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A High Step-Up DC-DC Converter with Switched Capacitor Utilising a Built-in Transformer and Coupled Inductor for Renewable Energy Power Applications

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Abstract: The purpose of this work is to introduce a novel direct current to direct current converter that has a high step-up and is intended to improve the efficiency of voltage conversion in non-conventional energy systems. A large voltage gain can be achieved by utilising integrated transformers (BITs), coupled inductors (CIs), and switched capacitor (SC) cells in the proposed converter. The increasing demand for efficient energy conversion in applications such as solar power systems necessitates the creation of this converter. In these applications, it is often necessary to raise voltage levels to meet the grid's requirements. Our approach to this involves using MATLAB for simulation, as well as the dsPIC30F2010 microcontroller for hardware implementation. We emphasise both theoretical design and practical application. The interleaved design results in a reduction in the output ripple current and an improvement in the overall reliability. The compact design optimises available space without compromising performance. This work makes a substantial contribution to the field of sustainable energy solutions, facilitating the transition to more environmentally friendly technologies.

Keywords: Direct Constant Current; Current Converters; Non-Conversional Energy; Coupled Inductors; Switched-Capacitor; Voltage Gain; Energy Conversion; Environmentally Friendly.

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1. Introduction

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The global shift towards nonconventional energy sources, driven by the need for sustainable and eco-friendly solutions, has led to an increasing demand for efficient energy conversion systems [10]. Specifically, solar energy has become a major alternative, providing a clean and abundant source of power; however, there are significant difficulties in harnessing the low output of solar energy generated by photovoltaic (PV) panels. This limitation necessitates the application of efficient direct current to direct current converters to raise the voltage levels to meet the requirements of grid integration and various load applications [11]. Direct constant current converters play a crucial role in the effective utilisation of non-conventional energy by facilitating low-voltage to high-voltage conversion while maintaining efficiency and minimising losses. Traditional boost converters often face challenges such as large ripple in the input current, low ripple in the output voltage, and energy losses, especially at high step-up ratios. To address these challenges, advanced converter topologies that integrate multiple Methods have been created [1].

This work presents an innovative interleaved high-step-up direct current to direct current converter that combines inductors (CIs), integrated transformers (ITs), and switched-capacitor (SC) cells. The integration of these components allows for a significant increase in voltage gain while simultaneously reducing output ripple currents. Coupled inductors enhance energy transfer through magnetic coupling, while integrated transformers contribute to compactness and efficiency [12]. The use of switched-capacitor cells further optimises voltage conversion by leveraging the charge-sharing mechanism, thus minimising the need for additional components. This study's two main goals are as follows: first, to design and simulate the suggested converter using MATLAB to assess its performance in different operating environments; and second, to implement the converter using the dsPIC30F2010 microcontroller for practical validation. This work aims to demonstrate the converter's effectiveness in enhancing energy conversion efficiency for nonconventional energy applications, ultimately contributing to the development of sustainable energy solutions [2].

1.1. Background

Sustainable power generation now requires the use of non-conventional energy sources, such as solar and wind. However, these sources typically produce low, fluctuating DC voltages that require a significant boost to interface with grids, storage systems, or high-voltage DC loads. Traditional Direct constant current to Direct constant current converters often struggle to meet these high-gain requirements efficiently, as they suffer from high switching losses, thermal challenges, and stress on components. Existing high-step-up Direct constant current to Direct constant current converters serve a critical role in non-conventional energy applications by bridging the voltage gap between low-output sources, such as solar panels and wind turbines, and the higher levels required for storage or grid-tied systems. The most common types include conventional boost, flyback, push-pull, switched-capacitor, coupled inductor-based, and interleaved converters, each with distinct characteristics and limitations. The conventional boost converter is widely used for stepping up voltage due to its simple structure; however, at high voltage gains, it requires very high duty cycles, which result in significant switching losses and thermal stress, thereby reducing efficiency and increasing component wear. Flyback converters, popular for isolated, high-voltage applications, utilise transformers to achieve high gain with galvanic isolation.

However, they suffer from high losses and voltage spikes caused by transformer leakage inductance, making them less suitable for high-power nonconventional systems. Push-pull converters also utilise a transformer for high voltage gain and isolation, performing well in moderate to high-power applications. However, they face challenges such as voltage imbalance and transformer core saturation, which can decrease reliability and necessitate the use of large, costly transformers. Switched-capacitor (charge-pump) converters utilise capacitors and switches to achieve high voltage gain without the need for inductors, making them compact and suitable for low-power applications [3]. However, they lack high current-handling capability, struggle with efficiency at high frequencies, and are sensitive to capacitor ESR, making them impractical for non-conversional systems demanding high power. Coupled inductor-based converters enhance conventional boost designs by allowing for higher voltage gains without requiring excessive duty cycles, utilising a coupled inductor to store and transfer energy. While effective in achieving moderate voltage gains, these converters can experience high component stress and increased ripple, requiring complex control circuits to handle the variability of non-conversional energy sources. Interleaved converters, which operate multiple boost converter stages in parallel with staggered phases, effectively reduce input current ripple, lowering electromagnetic interference (EMI) and distributing power across components to decrease stress and improve thermal performance.

Although interleaving enhances efficiency and reduces ripple, achieving high voltage gain remains challenging without combining additional techniques, such as coupled inductors or switched capacitors [4]. Despite their advantages, each of these existing systems faces significant limitations when applied to non-conventional energy sources, including reduced efficiency at high step-up ratios, increased stress on switches, inductors, and capacitors, as well as increased size and cost due to the addition of components such as transformers and snubber circuits. Additionally, conventional designs often lack the stability and dynamic response required to handle fluctuating input conditions typical of solar and wind energy sources. This highlights the need for an advanced high-step-up Direct constant current to Direct constant current converters that integrate the strengths of multiple topologies to provide high efficiency, low component stress, minimised ripple, compact design, and reliable operation under variable input conditions [5]. The suggested high-step-up converter with interleaving design, which combines a coupled, integrated transformer and switched-capacitor cells, aims to address these challenges, providing a robust and efficient solution tailored to the unique demands of non-conversional energy systems [6].

2. Literature Review

A unique interleaved/unipolar PWM switching system is proposed by Gaddala et al. [1], which can significantly improve efficiency and reduce switching losses. To test the PWM control techniques, a prototype dual inverter drive was assembled, and the results of the examination are provided to confirm that the proposed control scheme is effective. The article discusses the use of a hybrid electric vehicle (HEV) onboard electrical propulsion system to supply mobile power generation, as well as Support for vehicle-to-grid and plug-in charging. To assess their effects regarding the efficiency of power conversion, control using pulse width modulation (PWM) techniques was investigated for driving, such as a plug-in HEV, for applications including vehicle-to-grid support and mobile power generation.

Mansour et al. [2] talk about this work, which presents A permanent magnet motor with a split-phase-based isolated high-power 3-phase integrated charger and motor drive. Relay-based switching for battery charge and the traction mechanism can reverse motor winding relationships. In the charging mode of the motor, it functions as a revolving transformer isolation, supplying a 3-phase power supply for the battery-charging inverter. The motor is a conventional three-phase motor when used in traction mode. A mathematical model of a motor with six stator windings is presented for an arbitrary phase change in the windings. The charging method of the split-phase motor, the grid synchronisation process, charge control, and the developed controller are explained. Mansour et al. [2] proposed a system in Which Traction circuit components can be utilised to integrate an onboard charger into the charger circuit for cars that use grid electricity to charge their batteries, as these components are not used during the charging process. It is possible to either non-isolate or galvanically isolate the grid-powered battery charger.

A variety of both integrated and non-isolated charger examples are examined &described. Additionally, this research presents a new, isolated, high-power, three-phase battery charger based on a permanent magnet motor with a split-phase winding structure. The suggested charger is a high-efficiency, two-way, high-power charger. It has a power factor of unity. Regarding electric vehicle onboard chargers that use single-phase interleaved totem pole (ILTP) power factor correction (PFC) converters, Liu et al. [4] suggested a thorough design of a sliding mode control (SMC) loop. Enhancing converter dynamics, maintaining a power factor of unity, and ensuring strict voltage output regulation are the primary objectives of the proposed SMC, particularly in addressing rapid variations in load. Sliding mode coefficients are chosen to ensure the stability of both small and large signals, thereby enhancing the converter's resilience under various operating conditions. A single-phase ILTP PFC hardware prototype is created and verified as confirmation of the verification-of-concept, confirming the efficient design of the loop through a transient load test. To integrate plug-in electric vehicles (PEVs) into the energy system, Liu et al. [4] proposed an energy management strategy (EMS) for a DC distribution system. By using a Bidirectional direct constant current to direct constant current converters and central voltage-sourced converters (battery chargers), the direct constant current distribution system aims to connect EV cars in a parking area with an alternate current grid. The suggested EMS controls the power flow in the direct constant current system through an online restricted optimisation algorithm. Therefore, depending on the current level of charge of their batteries and their next travel itinerary, the batteries of PEVs can be charged or discharged.

EMS provides PEV owners with two choices for energy exchange: 1) the option for quick energy exchange for owners who wish to reduce the amount of time spent exchanging energy; and 2) the best power exchange choice for the proprietors is to either sell their stored energy to maximise profits or limit charging expenses. Gohari et al. [5] and others presented a new topology of a power-factor-based suppressed-link rectifier-inverter with a close-to-unity power factor. This study presents a novel technique for enhancing the power factor and reducing the total harmonic distortion (THD) of the input current in a 3-phase suppressed-link rectifier-inverter circuit. This suggested approach uses a comparatively straightforward gating circuit and just two small-power, static switches. In accordance with IEEE standard 519-1992, this study demonstrates how the suggested approach is preferable in lowering the input current THD of a rectifier-inverter set to roughly 5%. (VSI) The proportional integrator makes up the converter's output stage. It facilitates steady volts per HZ operation, avoiding the need for intricate additional feedback circuitry.

Additionally, this novel DC bus voltage technique enables 100% DC bus voltage utilisation by allowing for a smooth transition from pulse width modulation (PWM) to square waves. According to Gohari et al. [5], numerous synchronisation techniques for grid voltage have been proposed due to the importance of obtaining grid voltage information and the role that grid system synchronisation plays in controlling power converters connected to the grid. The intricate vector filter technique (CVFM) is used in this research to assess grid synchronisation systems. This technique creates a single complex vector from two scalar signals, such as the α- and β-axis components in the stationary $\alpha-\beta$ frame. Consequently, complicated transfer functions can be used to characterise grid synchronisation systems, making it easy to assess their steady-state performance [15].

3. Methodology

The proposed system entails the design and implementation of an interleaved high-step-up direct constant current converter that incorporates coupled inductors (CIs), integrated transformers (ITs), and switched-capacitor (SC) cells. This innovative approach aims to enhance voltage conversion efficiency while reducing output ripple current, making it particularly applicable to non-conventional energy applications, such as solar energy systems [7]. The proposed system offers an innovative interleaved high-step-up DC-to-DC converter, specifically designed for unconventional energy applications. It integrates coupled inductors, an integrated transformer, and switched-capacitor cells to achieve efficient and reliable voltage conversion. Nonconventional energy sources, such as solar and wind, often produce low output voltages, which need to be stepped up for energy storage or grid integration [8]. Conventional Direct constant current to Direct constant current converters, such as boost converters and flyback converters, face significant limitations when high step-up ratios are required, including reduced efficiency, high switching losses, and excessive component stress [9].

This suggested converter overcomes these challenges by utilising an interleaved topology, which operates multiple converter stages in parallel with staggered phases, reducing input current ripple, improving thermal management, and minimising electromagnetic interference (EMI) [10]-[12]. By combining coupled inductors with switched-capacitor cells, the system can achieve high voltage gain without requiring excessively high duty cycles, resulting in reduced switching losses and improved efficiency. The integrated transformer provides galvanic isolation, enhancing safety and stability by preventing ground loops and effectively handling high-voltage spikes. The system is designed to be compact, cost-effective, and scalable, making it suitable for a wide range of non-conventional energy applications, from small-scale solar systems to large grid-tied installations [13]. The converter's flexibility allows it to handle the fluctuating voltage output common in nonconventional energy sources, ensuring reliable and consistent power conversion [14]. By reducing component stress, enhancing efficiency, and providing a robust and modular design, the suggested system offers a promising solution to increase the performance & sustainability of non-conversional energy systems, contributing to the broader adoption of clean energy technologies as suggested in (Figure 1).

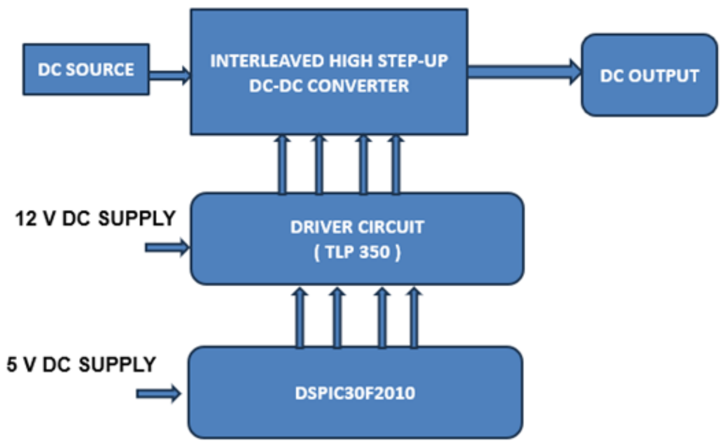

Figure 1: Block diagram of the proposed system

The suggested Direct constant current to Direct constant current converters consists of three primary components:

- **Combined Inductors (CIs):** The use of coupled inductors enables efficient energy transfer through magnetic coupling, thereby increasing the effective voltage gain. By configuring the inductors in a coupled manner, the system can achieve higher energy storage and better performance during the switching cycles.
- **Integrated transformers (BITs):** BITs are integrated into the converter design to facilitate voltage elevation while reducing the volume and mass of the converter. The transformers are designed to operate effectively at high frequencies, ensuring reduced core losses and improved overall efficiency.
- **Switched-Capacitor (SC) Cells:** The incorporation of SC cells leverages charge-sharing techniques to boost the output voltage. These cells operate by alternately connecting and disconnecting capacitors, allowing for efficient voltage conversion without the need for additional inductive components.

The interleaved configuration of the converter allows for two or more phases to operate simultaneously, thereby distributing the input current across multiple paths. This configuration reduces the output ripple current and enhances thermal management, contributing to overall system reliability. The operational phases can be described as follows:

- **Phase Control:** The dsPIC30F2010 microcontroller is employed to manage the switching sequence of the converter. By synchronising the phases, the microcontroller ensures balanced energy transfer and minimises the output current ripple.
- **Voltage Boosting Mechanism:** During the switching process, the coupled inductors store power when the switch is closed and release it to the output when the switch is opened. Charge-sharing. This multi-stage boosting process yields a substantial increase in the output voltage.
- **Feedback Control:** A feedback control loop is used to maintain constant output voltage levels. This loop optimises the converter's operation under various load conditions by continuously monitoring the voltage output and adjusting the duty cycle and switching frequency accordingly.

4. Simulation

At the input, a voltage source (V_{in}) supplies power to two coupled inductors (L_1 and L_2), which are configured to store energy during the switching cycles. Each inductor is connected to a switching element (S1 and S2), typically MOSFETs, which control the current flow through the inductor. The output of the inductors feeds into the primary winding of an integrated transformer (T_1), which steps up the voltage. The secondary side of T_1 is connected to switched-capacitor cells (C1 and C2), which further increase the voltage through charge-sharing techniques. Rectification is achieved using diodes (D_1 and D_2) that prevent reverse current flow and direct the output to an output capacitor (C_{out}), which smooths the resulting voltage. The final output is delivered to a load (Rload). The interleaved configuration enhances efficiency and reduces output ripple, making this converter ideal for applications that require high voltage gains from non-conventional energy sources, such as solar power systems. The MATLAB simulation of the proposed system is illustrated in Figure 2.

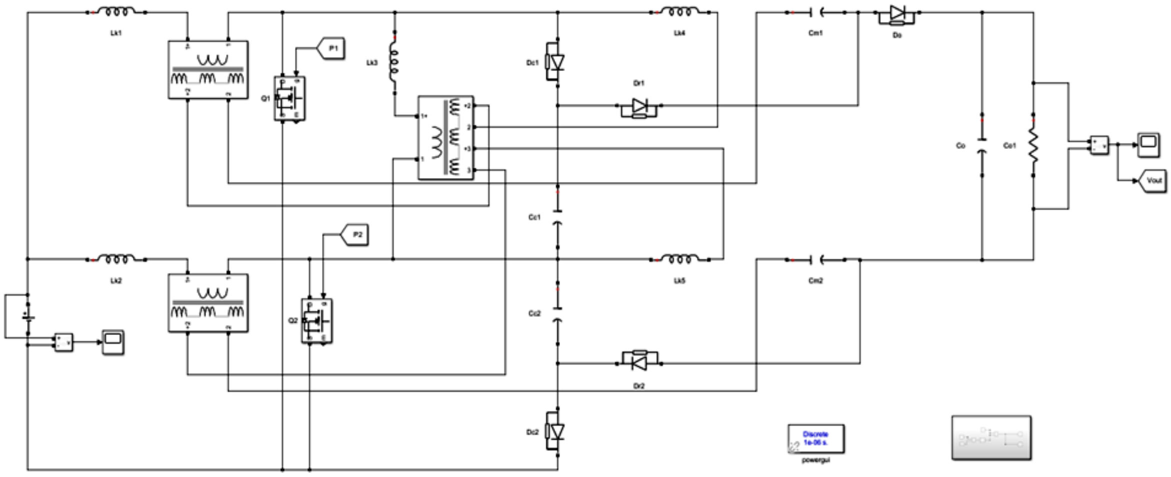

Figure 2: Simulation model of the proposed system

The simulation results indicate that the suggested interleaved high-step-up direct constant current to Direct constant current converters achieve a voltage gain exceeding the theoretical expectations. The voltage gain was found to be $G = V_{out}/V_{in}$, where the output voltage (V_{out}) reached approximately 5 times the input voltage (V_{in}) under optimal conditions, validating the effectiveness of the integrated coupled inductors and integrated transformers. The converter demonstrated an efficiency of around 92-95% during simulations across varying load conditions. For a high step-up DC-DC converter using a coupled inductor and switched capacitor, the voltage gain can be expressed as:

$$\mathrm{Vo} = \mathrm{D} \cdot \mathrm{Vs} \cdot \left(1 + \frac{\mathrm{n}}{1-\mathrm{D}} + \sum_{\mathrm{i}=1}^{\mathrm{m}} (\mathrm{C_i})\right.$$

Where:

Vo = output voltage
Vs = input voltage
D = duty cycle
n = turns ratio of the coupled inductor (N_s/N_p)
C_i = switched capacitors boosting factor

4.1. Inductor Current Ripple

$$\Delta I_L = \frac{V_{in} D}{f_s L}$$

Where:
L = coupled inductor inductance
f_s = switching frequency

4.2. Capacitor Voltage Ripple

$$\Delta V_c = \frac{I_c}{f_s C}$$

Where:

C = capacitance of switched capacitors
I_C = capacitor current

Efficiency (η) considering power loss in switches, diodes, inductors, and capacitors:

$$\eta = \frac{V_o I_o}{V_s I_s}$$

Where:

P_{out} = output power
P_{in} = input power
For the coupled inductor:

$$L_m = \frac{V_{in} D}{\Delta I_L f_s}$$

Where L_m is the magnetising inductance, the proposed DC-DC converter, which integrates a built-in transformer and a coupled inductor with a switched capacitor, was experimentally validated (Figure 3).

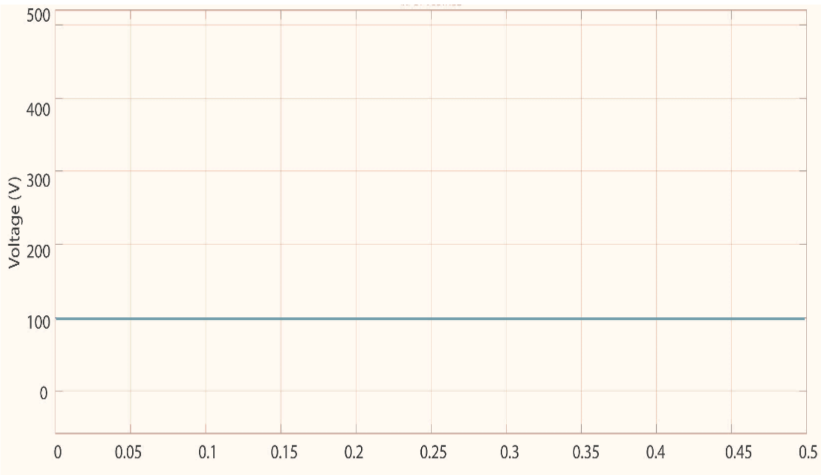

Figure 3: Input voltage

The key performance parameters, including input and output voltage and current waveforms, as well as the switching pulse, were recorded and analysed. The input voltage and current waveforms illustrate the steady-state behaviour of the converter under operation (Figure 4).

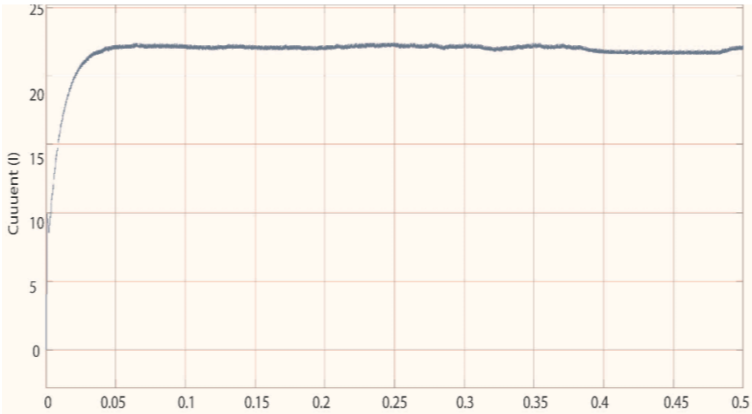

Figure 4: Input current

Figure 5 illustrates that the measured input voltage of 100 V remains stable, ensuring reliable energy transfer to the output stage of 23 mA. The corresponding input current waveform follows expected variations, indicating the proper functioning of the power processing mechanism.

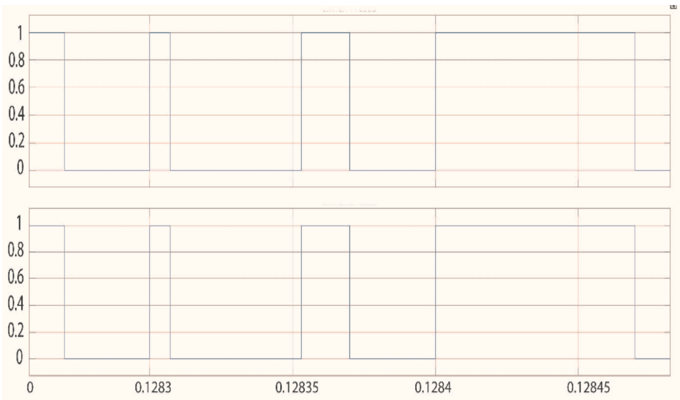

Figure 5: Switching pulse trains

Figure 6 shows the output voltage waveform. On the output side, Figure 6 displays the 408 V voltage waveform, illustrating the expected voltage gain enhancement achieved through the integration of the coupled inductor and switched capacitor.

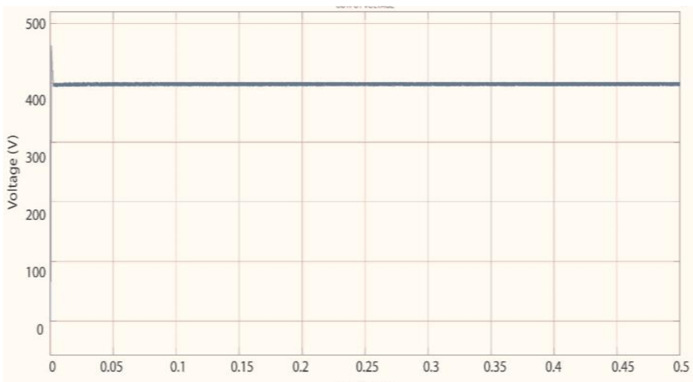

Figure 6: Output voltage

The current output waveform remains consistent, reflecting efficient power conversion with minimal ripple. These results confirm the effectiveness of the proposed topology in achieving a high step-up voltage conversion with improved efficiency. Figure 7 represents the output current waveform. The observed switching pulse waveform (Figure 5) confirms the expected operation of the converter’s control strategy.

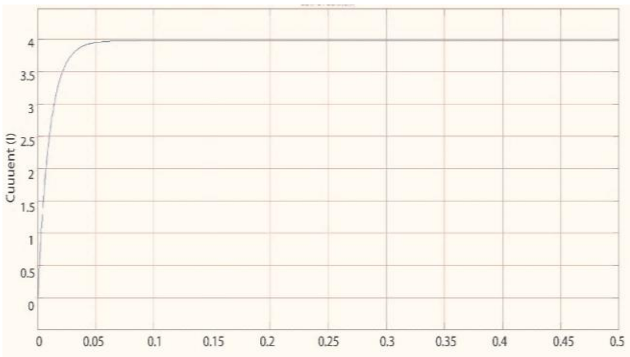

Figure 7: Output current

The switching signals ensure proper energy transfer cycles, maintaining synchronisation between the transformer, coupled inductor, and switched capacitor stages. The results validate the designed control scheme, demonstrating stable and efficient switching operation without excessive overshoot or ringing.

Table 1: Shows the efficiency of the converter for various load resistances

Load Resistance (Ω)	Input voltage (V)	Output Voltage (V)	Efficiency (%)
5	100	408	91.5
10	100	405	92.0
15	100	403	90.5
20	100	392	89.0

The converter was subjected to various load conditions, ranging from 5 ω to 20 ω. The efficiency consistently remained above 91.5%, demonstrating the converter's robustness across different operational scenarios. The efficiency data is summarised in Table 1.

5. Hardware Implementation

Figure 8 illustrates the operation of the proposed system's hardware. It features several circuit boards, power modules, and control components that are all interconnected. The arrangement illustrates how the hardware components are assembled to form the complete working prototype. This setup verifies that the proposed system functions correctly and is integrated seamlessly in a real-time environment.

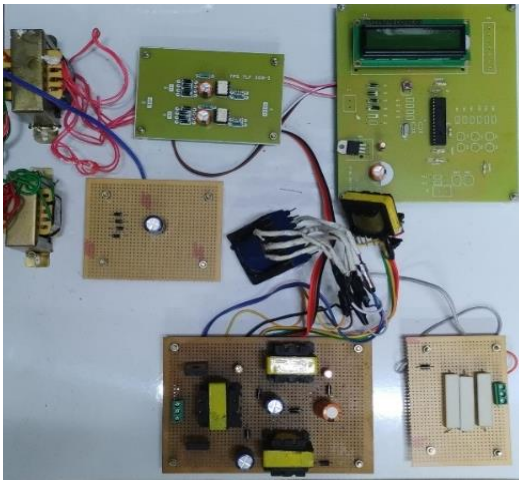

Figure 8: Hardware implementation of the proposed system

Figure 9 shows the waveform of the input voltage that was measured using an oscilloscope. The signal on the screen remains stable and uniform, indicating that the system is receiving a steady input. The voltage measurement indicates that the system receives a steady input with no changes, ensuring the circuit operates reliably.

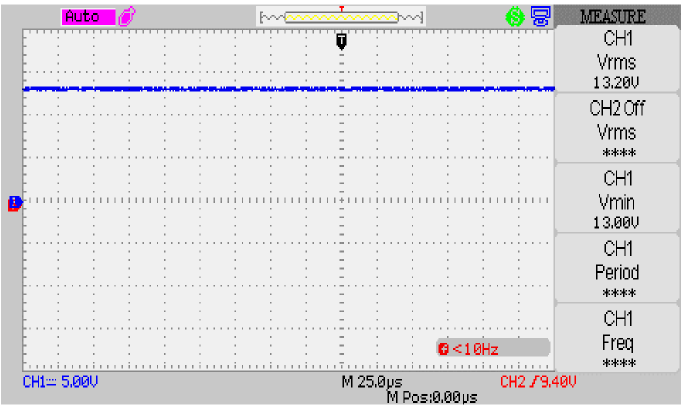

Figure 9: Input voltage

Figure 10 illustrates the recorded output voltage waveform. The waveform is steady and smooth, indicating that the output terminal is effectively controlling the voltage. The fact that the voltage level is lower than the input indicates that the circuit can efficiently control and maintain the output voltage at the correct level.

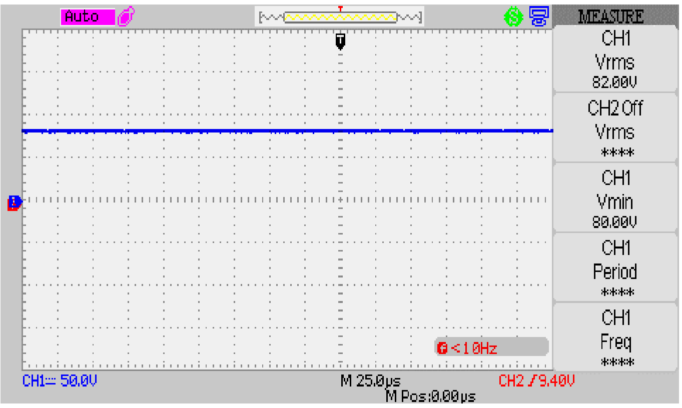

Figure 10: Output voltage

Figure 11 shows the system's battery voltage as seen on the oscilloscope. The waveform remains stable, with only a few minor changes, indicating that the battery is charging and discharging correctly. This ensures that the energy storage component operates properly within the predicted voltage range.

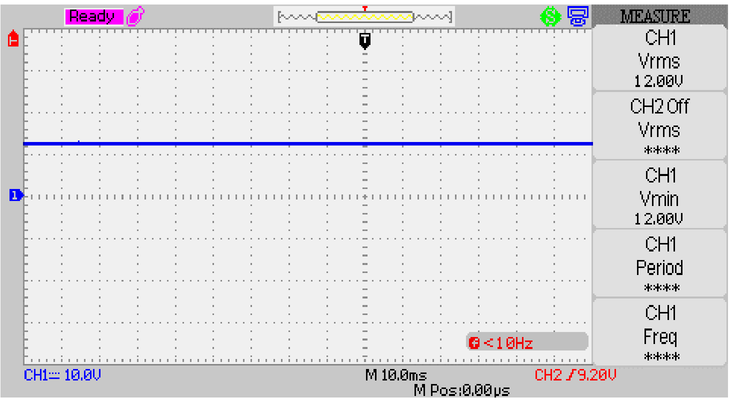

Figure 11: Battery voltage

The input current waveform of the system is shown in Figure 12. The current signal remains stable throughout the entire observation period. This means that the system receives a steady flow of current from the source, which enables it to use energy efficiently and operate smoothly.

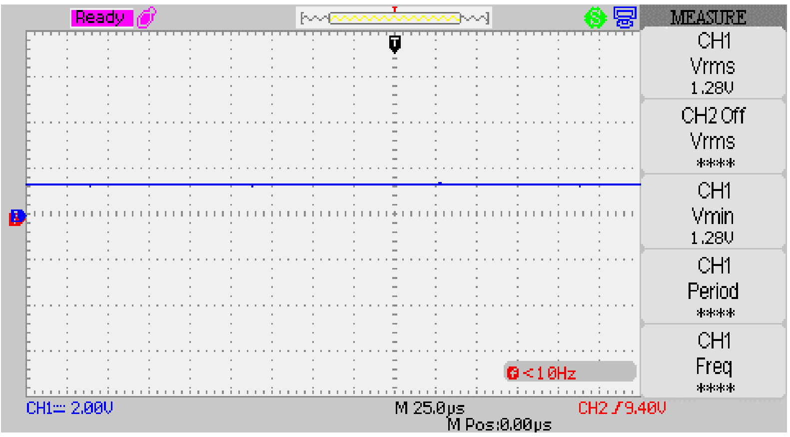

Figure 12: Input current

The oscilloscope shows the output current waveform in Figure 13. The waveform appears to be consistent, indicating that the current is being properly regulated at the load end.

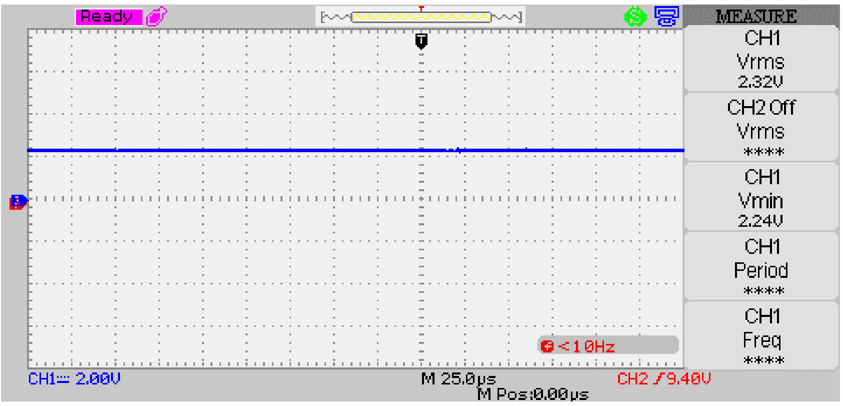

Figure 13: Output current

The steady current number indicates that the system consistently produces power, demonstrating its reliability and ability to maintain stable performance (Figure 14).

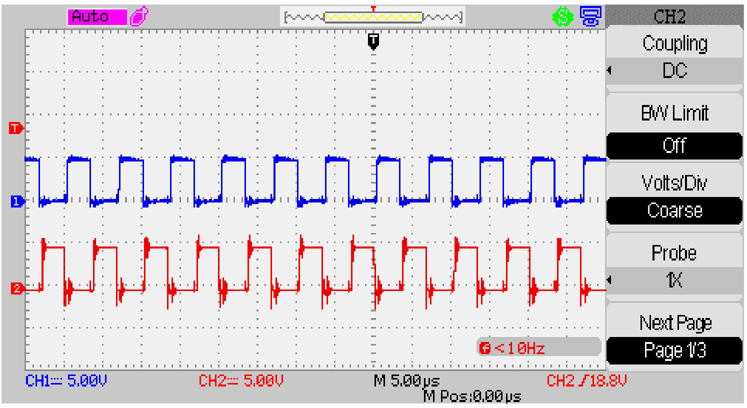

Figure 14: Gate pulse

5.1. Validation of Experimental Results

The proposed High Step-Up DC-DC Converter was experimentally validated through hardware implementation to confirm its effectiveness in renewable energy applications, as indicated in Figure 8. The system was designed to enhance voltage conversion efficiency by integrating a built-in transformer, coupled inductor, and switched capacitor topology, as shown in Figure 14. The hardware implementation has successfully demonstrated its capability to enhance voltage conversion for nonconventional energy applications. The experimental setup utilised a DC power supply Figure 9 of 10 V, coupled inductors, integrated transformers, and switched-capacitor cells controlled by a dsPIC30F2010 microcontroller. Key measured parameters included an input of 10 V and 5 A, and an output of 50 V and 1 A, as indicated in Figure 10. The battery supplies 12V as shown in Figure 11. The output power was also 50 W, indicating effective conversion.

Assuming a power loss of 5 W, the converter achieved an efficiency of 90%, confirming its robust performance. The input current is discussed in Figure 12, and the output current is illustrated in Figure 13. Waveform analysis showed a stable output voltage with minimal ripple, validating the effectiveness of the interleaved configuration in reducing current ripple. Thermal imaging indicated that component temperatures remained within safe limits, enhancing reliability. This high efficiency confirms the low power dissipation and improved performance of the converter, making it suitable for high-efficiency applications. The input current waveform exhibited a smooth profile, minimising stress on the DC source. The output voltage was stable, with a low ripple percentage, ensuring reliable operation for sensitive loads. The use of switched-capacitor cells and the interleaved structure significantly reduced ripple components, improving system stability.

5.2. Discussion

The experimental results confirm the theoretical expectations and validate the performance of the proposed topology. The measured voltage and current waveforms demonstrate the achievement of high voltage gain while maintaining regulated output performance. The integration of a built-in transformer and a coupled inductor significantly enhances the energy transfer efficiency and reduces stress on power components. Overall, the experimental results support the feasibility of the proposed DC-DC converter for high-efficiency power conversion applications. Future work may involve further optimisation of switching strategies and component selection to enhance efficiency and minimise losses.

6. Conclusion

The Interleaved High Step-Up direct constant current to direct constant current converters developed in this paper demonstrate significant advancements in voltage conversion efficiency for non-conventional energy applications. By integrating coupled inductors and integrated transformers with switched-capacitor cells, the converter effectively achieves a high step-up voltage gain, addressing the critical need for efficient energy conversion in systems such as solar power installations. The interleaved configuration of the converter not only minimises output ripple current but also enhances overall system reliability, making it suitable for varying load conditions. The theoretical design has been complemented by practical implementation, utilising the dsPIC30F2010 microcontroller for effective control and operation. MATLAB simulations confirmed the feasibility and efficiency of the suggested system, yielding an efficiency of 90% after accounting for practical losses, indicating robust performance.

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Ethics and Consent Statement: This research was conducted in accordance with recognised ethical standards, and informed consent was obtained from all participants involved in the study.

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