energy-efficient for high-power applications. Additionally, their smoother voltage waveform makes them ideal for EMI-sensitive applications, such as communication systems.

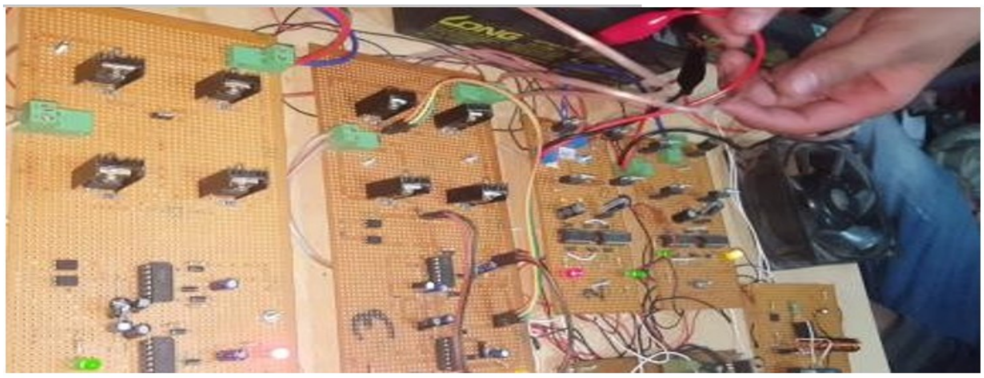

Figure 2 Multilevel Inverter

5.1 TYPES OF MULTILEVEL INVERTER

Modern power electronics would not be the same without multilevel inverters (MLIs), particularly for applications that need high voltage and power quality. To create a more sinusoidal output waveform, they use a range of voltage levels, which greatly lowers harmonic distortion and enhances system performance. The Diode-Clamped Multilevel Inverter (DC-MLI), one of the most popular MLI topologies, clamps the voltage levels between switches using diodes.

5.1.1 Diode-Clamped Multilevel Inverter (DC-MLI)

The Diode-Clamped Multilevel Inverter (DC-MLI), also referred to as the Neutral-Point Clamped (NPC) inverter, is a widely used topology in medium-voltage applications. It utilizes multiple power switches and diodes to clamp the voltage and produce various voltage levels. Typically, two capacitors split the incoming DC power, allowing the inverter to generate three distinct voltage levels: positive, zero, and negative. This design distributes the voltage stress across the switching devices, reducing switching losses and improving overall efficiency. A key advantage of the DC-MLI is its ability to lower total harmonic distortion (THD) in the output voltage, enhancing power quality. However, as the number of levels increases, the complexity of control and design also rises, to maintain neutral point voltage balance. Despite these challenges, the DC-MLI's reliability and durability make it a preferred choice for applications such as motor drives and renewable energy systems.

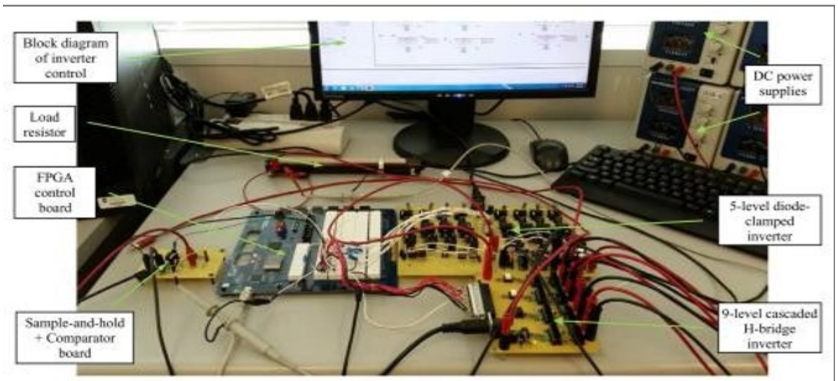

Figure3 Diode-Clamped Multilevel Inverter (DC-MLI)

5.1.2 Flying Capacitor Multilevel Inverter (FC-MLI)

The Flying Capacitor Multilevel Inverter (FC-MLI) is a prominent topology that uses capacitors to generate multiple voltage levels, offering several advantages over traditional inverters. In this configuration, each capacitor stores and supplies energy, enabling the creation of additional voltage levels at the output. Compared to diode-clamped inverters, the FC-MLI achieves more voltage levels with fewer components. Its modular architecture improves fault tolerance, making it a reliable choice for critical applications, as it can continue to operate even if some capacitors fail. This design is particularly beneficial for applications such as power quality enhancement and regenerative braking systems, where voltage balancing is essential.

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However, the control complexity increases as the number of voltage levels rises, as each capacitor's voltage must be carefully monitored and balanced. Additionally, the FC-MLI requires more space and incurs higher costs due to the need for multiple capacitors. Despite these challenges, its performance and versatility make it suitable for a wide range of power electronics applications.

One key advantage of the FC-MLI is its inherent redundancy, providing multiple switching states to generate the same voltage level.

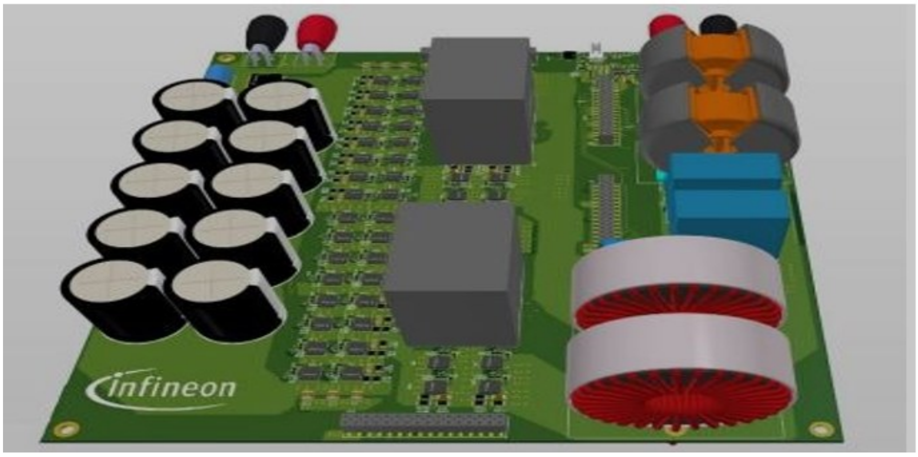

Figure 4 Flying Capacitor Multilevel Inverter

5.1.3 Cascaded H-Bridge Multilevel Inverter (CHB-MLI)

The Cascaded H-Bridge Multilevel Inverter (CHB-MLI) is known for its modularity and scalability, making it a popular choice in multilevel inverter applications. In this configuration, each H-bridge cell is connected in series and powered by an independent DC source, allowing the generation of multiple voltage levels. This modular approach simplifies system design and enables easy expansion to higher power levels without significant changes to the existing infrastructure. Applications that require flexibility and redundancy, such as industrial motors and renewable energy systems, greatly benefit from the CHB-MLI.

Each H-bridge can be operated independently, enhancing fault tolerance and simplifying maintenance, as malfunctioning units can be isolated without affecting the overall system performance. Additionally, the CHB-MLI delivers high output quality with low total harmonic distortion (THD), improving power quality in grid-connected applications.

5.1.4 Modular Multilevel Converters (MMC)

MMC is a state-of-the-art multilevel inverter architecture that is especially well-suited for high-voltage and high-power applications including large-scale renewable energy integration and HVDC transmission. The MMC is composed of numerous sub-modules, each containing power electronic switches and capacitors, connected in series. Scalability is made possible by its modular architecture, which makes it simple for designers to add more sub-modules to reach the required power level.

6.CONTROL STRATEGIES FOR MULTILEVEL INVERTERS

Control strategies for multilevel inverters (MLIs) play a vital role in optimizing performance and ensuring high-quality output voltage waveforms. Various modulation techniques are employed to control power switches, minimizing harmonic distortion while maintaining the desired output voltage. Effective control methods not only enhance inverter efficiency but also improve the overall reliability of the system.

6.1 Pulse Width Modulation (PWM)

INTERNATIONAL JOURNAL OF APPLIED SCIENCE ENGINEERING AND MANAGEMENT
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Pulse Width Modulation (PWM) techniques are essential control strategies in multilevel inverters, helping to minimize harmonic distortion and regulate output voltage. PWM adjusts the pulse width of the inverter's output waveform to control the average voltage supplied to the load. The core principle of PWM involves switching the inverter's power components on and off at a high frequency to achieve the desired voltage output. By varying pulse widths to form a waveform that closely resembles a sinusoidal shape, PWM effectively reduces total harmonic distortion (THD).

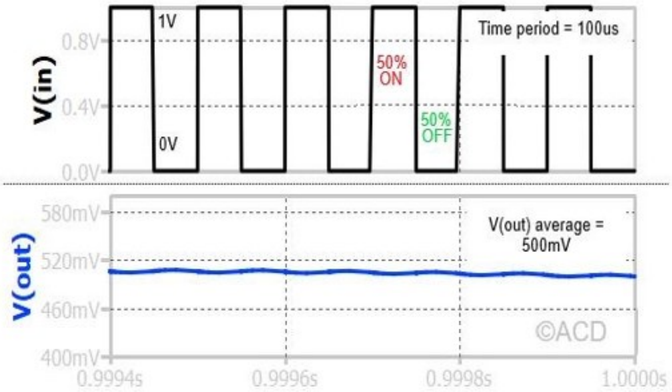

Figure 5 Pulse Width Modulation (PWM)

6.2 Sinusoidal PWM (SPWM)

Sinusoidal Pulse Width Modulation (SPWM) is a widely used technique in multilevel inverters, employing a reference sine wave to modulate pulse width and generate a sinusoidal output voltage. In SPWM, the switching times of inverter devices are determined by the intersection points of a high-frequency triangular carrier wave and the reference signal. By precisely adjusting pulse widths in relation to the sinusoidal reference, SPWM effectively reduces harmonic distortion and produces a smooth output waveform.

This technique is particularly beneficial in applications such as motor drives and renewable energy systems, where maintaining high output voltage quality is essential. One of SPWM's key advantages is its simplicity and ease of implementation, making it a preferred choice among engineers. However, while SPWM efficiently minimizes lower-order harmonics, it may be less effective in mitigating higher-order harmonics, which can impact overall system performance.

6.3 Space Vector PWM (SVPWM)

Space Vector Pulse Width Modulation (SVPWM) is an advanced modulation technique used in multilevel inverters to enhance efficiency and improve output voltage quality. Unlike conventional PWM methods, SVPWM models the inverter in a three-dimensional space, where each voltage vector corresponds to a specific switching state. By leveraging space vector principles, SVPWM generates output voltages that closely approximate a sinusoidal waveform while significantly reducing total harmonic distortion (THD).

6.4 Selective Harmonic Elimination (SHE-PWM)

Selective Harmonic Elimination Pulse Width Modulation (SHE-PWM) is an advanced modulation technique used in multilevel inverters to eliminate specific harmonic components from the output voltage while preserving the fundamental frequency. This method involves solving nonlinear equations that define the relationship between switching angles and output voltage harmonics. By precisely selecting switching angles, SHE-PWM effectively removes targeted harmonic frequencies, resulting in a cleaner output waveform with significantly reduced total harmonic distortion (THD).

SHE-PWM is particularly beneficial in applications where specific harmonics must be minimized, such as in sensitive electronic equipment or power quality enhancement systems.

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7.REDUCED SWITCHED CAPACITOR 13 LEVEL INVERTER

The reduced switched capacitor 13-level inverter converts a DC input into an AC output with 13 distinct voltage levels, ensuring high efficiency and low harmonic distortion. Compared to conventional multilevel inverters, this design requires fewer switches and capacitors, reducing complexity, cost, and power losses while maintaining reliable performance. It achieves stepped voltage levels by carefully controlling the charging and discharging of capacitors in coordination with the switching sequence of power semiconductor devices.

The inverter operates by first receiving power from the DC supply, with its topology determining the voltage levels at which the capacitors are charged. The DSPIC30F4011 controller generates pulse-width modulation (PWM) signals using a low-frequency modulation technique to regulate the switching sequence of the power devices. These switches are strategically arranged to combine the capacitor voltages with the input DC source, producing the desired stepped AC output.

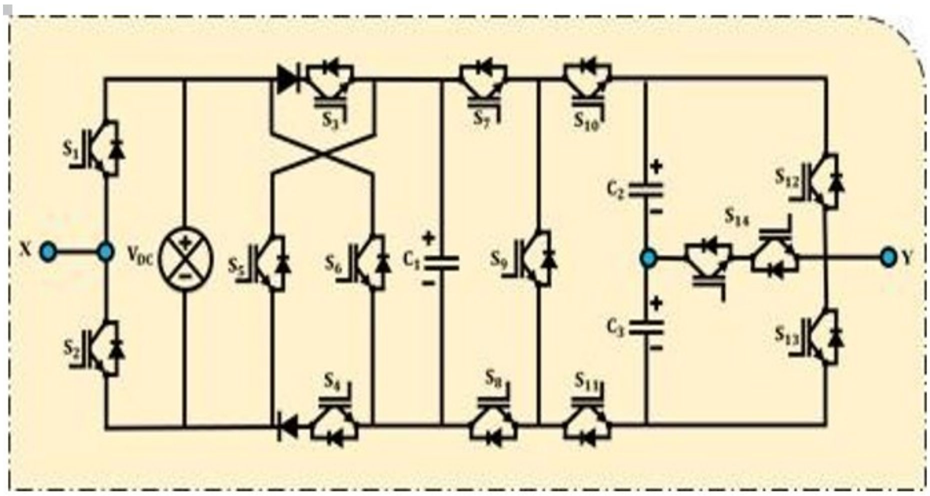

Figure 6 Circuit Design of 13 Level Sc-MLI

MODE OF OPERATIONS

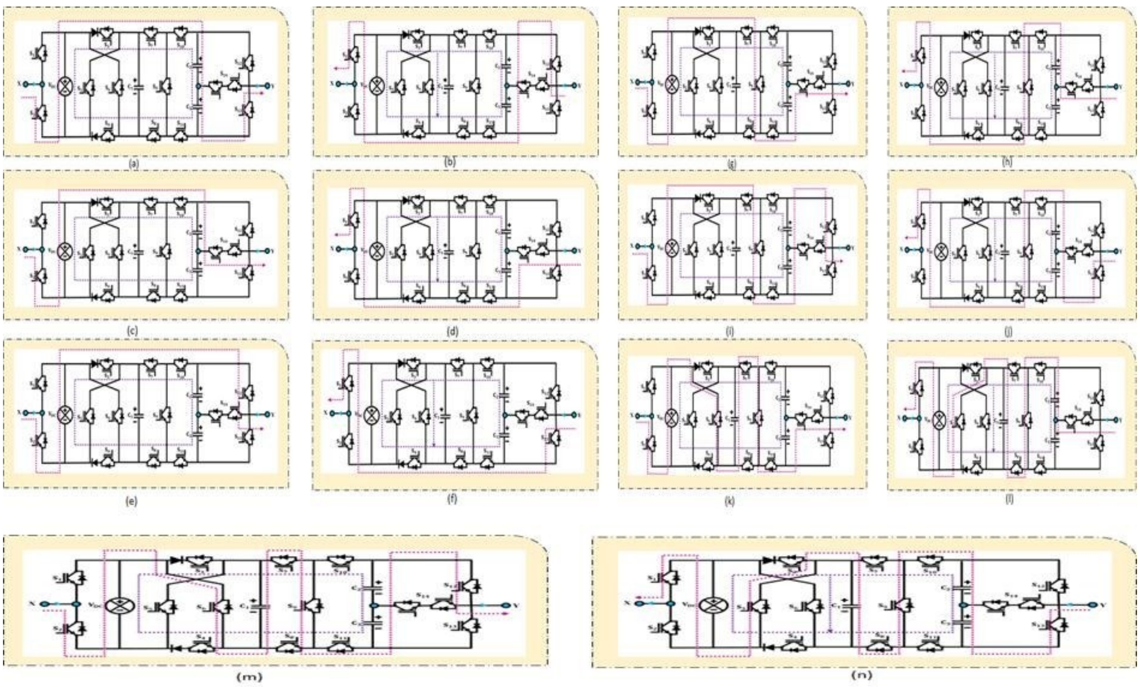

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Figure 7 Mode of Operations

- **Mode 1:** In this mode, Switches _2 , _3 , _4 , _7 , _8 , _10 , _11 and _13 are kept in ON condition where capacitor _1 is stored and _2 is charged to 0.5 _ since, all the capacitors are connected parallel to input supply. Similarly, for producing 0V, switches _1 , _3 , _4 , _7 , _8 , _10 , _11 and _12 are turned ON respectively.

- **Mode 2:** In this mode, switches _2 , _3 , _4 , _7 , _8 , _10 , _11 and _14 are kept in ON condition where capacitors _1 , _2 and _3 are connected parallel to input source. Thus, _1 is charged to _ and _2 , _3 are charged to 0.5 _. Similarly, to attain -0.5 V, switches _1 , _3 , _4 , _7 , _8 , _10 , _11 and _14 are turned ON.

- **Mode 3:** In this mode, switches _2 , _3 , _4 , _7 , _8 , _10 , _11 and _12 are kept in ON condition where capacitors _1 , _2 and _3are connected parallel to DC source. Thus, _1 is charged to _ and _2 , _3 are charged to 0.5 _. Similarly, to attain -1 V, switches _1 , _3 , _4 , _7 , _8 , _10 , _11 and _13 are turned ON respectively.

- **Mode 4:** In this mode, switches _2 , _3 , _4 , _7 , _9 , _11 and _14 are kept in ON condition where _1 is charged to _ and _3 releases the stored energy to load. Similarly, to attain -1.5 V, switches _1 , _3 , _4 , _8 , _9 , _11 and _14 are turned ON.

- **Mode 5:** In this mode, switches _2 , _3 , _4 , _7 , _9 , _11 and _12 are kept in ON condition where _1 is connected in series thus, releases the stored energy. Similarly, to attain -2V switches _1 , _3 , _4 , _8 , _9 , _10 and _13 are turned ON.

- **Mode 6:** In this mode, switches _2 , _6 , _7 , _9 , _11 and _14 are kept in ON condition where _1 and _3 are connected in series releases stored energy to load. Similarly, to attain -2.5V, switches _1 , _5 , _7 , _9 , _11 and _14 are turned ON.

- **Mode 7:** In this mode, switches _2 , _6 , _7 , _9 , _11 and _12 are kept in ON condition where _1 , _2 and _3 are connected in series releases stored energy to load. Similarly, to attain -3V, switches _1 , _5 , _8 , _9 , _11 and _13 are turned ON.

8.PWM GENERATOR

A Pulse Width Modulation (PWM) generator is a key component in many electronic systems, allowing efficient power control by adjusting the duty cycle of a periodic pulse signal while maintaining a constant frequency. The duty cycle determines how long the signal stays "high" in each cycle, directly affecting the average power delivered to a load. By varying the duty cycle, PWM controls power without generating excessive heat, making it ideal for applications like motor control, LED dimming, power regulation, and communication systems.

The PWM generator operates by comparing a high-frequency clock signal with a modulating signal, which can be a constant value or vary based on system requirements. A comparator circuit switches the output "on" when the modulating signal exceeds the clock threshold and "off" when it falls below, creating a sequence of square wave pulses. The longer the "on" time in each cycle, the higher the power delivered. This precise duty cycle control enables smooth and efficient operation in devices such as motors and LEDs, preventing issues like flickering or noise.

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One of the main advantages of PWM is its high efficiency compared to traditional power control methods, which dissipate excess energy as heat. Since PWM rapidly switches power devices fully on or off, energy losses are minimized. This efficiency makes PWM essential in applications like DC-DC converters, motor drivers, and power supplies, ensuring optimal energy usage and performance.

9.LOAD

The working process of a load in an electrical or electronic circuit involves the conversion and consumption of electrical energy to perform a specific task, such as powering a motor, illuminating a light bulb, or driving a speaker. A load be any device or component that draws electrical power from a circuit and uses it to produce useful output, such as mechanical work, heat, or light. Understanding the working process of a load requires exploring its interaction with the power source, the type of load, and the specific manner in which the load consumes or transforms electrical energy. The operation of a load vary significantly depending on the nature of the device whether it is resistive, inductive, capacitive, or complex with multiple elements each of which influences the way energy is drawn and utilized from the electrical circuit.At its core, the load works by drawing current from a power supply, which delivers voltage through the wiring and components of the circuit. According to Ohm's Law, the load is usually identified by its impedance or resistance, which controls the amount of current that flows for a specific applied voltage: $I = V/R$, where V is the voltage, R is the load's resistance or impedance, and I is the current. The energy from the power source is mostly transformed into heat or light in a resistive load, like an electric heater or light bulb. This happens when electrons passing through a resistive material such as a heater's coil or a light bulb’s filament collide with the material's atoms, dissipating energy as heat. The power consumed by the resistive load is determined by the equation $P = V^2/R$, where P is the power, V is the applied voltage, and R is the resistance.

10. RESULTS AND DISCUSSIONS

The proposed work is implemented in MATLAB simulation and the following results are obtained.

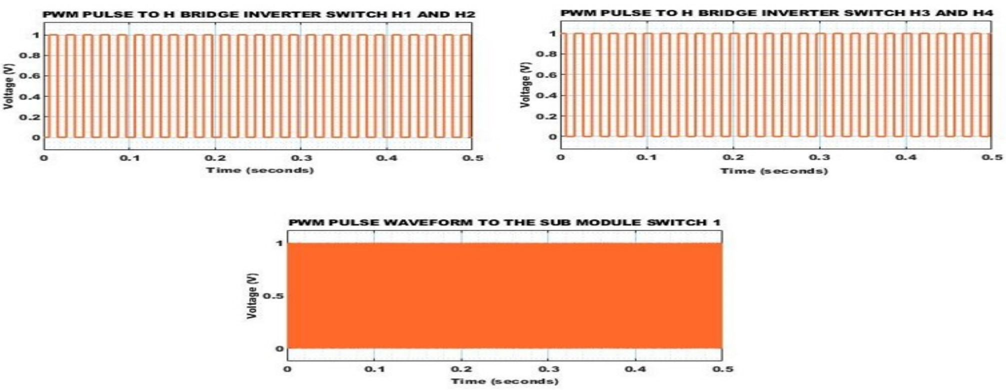

Figure 8 PWM Pulses Waveform

The figure 8 illustrates the PWM pulse outputs for H Bridge inverter switches H1, H2, H3, and H4 over a time span of 0.5 seconds, demonstrating consistent voltage levels of 0.8 V and 0 V. Additionally, the PWM pulse waveform for Sub Module Switch 1 is displayed, showing minimal voltage variation throughout the same time period.

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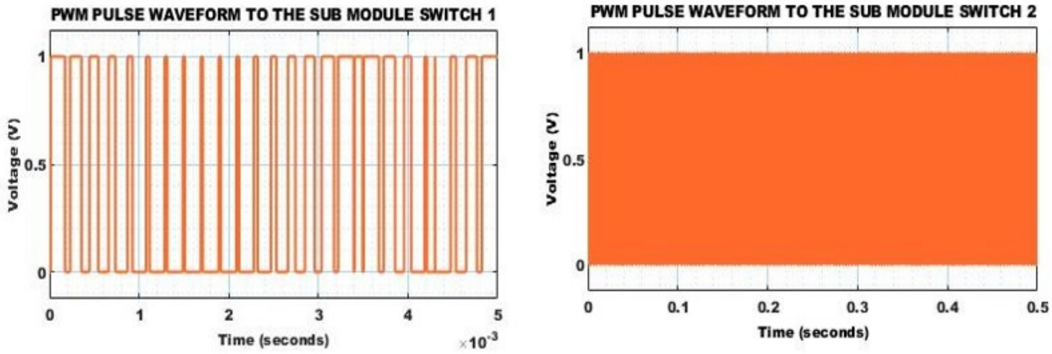

Figure 9 Sub Module Switch 1 & 2 PWM Pulse Waveform

Figure 9 presents the PWM pulse waveforms for sub module switch 1 and sub module switch 2 over a time duration of 5 milliseconds. Sub Module Switch 1 exhibits multiple oscillations with a voltage range of 0 to 1 V, while Sub Module Switch 2 shows a steady voltage at 1 V throughout the measurement period.

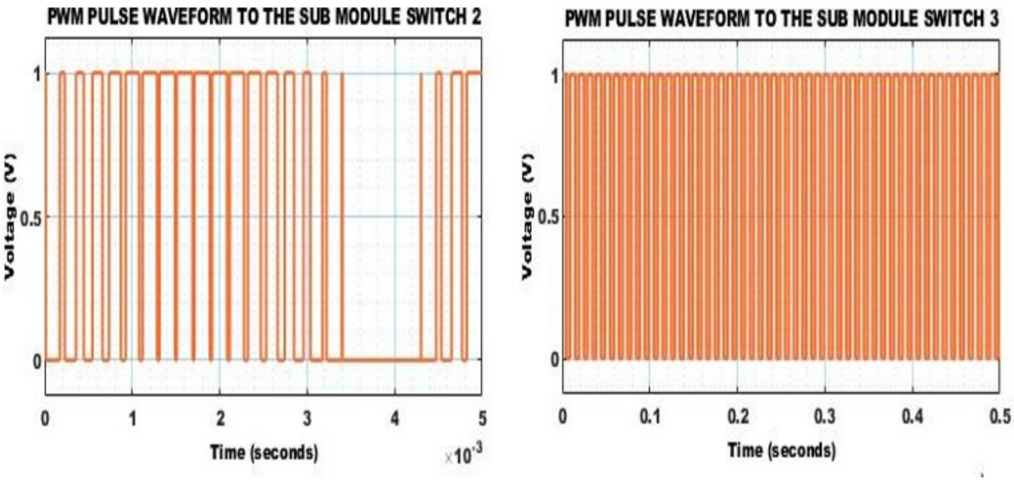

Figure 10 Sub Module Switch 3 & 4 PWM Pulse Waveform

PWM pulse waveforms for sub module switch 2 and sub module switch 3 over a time span of 5 milliseconds are shown in figure 5.3. Sub Module Switch 2 displays fluctuating voltage levels between 0 and 1 V, while Sub Module Switch 3 maintains a constant voltage of 1 V throughout the duration.

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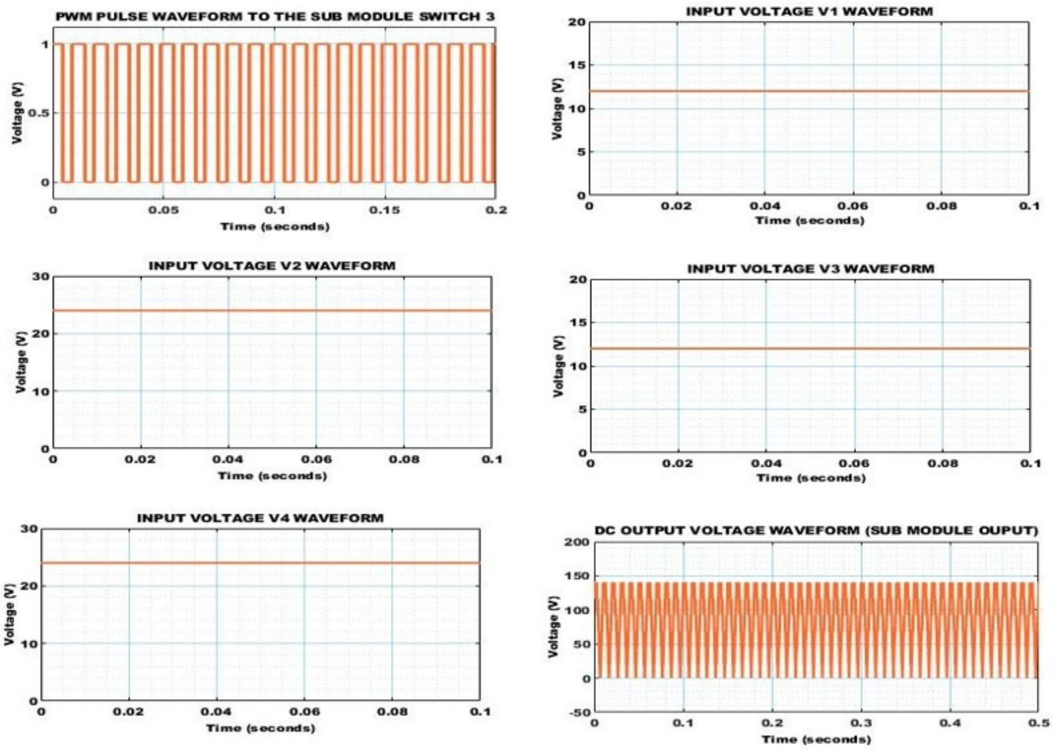

Figure 11 Sub Module Switch 3 and Input Voltage Waveform

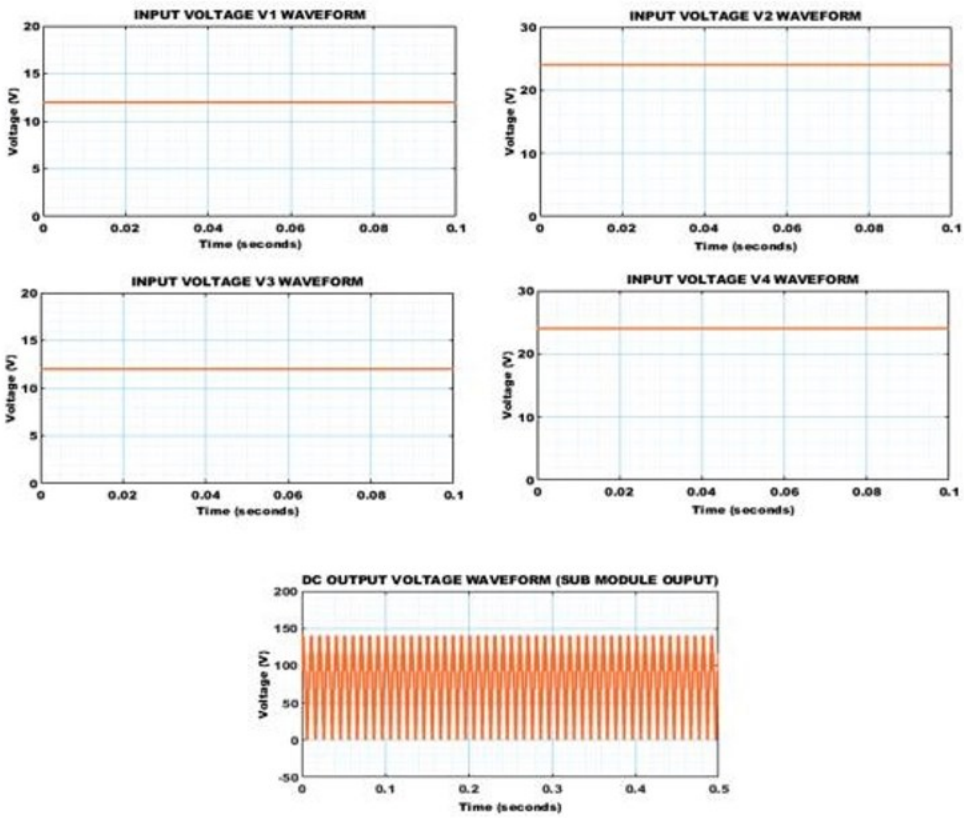

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Figure 12 Input Voltage Waveform and DC Output Voltage Waveform

The output image illustrate the working process of the PWM modulation, with the input voltages (V1 to V4) maintained at 20 V. The bottom figure represents the DC output waveform, demonstrating a consistent sub-module output of approximately 50 V over time.

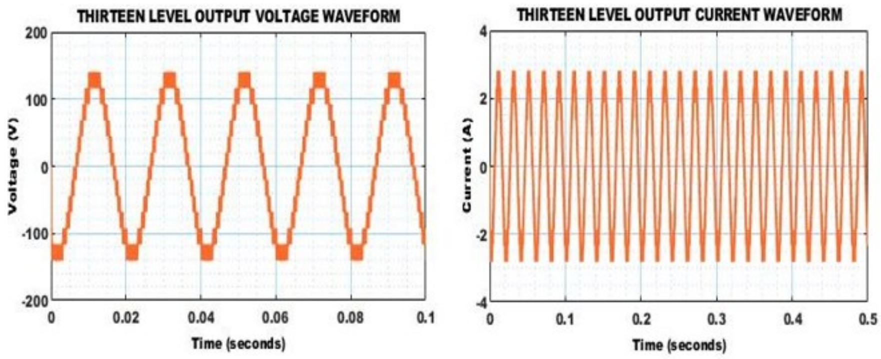

Figure 13 Output Voltage and Current Waveform for 13 Level

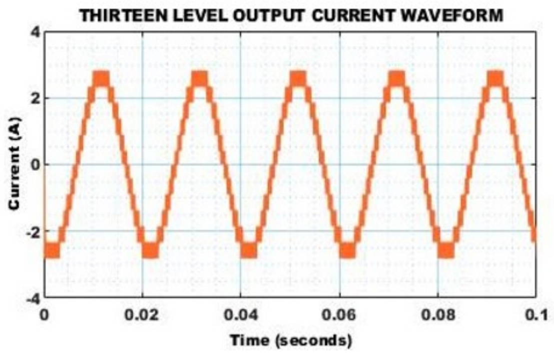

Figure 14 Output Current Waveform for 13 Level

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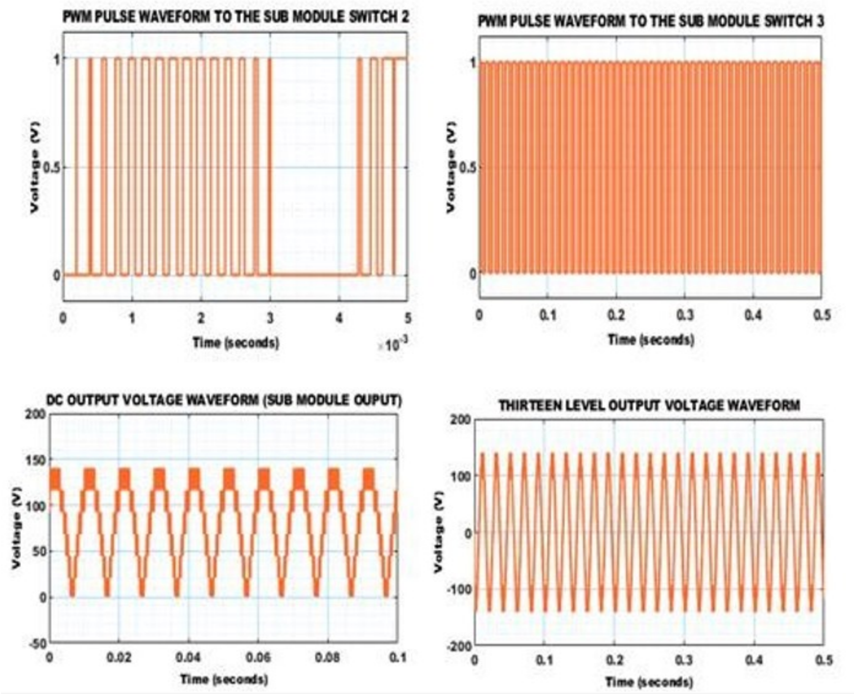

Figure 15 Waveforms of Output Voltage

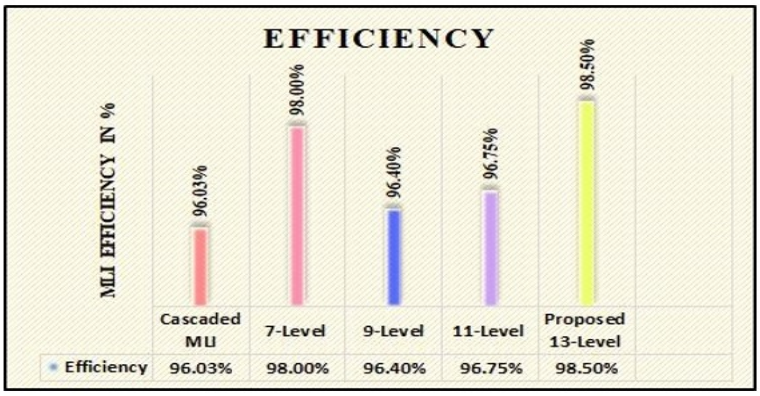

Figure 16 Efficiency Graph

Figure 16 shows the efficiency graph. The efficiency of the 11-level system is 96.75%, whereas the efficiency of the proposed 13-level system is 98.50%. In comparison, the cascaded multi-level (MLI) system shows an efficiency of 96.03%, highlighting significant improvements with higher-level designs.

5. CONCLUSION

The analysis of a simplified 13-level inverter using reduced switched capacitor technology highlights significant advancements in multilevel inverter design. The proposed topology effectively addresses major challenges by minimizing the number of components, simplifying control strategies, and enhancing overall system efficiency. Utilizing a single DC source and the switched capacitor technique, the system eliminates the need for multiple isolated voltage sources, resulting in a more compact and cost-effective solution. The self-balancing capability of the capacitors ensures stable and reliable operation without additional circuitry. Furthermore, the integration of a PWM generator improves control precision, enabling efficient harmonic suppression and high-quality sinusoidal output. MATLAB/Simulink simulations validate the inverter's performance, achieving an impressive efficiency of 98.50% while maintaining a stepped AC output with minimal

ISSN 2454-9940

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total harmonic distortion (THD). These attributes make the proposed inverter design highly suitable for renewable energy systems, industrial motor drives, and other high-performance power applications.

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