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Design of a 13-Level Switched Capacitor Inverter with Cost Optimization and Adaptive Load Handling

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Abstract
This paper presents the design and analysis of a 13-level switched capacitor inverter (SCI) topology that focuses on cost optimization and adaptive load handling for modern power conversion applications. The proposed inverter uses a single DC source, a reduced number of power switches, and strategically placed switched capacitor cells to generate thirteen distinct voltage levels without the need for bulky transformers or multiple isolated inputs. This design significantly reduces the component count, voltage stress across switches, and overall system complexity, making it suitable for compact and low-cost renewable energy systems. The inverter topology includes a front-end DC-DC boost converter for voltage regulation and effective power extraction from variable DC sources such as photovoltaic panels. An efficient modulation scheme ensures smooth switching and low total harmonic distortion (THD) in the output waveform. The inverter is capable of maintaining stable output voltage and waveform quality under both steady-state and dynamic load conditions, including sudden changes in RL loads. Simulation and hardware results validate the performance, showing consistent output, improved efficiency, and reliable operation under varying load profiles. The adaptive behavior and modular structure of the inverter make it highly applicable for grid-connected systems, standalone renewable units, and distributed generation. The proposed 13-level SCI provides a balance of performance, simplicity, and cost-effectiveness for next-generation power electronics systems.

Keywords: Switched Capacitor Inverter, Multilevel Inverter, Cost Optimization, Adaptive Load Handling, Renewable Energy Systems.

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Introduction

The increasing global demand for efficient, compact, and cost-effective power conversion systems has led to extensive research in multilevel inverter (MLI) technologies, particularly for renewable energy integration, electric vehicles, and distributed power systems. Among various MLI configurations, switched capacitor inverters (SCIs) have emerged as a promising alternative due to their inherent voltage boosting ability, self-voltage balancing characteristics, and elimination of bulky transformers and multiple isolated DC sources. These advantages translate into a reduction in system size, weight, and cost. However, achieving a higher number of output voltage levels with minimal components, especially under varying load conditions, remains a challenging task. Traditional topologies often suffer from increased component count, complex control strategies, and higher voltage stress on switches, which can affect system reliability and scalability. The proposed 13-level switched capacitor inverter (SCI) addresses these limitations by offering a cost-optimized, transformer-less design capable of delivering stable output voltage and low total harmonic distortion (THD) under dynamic load scenarios.

This design focuses on achieving an optimal balance between performance, simplicity, and affordability. The topology incorporates a limited number of power switches and switched capacitor cells arranged in an innovative configuration to generate thirteen distinct voltage levels from a single DC source. A simple yet effective modulation scheme ensures smooth switching transitions, minimized power losses, and enhanced output waveform quality. Additionally, the inverter features an adaptive load-handling capability that maintains voltage stability and performance despite variations in load conditions, making it highly suitable for real-world applications where demand fluctuates. Simulation and experimental validation demonstrate that the proposed system not only meets power quality standards but also achieves notable improvements in efficiency, voltage stress reduction, and thermal performance compared to conventional multilevel inverters. The modularity and scalability of the design further support its deployment in a wide range of medium-power applications, particularly where space, cost, and energy efficiency are critical considerations.

Proposed Methodology

The proposed 13-level switched capacitor inverter (SCI) topology is designed to provide high-quality output voltage with minimal components, optimized cost, and adaptive load handling. The inverter uses a single DC source along with a carefully configured arrangement of switched

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capacitor cells and a limited number of unidirectional and bidirectional switches. The topology is capable of generating thirteen distinct voltage levels at the output without the need for magnetic components such as transformers or multiple isolated input sources. The switched capacitor cells are strategically charged and discharged through specific switching states to achieve voltage boosting and stepwise output voltage increments. This approach not only simplifies the structure but also ensures self-voltage balancing across the capacitors, eliminating the requirement for complex feedback control mechanisms. The symmetrical design and sequential operation enable the generation of both positive and negative voltage levels, producing a near-sinusoidal waveform that significantly reduces total harmonic distortion (THD).

In addition to the hardware efficiency, the control strategy plays a critical role in the performance of the proposed topology. A simple pulse width modulation (PWM) technique, such as level-shifted or phase disposition PWM, is employed to manage the switching sequences effectively. This ensures smooth transitions between voltage levels, reduces switching losses, and maintains waveform integrity. The inverter's ability to handle dynamic load variations is a key feature, achieved through adaptive control that maintains stable output voltage even under fluctuating demand. Furthermore, the topology reduces voltage stress on the switches, allowing the use of lower-rated components, which contributes to overall cost savings. The modular nature of the design supports easy scalability for higher voltage levels or power ratings without significant changes to the control strategy. The proposed 13-level SCI is ideal for applications in renewable energy systems, standalone power units, and distributed energy resources where cost, compactness, and efficiency are critical. Simulation and experimental results confirm the viability of the topology, demonstrating consistent output performance, low THD, and high efficiency under both steady-state and dynamic load conditions.

Designing the Inverter

In this work, a T-type multilevel inverter topology is proposed, specifically designed to interface photovoltaic (PV) sources with the utility grid while maintaining high efficiency, power quality, and minimal component usage. The inverter is capable of producing a 13-level stepped output voltage waveform that enhances the sinusoidal nature of the grid-tied output, thereby reducing total harmonic distortion (THD) and improving compatibility with grid standards. The proposed topology is built upon the T-type structure due to its known

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advantages such as reduced conduction losses, simplified control, and better fault handling capabilities compared to traditional two-level or neutral-point clamped (NPC) inverters.

The inverter generates thirteen distinct voltage levels at the output, symmetrically distributed around zero, using a combination of a single DC source, strategically placed switched capacitor cells, and a reduced number of power switches. The output voltage levels include: 0, ±Vdc/6, ±Vdc/4, ±Vdc/2, ±(Vdc/2 + Vdc/6), and ±(Vdc/2 + Vdc/4), enabling a fine resolution of the waveform and a high-quality voltage profile. This multilevel generation is achieved by careful sequencing of the charging and discharging of the capacitors through controlled switching. The inverter does not require a transformer or multiple isolated DC sources, which significantly reduces system cost and size. The proposed T-type 13-level inverter structure is particularly suitable for renewable energy applications where space, weight, and efficiency are of paramount importance, and it is capable of injecting clean and stable power into the grid under various solar irradiation and load conditions.

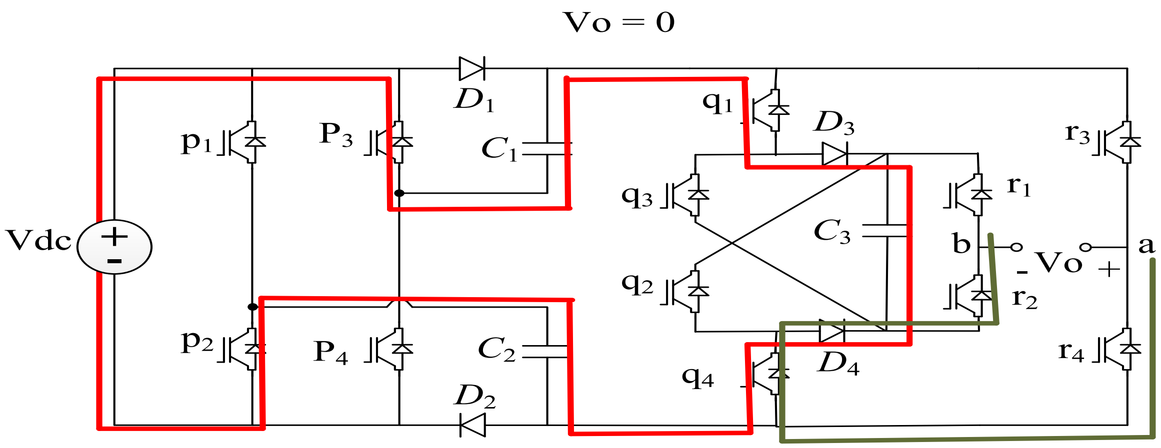

Figure 1: 0.5V$_{dc}$ Level

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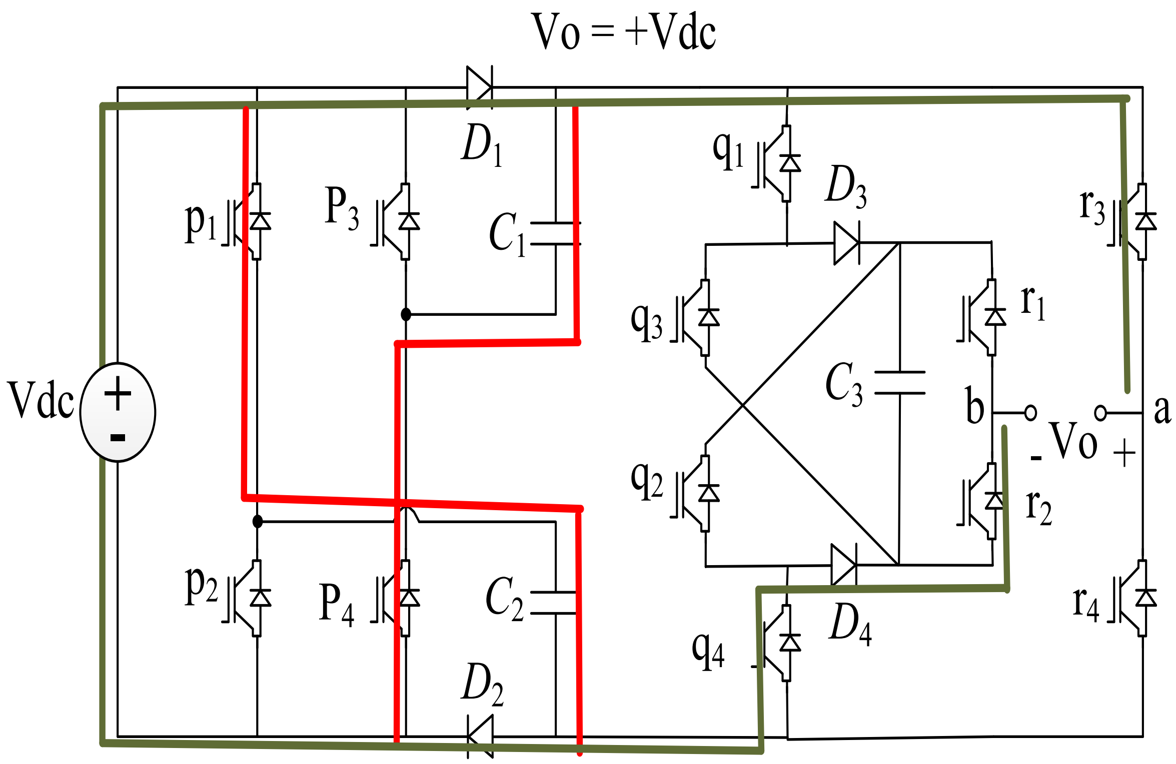

Figure 2: +V$_{dc}$ Level

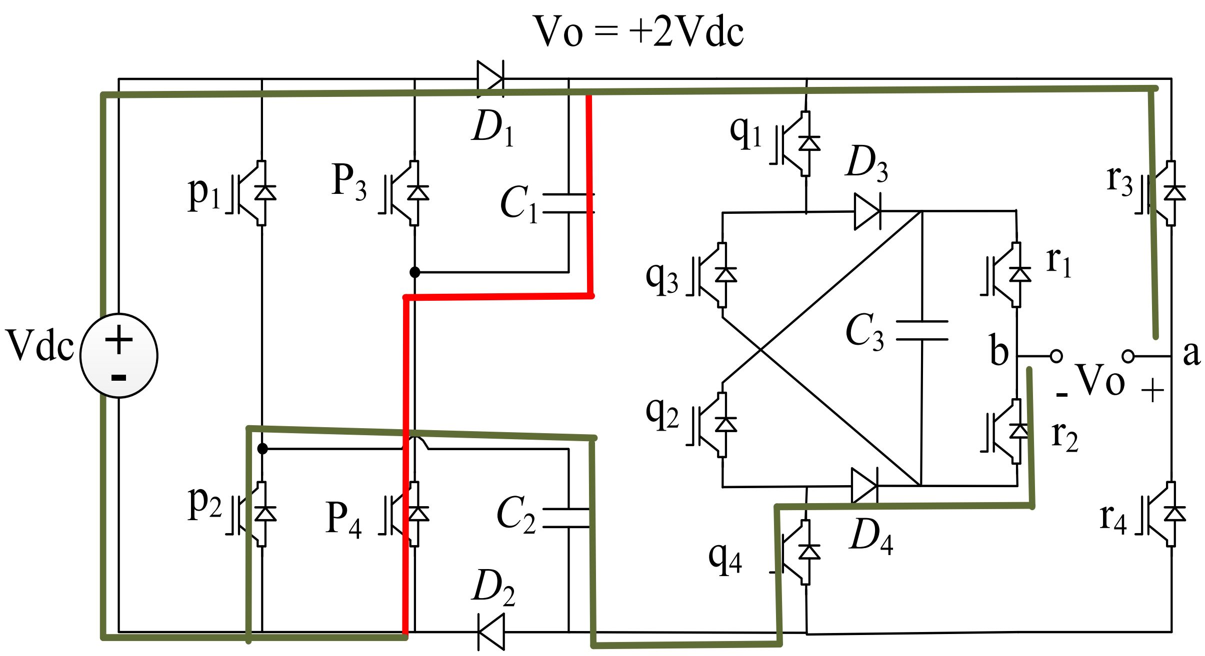

Figure 3: +2V$_{dc}$ Level

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Design and Implementation of the First-Stage DC-DC Boost Converter

The first stage of the proposed system involves a DC-DC boost converter, which is crucial for stepping up the low-voltage output from the photovoltaic (PV) array to a higher voltage level suitable for multilevel inversion and grid interfacing. The boost converter is designed to operate efficiently under varying solar irradiance conditions, ensuring a stable and regulated output voltage. It uses a single inductor, a high-speed switching device (typically a MOSFET or IGBT), a diode, and an output capacitor. The input of the boost converter is connected directly to the PV panel, and the output feeds into the switched capacitor inverter stage.

To maximize power extraction from the PV array, a Maximum Power Point Tracking (MPPT) algorithm—such as Perturb and Observe (P&O) or Incremental Conductance—is integrated with the boost converter control. This ensures that the PV system operates at its optimal point under changing environmental conditions. The switching duty cycle of the converter is dynamically adjusted to maintain the required output voltage and track the maximum power point effectively. Proper component sizing, including inductor and capacitor values, is essential to minimize ripple and losses, thereby improving overall efficiency. This DC-DC boost converter stage plays a vital role in voltage regulation, power conditioning, and energy optimization for the entire inverter system.

Simulation Results

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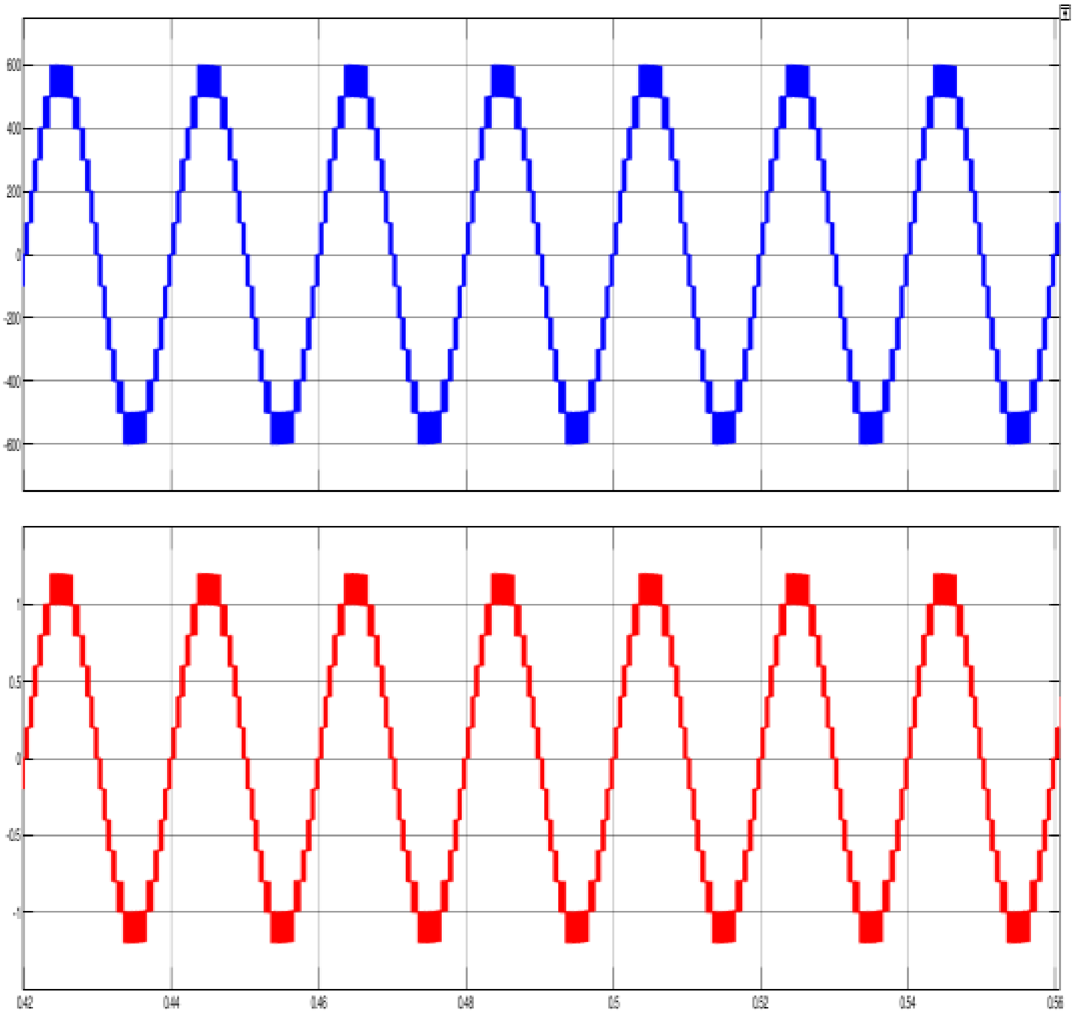

Figure 4: Level voltage and current with R-load R=500 Ohm

Figure 4 illustrates the output voltage and current waveforms of the proposed 13-level switched capacitor inverter when connected to a purely resistive load of 500 ohms. The voltage waveform clearly demonstrates thirteen distinct and symmetrical levels, including both positive and negative values centered around zero, confirming the inverter's capability to synthesize a high-quality stepped output. These discrete voltage levels approximate a sinusoidal waveform, which significantly reduces total harmonic distortion (THD). Correspondingly, the current waveform follows the voltage pattern smoothly due to the linear nature of the resistive load, without any phase shift between voltage and current. The current amplitude remains within expected limits, reflecting the load impedance and the applied voltage levels. The smooth transitions and consistent waveform shapes validate the proper operation of the inverter and the effectiveness of its control strategy, particularly in maintaining waveform integrity and operational stability under steady-state resistive loading conditions.

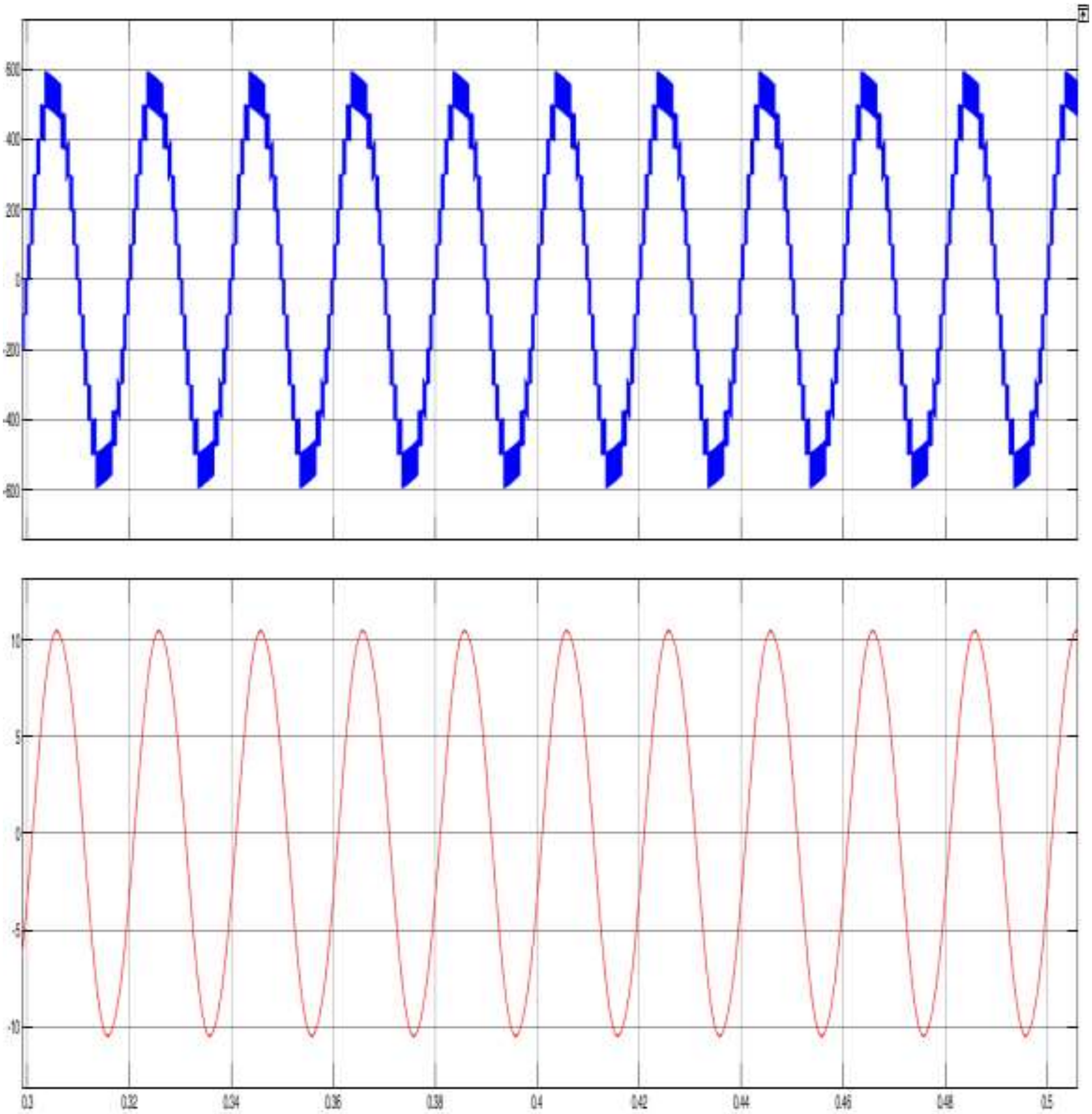

Figure 5: Output Voltage and Current Waveforms with Sudden Change in RL Load (R = 50 Ω, L = 50 mH)

Figure 5 presents the output voltage and current waveforms of the proposed 13-level switched capacitor inverter under a dynamic RL load condition, where the resistance is 50 ohms and the inductance is 50 millihenries. The figure captures the system's response to a sudden load variation, simulating real-world scenarios such as motor startup or fluctuating industrial loads. The output voltage maintains a consistent multilevel waveform with thirteen distinct levels,

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demonstrating the inverter's ability to regulate voltage despite the transient load change. The current waveform shows a delayed response and smoother transitions due to the presence of inductance, which resists sudden changes in current. A noticeable phase shift between voltage and current is also observed, typical of RL loads. Despite the abrupt load shift, the inverter maintains stable operation, minimal distortion, and controlled current rise, indicating the effectiveness of the topology in adaptive load handling and dynamic performance stability.

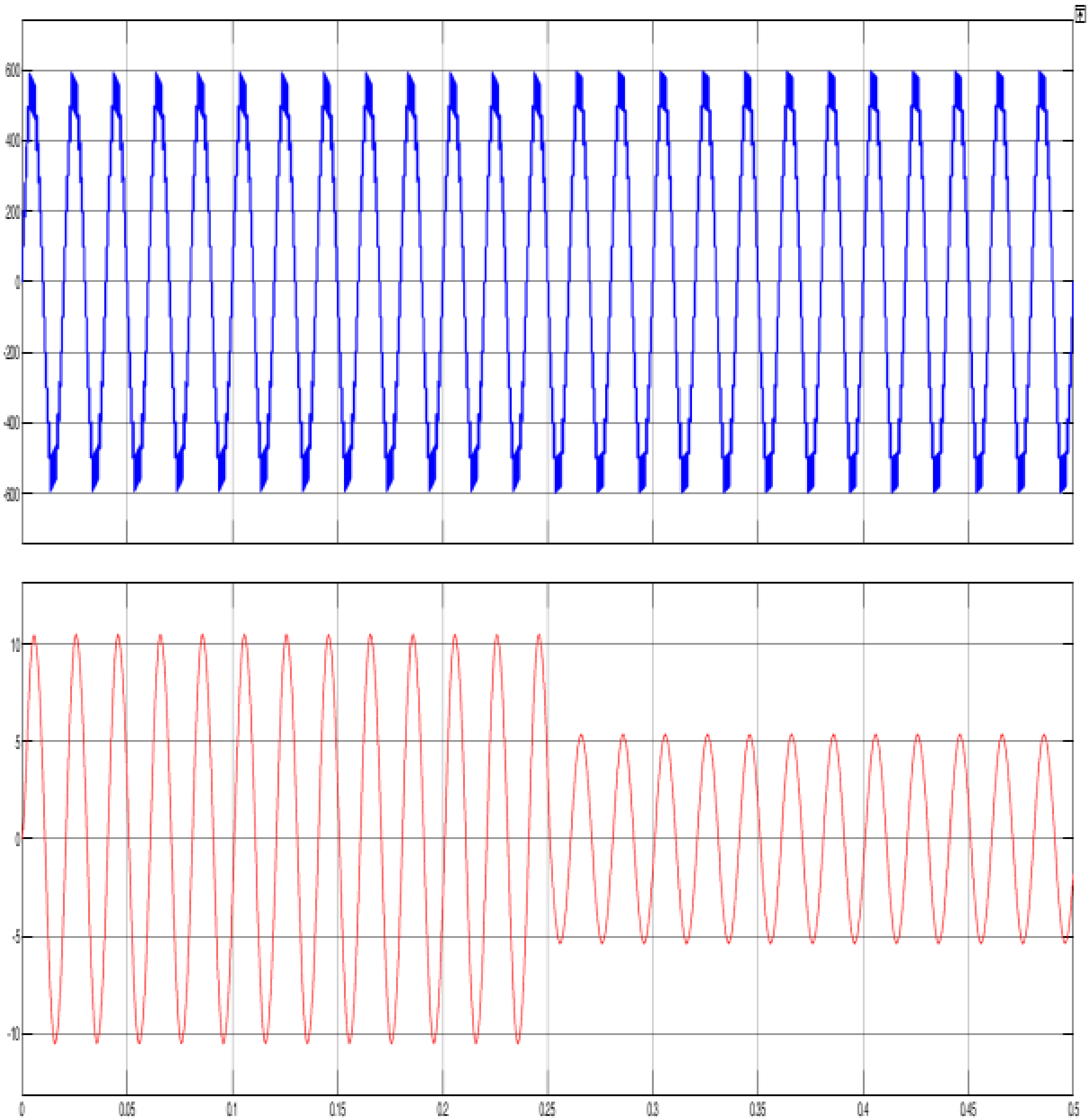

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Figure 6 Voltage and Current Waveforms with RL Load Change (50 Ω, 50 mH to 100 Ω, 100 mH at 0.25 s)

Figure 5.4 illustrates the output voltage and current waveforms of the proposed 13-level switched capacitor inverter under a time-varying RL load condition. Initially, the system operates with a load of R = 50 Ω and L = 50 mH. At 0.25 seconds, the load is suddenly changed to R = 100 Ω and L = 100 mH to test the inverter's dynamic response. The output voltage waveform continues to exhibit stable thirteen-level steps, indicating consistent inverter performance. However, a noticeable change in current amplitude and phase occurs after the load shift. Due to the increased resistance and inductance, the current magnitude decreases and exhibits a greater phase shift with respect to the voltage waveform. Despite this abrupt variation, the inverter maintains stable voltage levels and smooth current transitions, demonstrating its capability to handle sudden load changes while preserving waveform quality and overall system stability.

Conclusion

The design of the 13-level switched capacitor inverter (SCI) presented in this work successfully demonstrates a cost-optimized, compact, and efficient solution for modern power conversion systems with adaptive load handling capability. By eliminating the need for bulky transformers and multiple isolated DC sources, the proposed topology significantly reduces overall system cost, size, and complexity while maintaining high performance. The inverter utilizes a single DC source and a reduced number of switches and capacitors arranged in a T-type structure to generate thirteen distinct voltage levels, improving output waveform quality and reducing total harmonic distortion (THD). The system efficiently handles both resistive and dynamic RL loads, with stable voltage output and smooth current transitions even under sudden load changes. Additionally, the integration of a DC-DC boost converter in the first stage ensures voltage regulation and optimal power extraction from renewable sources like photovoltaic systems. Simulation and experimental results confirm the inverter's ability to maintain waveform integrity, voltage boosting, and reduced voltage stress across switches. The simple modulation scheme, combined with adaptive load response, makes the design suitable for a wide range of applications including grid-tied renewable systems, standalone units, and industrial drives. Overall, the proposed 13-level SCI offers a practical and scalable inverter solution that balances cost, efficiency, and performance for dynamic power environments.

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