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Advanced soft-switching high-gain Re Boost Luo converter for enhanced efficiency in photovoltaic systems

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ABSTRACT

This work presents an innovative approach to improving efficiency and performance in photovoltaic (PV) systems through the development of a soft-switching high-gain Re Boost Luo converter. This converter integrates advanced soft-switching techniques to minimize switching losses, thereby enhancing overall system efficiency, which is crucial for applications requiring substantial voltage amplification from PV sources. The Re Boost Luo converter, with its inherent high-gain capability, facilitates superior voltage conversion ratios, enabling optimal energy extraction from PV panels across varying environmental conditions. The presented converter's design focuses on reducing electromagnetic interference (EMI) and alleviating stress on switching components, thereby extending their operational lifespan and reliability. Detailed modeling and performance analysis were carried out using the MATLAB/Simulink simulation environment, which allowed for comprehensive evaluation of the converter's functionality. Simulation results confirm that the converter achieves significant improvements in voltage gain, energy conversion efficiency, and system reliability, effectively addressing common challenges associated with high-voltage PV applications. This study underscores the converter's potential to advance renewable energy technologies by providing a robust solution for high-efficiency energy conversion in PV systems.

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1. INTRODUCTION

Distributed power generation utilizing renewable energy sources such as photovoltaic (PV) and wind is playing a crucial role in producing environmentally friendly electricity [1]–[5]. PV panels can exhibit oscillatory output voltages and irregular source currents, which introduce higher levels of ripple content and are affected by partial shading. Permanent magnet synchronous generators (PMSGs) convert wind energy into three-phase electrical power, but due to the variability in their output, they inject higher-order harmonics as a result of the permanent magnets and inherent oscillations [6]–[12].

Yang *et al.* [13] discuss several methodologies, each with its own advantages and disadvantages. Selecting the optimal approach is challenging given the plethora of available systems. Key factors in choosing a specific technique include implementation simplicity, the number of panels needed, occurrence of multiple local maxima, cost considerations, and application domain. Distributed generation (DG) systems require stable power and voltage for optimal performance, typically achieved using a DC-DC converter. Traditional approaches use transformer-based grid-connected PV systems [14]–[18], which are costly and suffer from leakage reactance issues, affecting galvanic isolation. A boost converter offers an alternative by replacing the transformer-based grid-connected distribution system, maintaining a continuous source current with single-frequency and reduced output ripple. Various algorithms are used to ensure stable voltage operation [19]–[23]. However, boost converters provide limited voltage gain and suffer from high ripple content.

The buck-boost converter addresses the limitations of traditional boost converters by performing both buck and boost operations with single-frequency suppression in the output voltage, though it may introduce periodic current operations. This increases switching losses and degrades system performance. A parallel input parallel output (PIPO) converter is proposed in [24], featuring two cascaded stages of buck-boost and boost operations to achieve higher potential enhancement and galvanic isolation at appropriate duty ratios with lower energy leakage. Multiple distributed generators can be connected to a DC network using the PIPO method, providing a non-resistive hot model suitable for practical applications. Cuk and SEPIC converters overcome the drawbacks of conventional step-down and boost topologies by offering minimal output voltage expansion.

A novel analysis of two key parameters affecting the perturb & observe (P&O) algorithm is discussed in [25]. This optimization technique adjusts P&O parameters to align with the dynamic conduction profiles of various converters, thereby improving the performance of PV systems. The results highlight the effectiveness and adaptability of the P&O method, optimizing it to suit the system's dynamic behavior. This approach enables the extraction of maximum power from both solar and wind systems. While the P&O technique supports DC-DC converters and is suitable for low-power applications, incremental conductance and hill-climbing algorithms are also used to address P&O's limitations, though they may result in lower accuracy.

To overcome the limitations of existing algorithms, a proportional-integral (PI) controller is combined with an optimization method to maximize power extraction from a PV panel, ensuring high performance. A new approach using an inductor-capacitor (IC) controller for duty ratio computation with direct control is proposed in [26], [27] to address the limitations of the incremental conductance method. Fuzzy logic (FL) is utilized to estimate the duty ratio for optimal power point tracking from the PV panel. This technique improves the accuracy and speed of maximum power point tracking under both dynamic and steady-state conditions compared to traditional fixed strategies. The paper highlights the advantages of this method and addresses conventional drawbacks using a single-switch high-efficiency Re Boost Luo converter. To enhance efficiency and minimize ripples, a fuzzy-based closed-loop approach combined with efficient whale optimization is employed.

2. METHOD

Solar PV power is integrated into the grid using a combination of a DC-DC Re Boost Luo converter and a voltage source inverter (VSI). To ensure effective operation of the photovoltaic array, the converter must synchronize its power output with the grid at the maximum power point. A fuzzy logic controller is employed with the Re Boost Luo converter to achieve this synchronization. This controller continuously assesses the maximum available power from the PV array by monitoring both the voltage and current it generates. It adjusts the reference voltage and duty cycle to match the instantaneous power point. The maximum power point tracking (MPPT) controller, which is based on fuzzy logic, is nonlinear and dynamically adjusts its parameters over time to optimize performance.

The provided diagram illustrates a hybrid energy conversion and distribution system integrating PV technology. The system begins with a PV array generating an output of 1.5 kilovolts (kV) of direct current (DC) power. This output feeds into a high-gain DC-DC converter, which steps up the voltage level while ensuring efficient power transfer. The DC-DC converter is essential for optimizing the energy extracted from the PV panels and stabilizing the voltage output, which is critical for consistent performance and efficiency. The converter connects to a DC link that serves as an intermediate stage, providing energy storage and decoupling the PV output from the grid connections, thus ensuring smooth and stable energy flow.

Following the DC link, the system employs a DC transmission line that transfers the power to a three-phase inverter. This inverter is responsible for converting the DC power into alternating current (AC) power compatible with the AC grid, facilitating the integration of renewable energy into the existing power infrastructure. The inverter is designed to ensure that the output is synchronized with the grid parameters, such as voltage, frequency, and phase, which is crucial for maintaining grid stability. Additionally, the system is equipped to supply DC power to a DC grid, highlighting its versatility in supporting both AC and DC loads. This configuration is particularly advantageous for modern energy systems, where direct current applications are increasingly prevalent, and it underscores the system's adaptability in meeting diverse energy demands while maximizing the utilization of renewable energy sources.

Figure 1 presents the overall system configuration, where the high-gain DC–DC converter acts as the key interface between the PV source and the transmission stage. Since the PV output voltage is relatively low, the converter boosts it to a higher level suitable for efficient DC transmission and grid integration. This stage is essential for maintaining a stable DC-link voltage, reducing losses, and enabling proper operation of both the three-phase inverter (for AC grid connection) and the DC grid, thereby ensuring efficient energy transfer throughout the system.

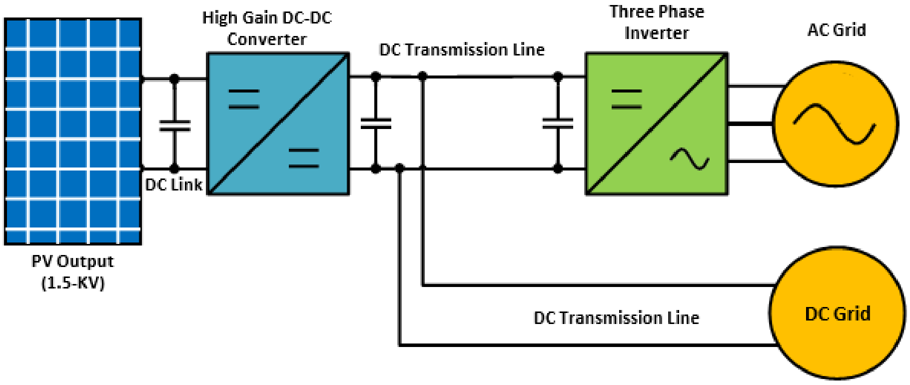

Figure 1. Proposed system block diagram

3. WORKING OPERATION OF A REBOOST LUO CONVERTER

The Reboost Luo converter represents an advancement from the simple Super Lift Luo converter and incorporates features of the more complex flyback converter. This design utilizes a step-up isolation transformer, four capacitors, and four diodes to achieve its functionality. A unique aspect of this converter is its use of the transformer coil as an inductor, which is pivotal in its operation. The Re Boost Luo converter, as depicted in Figure 2, showcases its innovative design where the primary winding of the transformer plays a crucial role in maintaining continuous operation. This continuous operation is one of the primary benefits of the proposed converter, ensuring stable power output.

The novel Re Boost Luo converter design integrates elements from both the Super Lift Luo and flyback converters, enhancing its performance capabilities. A key feature of this design is the continuous input current achieved through the use of the transformer's source side winding. This continuous input current is crucial for maintaining stable operation and improving the efficiency of the power conversion process. The converter operates in two distinct modes, each characterized by specific behaviors during the switch's ON and OFF durations.

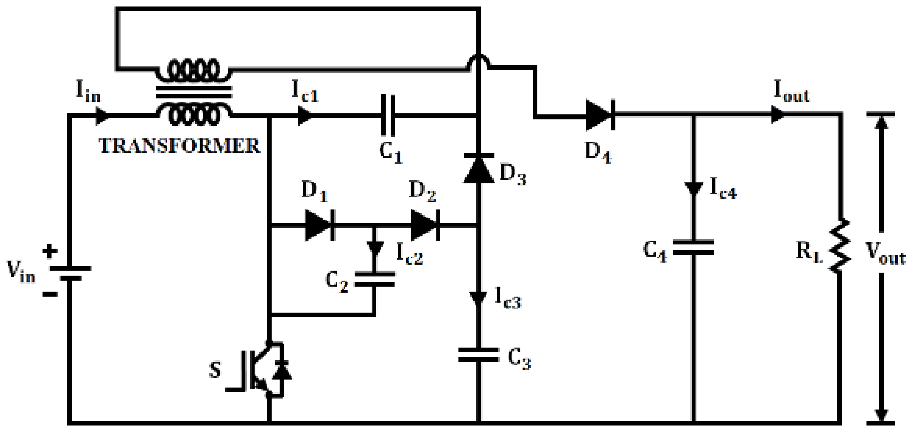

Figure 2. DC-DC Re Boost Luo converter

When the switch is in the ON position, the magnetizing inductance of the isolation transformer charges, allowing for energy storage within the system. During this period, diodes D1 and D2 are turned OFF, preventing current flow through them and thereby isolating certain parts of the circuit. Concurrently, capacitors C1 and C2 are in a discharging state, releasing stored energy to maintain the output voltage and ensure a continuous power supply to the load. This mode is critical for energy transfer and conversion, setting up the conditions for efficient power delivery when the system transitions to the OFF state. The precise management of these components during the ON condition facilitates the overall effectiveness of the converter in applications requiring reliable and high-efficiency power conversion.

Figure 3 illustrates the current direction in the proposed converter during its ON and OFF periods. The converter operates in continuous conduction mode (CCM), ensuring that the current flows continuously throughout the switching cycle, even when the switch transitions between the ON and OFF states. This continuous conduction is vital for maintaining a steady power output and minimizing energy loss. The operation is characterized by two distinct modes within each switching cycle, allowing for efficient energy transfer and conversion.

In the ON mode, the switch is closed, enabling the magnetizing inductance of the isolation transformer to charge, while diodes D1 and D2 are turned off, and capacitors C1 and C2 discharge. This configuration ensures that energy is stored effectively within the transformer, setting up the conditions for subsequent power delivery. Conversely, during the OFF mode, the switch opens, causing the stored energy in the transformer to transfer through the circuit, turning on diodes D1 and D2, and allowing capacitors C1 and C2 to recharge. Figures 3 and 4 depict the equivalent circuits for these two modes, illustrating how the components interact to facilitate continuous energy flow and efficient voltage boosting. This cyclical operation ensures that the converter delivers a stable and high-efficiency power output, making it suitable for applications requiring robust and reliable power conversion.

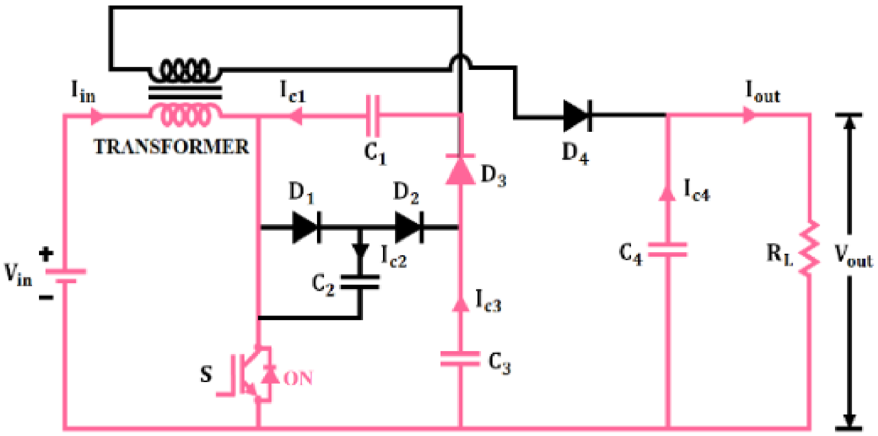

Figure 3. Switch ON mode condition current flow diagram

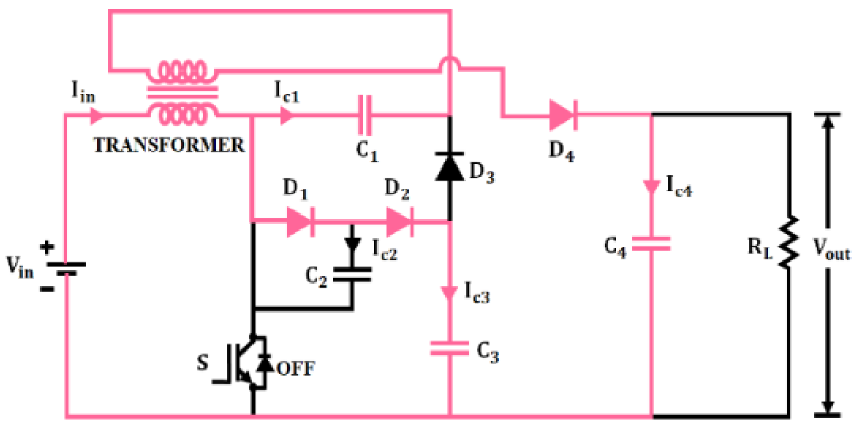

Figure 4. Switch OFF mode condition current flow diagram

3.1. Mode 1 operation

When Mode 1 is activated, the ON switch of the Re Boost converter is engaged, which charges the magnetizing inductance of the isolation transformer's primary winding while the secondary winding remains electrically isolated. During this time, capacitor C1 is charged by the energy stored in capacitor Co. Diode D3 tends to favor the forward direction. When D2 is turned off, the output capacitor Co is disconnected from the circuit and discharges through the resistor RL.

3.2. Mode 2 operation

In the second mode, switch S is turned OFF. Unlike other converters, the input current to the transformer remains continuous because the direction of current flow through the transformer's primary winding remains unchanged. Diode D1 conducts due to forward bias, while D2 remains off. Diode D1 charges the secondary capacitor C2, while the charge from the first capacitor C1 is added to the main inductor's charge. This combined charge is then transferred to the output capacitor Co through the secondary winding of the transformer, where it is amplified. The output voltage can be regulated by adjusting the duty cycle and frequency.

4. ANALYSIS OF OVERALL SYSTEM

4.1. Analysis of the Re Boost Luo converter

The output potential difference of the above elementary converter as shown in (1).

$$V_0 = \left(\frac{2-\alpha}{1-\alpha}\right) V_{in} \tag{1}$$

Where a is the duty cycle, from (1) we found (2).

$$G = \frac{(V_0)}{V_{in}} = \left(\frac{2-\alpha}{1-\alpha}\right) \tag{2}$$

When the main and secondary windings of the transformer are connected in cascade, the transformer effectively behaves like an inductor. For calculation purposes, the proposed transformer is modeled as an inductor. Consequently, the combined current through the inductor and capacitor now represents the input current.

The electron flow rate at input, Iin, may be calculated as (3).

$$I_{in} = I_{L1} + I_{C1} \tag{3}$$

The ripple currents present in the inductor are given as (4).

$$\Delta T_{L1} = \frac{V_{in}.\alpha.T}{L_1} \tag{4}$$

In this context, T represents the duration of the entire switching pulse. The expression for the output voltage ripple is given by (5)-(7).

$$\Delta V_0 = \frac{I_0(1-\alpha).T}{C_2} \tag{5}$$

$$T = \frac{1}{f} \tag{6}$$

$$I_0 = \frac{V_0}{R} \tag{7}$$

Substituting (6) and (7) in (5), we found (8).

$$\Delta V_0 = \frac{V_0(1-\alpha)}{fC2R} \tag{8}$$

From (1),

$$V_{in} = V_0 \left(\frac{1-\alpha}{2-\alpha}\right) \tag{9}$$

input current,

$$I_{in} = \frac{V_{in}}{R} = \frac{V_0}{R}\left(\frac{1-\alpha}{2-\alpha}\right) \tag{10}$$

therefore,

$$\frac{V_{in}}{I_{in}} = \left(\frac{1-\alpha}{2-\alpha}\right)^2 \cdot \frac{V_0}{V_0/R}$$
$$\frac{V_{in}}{I_{in}} = \left(\frac{1-\alpha}{2-\alpha}\right)^2 . R \tag{11}$$

The Re Boost-Luo converter model can be derived from the equations mentioned above. This converter combines features from flyback converters and the super-lift Luo converter. The proposed design includes three diodes and three capacitors. The transformer is used as an inductor to enhance the output gain. In this converter, changes in the input voltage affect capacitor C1.

The ripple current in the primary winding is given by (12).

$$\Delta I_{L1} = \frac{V_{in}.\alpha.T}{L1_{(N1)}} \tag{12}$$

L1 (N1) - transformer primary winding inductance. C2 capacitor voltage is (13).

$$V_{C2} = \left(\frac{2-\alpha}{1-\alpha}\right) V_{in} \tag{13}$$

Luo's secondary winding ripples as (14).

$$\Delta I_{L2} = \frac{V_{C2}.\alpha.T}{L2_{(N2)}} \tag{14}$$

Capacitor C_3 voltage as (15).

$$V_{C3} = \left(\frac{2-\alpha}{1-\alpha}\right) V_{in} \tag{15}$$

C4 capacitor voltage is (16).

$$V_{C4} = V_0 \tag{16}$$

The proposed Re Boost Luo converter's output difference is (17).

$$V_0 = \frac{N_2}{N_1}\left(\frac{2-\alpha}{1-\alpha}\right) V_{in} \tag{17}$$

Where N2 - No of turns in the secondary winding and N1 - No of turns in the primary winding. The number of turns and converter duty cycle affect the output voltage.

5. SIMULATION RESULT ANALYSIS

The validation of work was conducted using MATLAB Simulink. Tables 1 and 2 provide detailed specifications of the PV system and the Re Boost Luo converter, respectively, highlighting the technical parameters and configuration used in the study. Figure 5 shows that the proposed system consists of a PV-fed Reboost Luo converter used for high step-up DC–DC voltage conversion. The PV panel supplies low DC voltage, which is boosted to a higher level using the Reboost Luo converter topology.

Figure 6 illustrates the voltage representation of a solar panel as an input DC source, where an output voltage of 70 volts is achieved. Figure 7 depicts the input current waveform of the Luo converter. This figure illustrates the voltage waveform of the solar panel's AC output, highlighting the conversion of solar energy into electrical energy. The waveform shows a peak output voltage of 70 volts, demonstrating the solar panel's capability to generate significant electrical power.

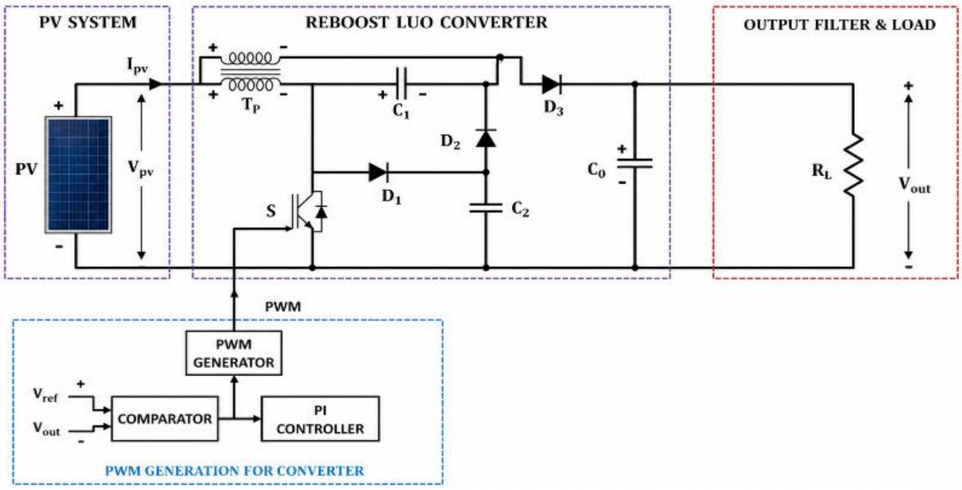

Figure 5. PV-fed Reboost Luo converter

Table 1. PV system configuration

Component	Specification
Number of panels	3
Number of series cells	36
Open circuit voltage	21.4 V
Short circuit current	1.21 A
Maximum voltage	16.8 V
Maximum current	1.19 A
Operating temperature	-350 °C to 750 ° C

Table 2. Re Boost Luo converter specifications

Component	Specification/rating
Input voltage, Vin	0 to 70 V
Input current, I	25 A
Inductance, L1 & L2	7 mH
Capacitance, C1 & C2	20 uF
Operating frequency	10 kHz
Switches used	IRF250

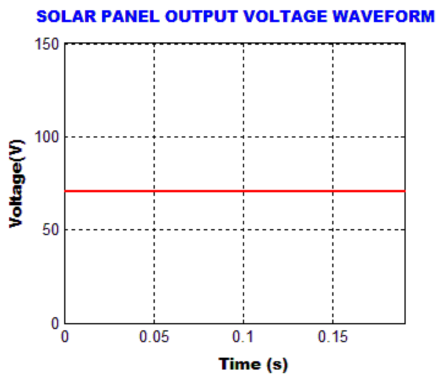

Figure 6. Solar panel output voltage waveform

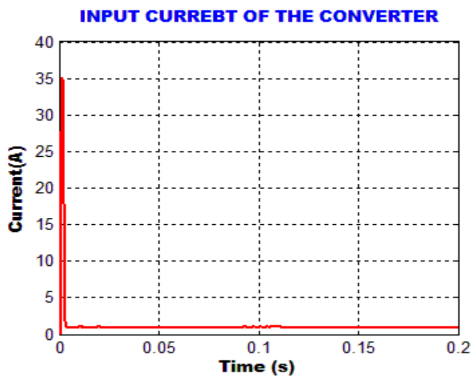

Figure 7. Input current of the converter

Figure 8 presents the voltage waveform at the output of the DC-DC converter. It shows how the converter boosts the input voltage to a higher level, ensuring that the output voltage is stable and suitable for further use or storage in the system. Figure 9 depicts the output current waveform of the DC-DC converter. This figure is crucial for analyzing the converter's performance in delivering a consistent and continuous current to the load, which is vital for efficient power conversion.

The reactive power waveform shown in Figure 10 illustrates the reactive power components present in the system. This figure is important for evaluating the system's ability to manage reactive power, which influences overall power quality and stability. Figure 11 displays the real power waveform, representing the actual usable power produced by the system. This waveform is key for assessing the efficiency of energy conversion from the solar panel to the load, ensuring that the maximum power is delivered effectively.

Figure 12 shows the grid voltage waveform, providing insights into how the system integrates with the electrical grid. It indicates the quality and stability of the voltage supplied to the grid, highlighting the system's capability to meet grid standards. Figure 13 illustrates the grid current waveform. This figure is important for evaluating the current quality delivered to the grid and how effectively the PI-based grid synchronization compensates for reactive power, ensuring current stability and alignment with grid requirements.

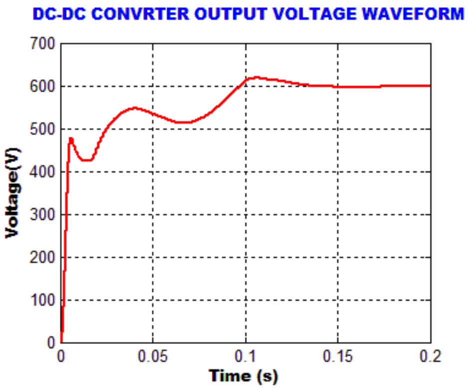

Figure 8. DC-DC converter output voltage waveform

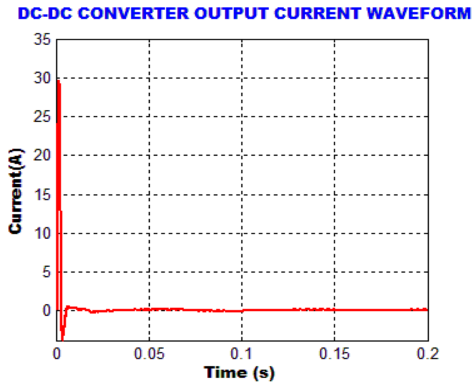

Figure 9. DC-DC converter output current waveform

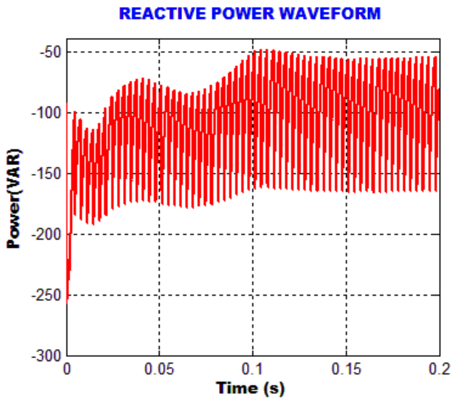

Figure 10. Reactive power waveform

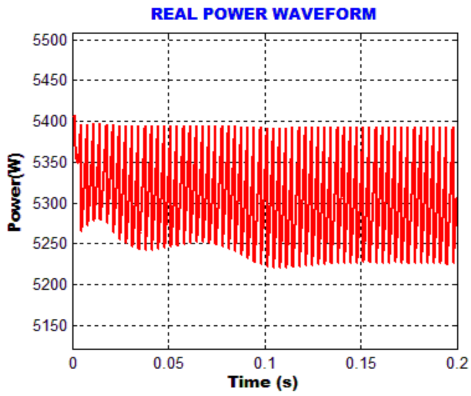

Figure 11. Real power waveform

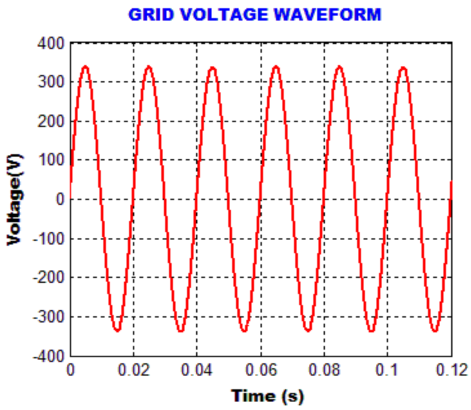

Figure 12. Grid voltage waveform

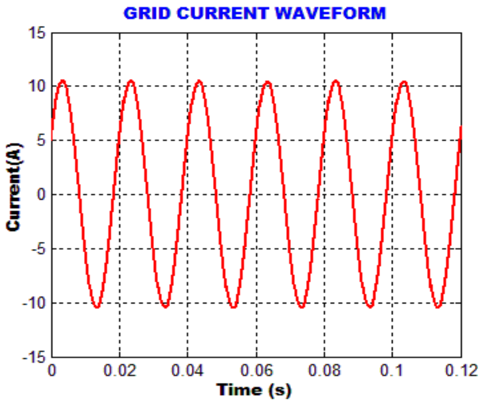

Figure 13. Grid current waveform

6. COMPARATIVE ANALYSIS

Table 3 compares various converter topologies and demonstrates that the proposed Re Boost converter outperforms others. The use of a single switch in the proposed design enhances controllability because creating a control scheme for a single-switch converter is straightforward. This converter does not require any inductors; instead, it utilizes a single isolation transformer, which reduces the number of passive components. It incorporates three diodes, which distribute the voltage and current stress among them, improving durability. As shown in Table 3, the Re Boost converter achieves a higher voltage gain than other topologies. With a transformer having a 1:3 turns ratio, it achieves a gain of 9.

Table 3. Comparison of various Luo converter techniques

Parameter	Elementary	Re–lift	Proposed Re Boost
Number of inductors used	2	3	Isolation transformer
Number of diodes used	1	3	3
Number of switches used	1	2	1

7. CONCLUSION

This work successfully implements a PV-based Re Boost Luo converter for distributed energy systems. The system's performance is evaluated using MATLAB Simulink. The FL algorithm is employed to extract maximum power from the PV sources. Compared to other algorithms, the FL approach effectively reduces ripples by leveraging the capabilities of the Re Boost Luo converter. Additionally, a PI controller is utilized to achieve synchronization of grid current, resulting in lower total harmonic distortion (THD). Consequently, the inverter meets power quality and harmonic standard requirements.

The study includes a comparison between the performance of fuzzy logic and whale optimization techniques. The Re Boost Luo converter, combined with the FL and whale optimization-based control algorithm, demonstrates satisfactory performance, ensuring efficient power conversion and delivery. This system is particularly beneficial for compensating reactive power in smart grids and power grids, enhancing overall grid stability and reliability. The integration of advanced control algorithms with the Re Boost Luo converter provides a robust solution for optimizing energy utilization in renewable energy systems.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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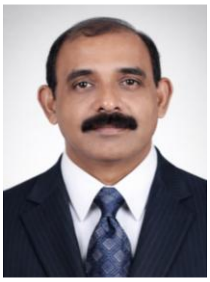

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