IJIREEICE

ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 8.414 ⚟ Peer-reviewed & Refereed journal ⚟ Vol. 14, Issue 5, May 2026

DOI: 10.17148/IJIREEICE.2026.14511

Two-Phase Interleaved Boost Converter with MPPT Control for Solar PV System

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Abstract: This paper presents the development of a solar photovoltaic energy conversion system using a two-phase interleaved boost converter integrated with a maximum power point tracking control strategy. Due to environmental variations, the output of a solar panel is non-linear and fluctuating, which reduces system efficiency if not properly controlled. To address this issue, a perturb and observe-based MPPT algorithm is implemented using a microcontroller to dynamically adjust the duty cycle of the converter. The proposed converter employs two parallel boost stages operating with a 180-degree phase shift, which significantly reduces input current ripple and output voltage fluctuations. The system continuously monitors voltages using sensing circuits and provides real-time feedback. The boosted output is stored in a battery and used to drive a DC load. Experimental prototype level results indicate improved performance in terms of voltage stability, ripple reduction, and power extraction efficiency.

Keywords: Solar PV, MPPT, Interleaved Boost Converter, PWM, Ripple Reduction, Arduino, Power Electronics, Perturb and Observe (P&O), Voltage Boosting, Battery Charging, Phase Shift Control.

I. INTRODUCTION

Renewable energy sources have gained significant importance in recent years due to the depletion of fossil fuels and growing environmental concerns. Among these, solar photovoltaic (PV) systems are widely adopted because of their clean, sustainable, and abundant nature [1], [2]. However, the performance of PV systems is inherently affected by environmental conditions such as solar irradiance and temperature, leading to continuous variations in output voltage and current. This results in inefficient power extraction if the operating point is not properly controlled [3], [4].

To ensure maximum energy utilization, Maximum Power Point Tracking (MPPT) techniques are employed [5], [6]. These techniques enable the PV system to operate at its maximum power point by dynamically adjusting the duty cycle of the power converter. Among various MPPT methods, the Perturb and Observe (P&O) algorithm is commonly used due to its simplicity, ease of implementation, and suitability for real-time embedded applications.

In addition to control strategies, the choice of power converter plays a crucial role in improving system performance. Conventional boost converters are widely used to step up the PV output voltage [1]; however, they suffer from limitations such as high input current ripple, increased switching stress, and reduced efficiency, especially under dynamic operating conditions [7]. These drawbacks negatively impact the overall stability and reliability of the system.

To overcome these challenges, interleaved boost converter topologies have been introduced. An interleaved boost converter consists of multiple parallel converter phases operating with a phase shift, typically 180° in a two-phase configuration [8], [9]. This structure enables current sharing between phases, leading to significant reduction in input current ripple and output voltage ripple. Additionally, it distributes thermal stress across components and improves overall efficiency. The ripple frequency is effectively increased while its amplitude is reduced, resulting in smoother operation compared to conventional converters.

Recent developments in PV systems emphasize the integration of efficient MPPT algorithms with advanced converter topologies to enhance energy extraction and system stability [3], [10]. While many studies have demonstrated effective MPPT techniques, the use of conventional single-phase converters limits performance due to higher ripple and switching losses [11]. Therefore, combining MPPT control with an interleaved converter structure provides a more efficient and reliable solution for modern PV applications.

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In this work, a solar PV system integrated with a two-phase interleaved boost converter and MPPT control is presented [14], [15]. The proposed system aims to improve power extraction efficiency, reduce ripple content, and ensure stable operation under varying environmental conditions. The implementation is based on a microcontroller-driven control strategy, making it suitable for low-cost and practical renewable energy applications.

II. PROPOSED SYSTEM

A. System Architecture

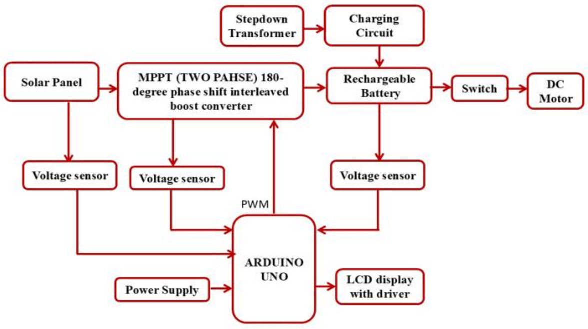

Fig. 1: Block diagram of proposed Two-Phase IBC with MPPT Control for Solar PV System

The overall architecture of the proposed system is illustrated in Fig.1. The proposed system is designed to efficiently extract, process, and utilize energy from a solar photovoltaic (PV) source using an integrated control and power conversion approach. It consists of several interconnected functional blocks that together ensure stable operation and improved energy utilization. The system begins with a solar panel, which converts solar irradiation into DC electrical energy [1]. However, due to variations in sunlight intensity and temperature, the output of the solar panel is not constant. To address this issue, the generated voltage is continuously monitored using voltage sensors, which provide real-time feedback to the controller.

The sensed signals are processed by the Arduino UNO, which acts as the central control unit of the system. It implements the MPPT (Maximum Power Point Tracking) algorithm to ensure that the solar panel operates at its maximum power point under varying environmental conditions [3], [4]. Based on this algorithm, the Arduino generates appropriate PWM (Pulse Width Modulation) signals.

These PWM signals are applied to the two-phase interleaved boost converter, which is the core power conversion stage [8], [16]. The converter boosts the input voltage to a higher level while reducing ripple through interleaving operation. The 180° phase-shifted switching of the two converter phases ensures continuous energy transfer, improved efficiency, and reduced stress on components [9].

The boosted output is then directed to a rechargeable battery, which acts as an energy storage element. This allows the system to supply power even when solar input is unavailable or fluctuating. Additional voltage sensing at the output side helps maintain proper charging conditions and prevents overcharging.

Finally, the stored energy is supplied to a DC motor load through a controlled switching mechanism. The overall system operation, including voltage levels and status parameters, is displayed using an LCD module, providing real-time monitoring to the user. Thus, the integration of MPPT control [12,13] with a two-phase interleaved boost converter ensures efficient power extraction, stable voltage regulation, reduced ripple, and reliable energy utilization in the proposed solar PV system.

B. Interleaved Boost Converter (IBC):

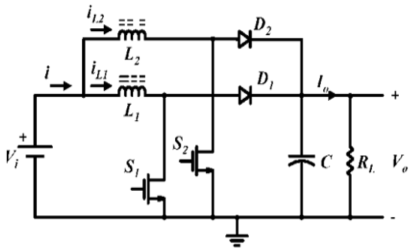

Fig. 2: Circuit Diagram of IBC

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Impact Factor 8.414 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 14, Issue 5, May 2026
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The proposed converter is a two-phase interleaved boost converter, which is an advanced form of the conventional boost converter designed to improve performance by operating two identical converter stages in parallel with a phase shift [8], [9]. The solar panel acts as the primary input source. This input is directly fed into the interleaved boost converter circuit, as shown in the circuit diagram.
The circuit configuration of the interleaved boost converter is shown in Fig. 2, which the circuit consists of two inductors (L_1 and L_2), two power switches (S_1 and S_2, typically MOSFETs), two diodes (D_1 and D_2), and an output capacitor (C). Both phases are connected to the same input source and share a common output, but they operate in an interleaved manner with a 180° phase shift between their switching signals.

(i) Operating Principle:

The working of the converter can be understood by analyzing two main modes of operation:

Mode 1 (S_1 ON, S_2 OFF): When switch **S_1** is turned ON, inductor L_1 is directly connected to the input source and starts storing energy in the form of magnetic flux. During this interval, switch S_2 remains OFF, and the energy previously stored in inductor L_2 is transferred to the output through diode D_2. Thus, one phase is in energy storage mode while the other is in energy transfer mode.

Mode 2 (S_2 ON, S_1 OFF): In the next interval, switch S_2 is turned ON and L_2 begins to store energy. Simultaneously, switch S_1 is turned OFF, and the stored energy in L_1 is delivered to the output through diode D_1. This alternating operation continues cyclically, ensuring that at any instant, at least one inductor is supplying energy to the load.

(ii) Interleaving Effect (180° Phase Shift):

Interleaving refers to the technique of operating multiple converter phases in parallel with a specific phase difference between their switching signals. In this case, the two phases operate exactly out of phase, meaning when one switch is in the ON state, the other is in the OFF state for half of the cycle.

In the proposed system, the switching operation of the interleaved boost converter is controlled using Pulse Width Modulation (PWM) signals generated by the microcontroller. Two separate PWM signals are produced:

- PWM1 is applied to switch S_1
- PWM2 is applied to switch S_2

Both signals have the same switching frequency and duty cycle; however, they are intentionally shifted in time by 180 degrees. This phase shift is the key factor that enables interleaved operation. Thus, the converter boosts the low solar voltage and this boosted voltage is stored in the battery, supplied to the DC motor (load).

(iii) Voltage Gain Equation:

For an ideal boost converter operating in continuous conduction mode (CCM), the voltage gain is given by:

$$V_o = \frac{V_{in}}{1-D} \quad (1)$$

Where:

V_o= Output voltage
V_{in}= Input voltage
D= Duty cycle of the switch

In the interleaved configuration, the voltage gain remains the same as a conventional boost converter, but the ripple and current stress are reduced due to phase-shifted operation [11].
(iv) Inductor:
The inductors L_1 and L_2 are designed to ensure continuous current operation with controlled ripple. The inductance value can be calculated using:

$$L = \frac{V_{in} \cdot D}{f_s \cdot \Delta I_L} \quad (2)$$

Where:
f_s= Switching frequency
ΔI_L= Inductor ripple current (typically 20–30% of average current)
(v) Output Capacitor:
The output capacitor is used to reduce voltage ripple and maintain a stable DC output. Its value is selected based on allowable ripple voltage using:

DOI: 10.17148/IJIREEICE.2026.14511

$$C = \frac{I_O \cdot D}{f_S \cdot \Delta V_O} \tag{3}$$

Where:

I_o = Output current

ΔV_o = Output voltage ripple

III. MPPT TECHNIQUE

a) Introduction:

In a solar photovoltaic (PV) system, the output power is not constant and varies continuously [3], [6], with environmental conditions such as solar irradiation, temperature, and load changes. For every operating condition, there exists a unique point on the V–I curve of the solar panel where the product of voltage and current is maximum. This point is known as the Maximum Power Point (MPP) [2].

To ensure that the solar panel always operates at or near this optimal point, a control technique called Maximum Power Point Tracking (MPPT) is used. MPPT improves the overall efficiency of the system by extracting the maximum possible power from the PV panel under varying conditions.

b) Perturb and Observe (P&O) Algorithm:

Among various MPPT techniques, the Perturb and Observe (P&O) method is widely used due to its simplicity [4], [5], ease of implementation, and suitability for microcontroller-based systems like Arduino.
The fundamental idea of the P&O algorithm is to slightly perturb (disturb) the operating point of the system and observe the resulting change in output power [5]. The flowchart of the Perturb and Observe (P&O) MPPT algorithm is depicted in Fig. 3. Based on this observation, the algorithm decides the direction in which the operating point should be adjusted.

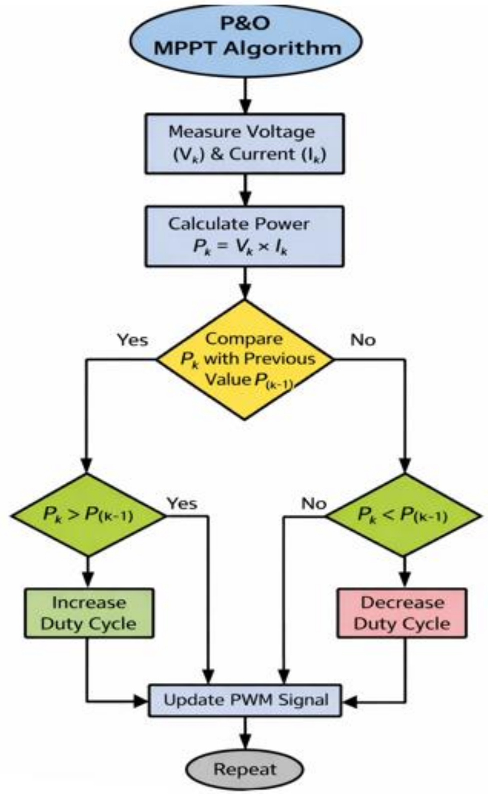

Fig. 3: Flow Chart of P&O Algorithm

DOI: 10.17148/IJIREEICE.2026.14511

c) Working Principle:
The operation of the P&O algorithm follows a continuous loop consisting of the following steps:
1)Measurement of Parameters: The system measures the instantaneous solar panel voltage (V_k) and current (I_k) using sensors.
2) Power Calculation: The output power at the current instant is calculated as: $P_k = V_k \times I_k$
3) Comparison with Previous Value: The calculated power P_k is compared with the previously measured power P_{k-1}
4) Decision Making (Control Logic):

- If $P_k > P_{k-1}$, it indicates that the operating point is moving towards the maximum power point. Therefore, the system continues to change the duty cycle in the same direction.
- If $P_k < P_{k-1}$, it means the operating point has moved away from the maximum power point. Hence, the direction of perturbation is reversed.

5) Duty Cycle Adjustment: Based on the decision, the duty cycle of the PWM signal is either increased or decreased. This directly controls the switching of the boost converter.
6) PWM Signal Update: The updated duty cycle is applied to the converter switches through PWM signals generated by the controller.
7) Continuous Operation: This process repeats continuously, ensuring that the system dynamically tracks the maximum power point under changing conditions.
The term "change in direction" in the P&O algorithm does not refer to physically moving the solar panel. Instead, it refers to adjusting the electrical operating point of the converter by modifying the duty cycle of the switching signals. This effectively changes the input impedance seen by the solar panel, allowing it to operate at maximum power.
Advantages of P&O Algorithm:

- Simple and easy to implement using microcontrollers.
- Requires fewer sensors and computational resources.
- Provides acceptable tracking performance under steady conditions.

IV. SYSTEM COMPONENTS

Table 1: System Components and their Functions

Component	Function
Solar Panel (12V, 10W)	Converts solar energy into DC electrical power; output varies with irradiation and temperature.
Arduino UNO	Implements MPPT (P&O) algorithm; processes voltage data and generates two 180° phase-shifted PWM signals.
Interleaved Boost Converter (Power Stage)	Consists of MOSFETs (S_1, S_2), inductors, diodes, and capacitor; performs voltage boosting with reduced ripple and improved efficiency through interleaved operation.
Voltage Sensor (Resistor Divider)	Measures input and output voltages and scales them to safe levels for Arduino ADC.
Battery (12V)	Stores energy and provides backup power for continuous operation.
LCD Display (16×2)	Displays real-time system parameters such as voltages and operating status.
DC Motor (Load)	Acts as a practical load to demonstrate power utilization.
Auxiliary Supply (Transformer & Charging Circuit)	Provides regulated supply and supports battery charging when solar input is insufficient.

Table 1 summarizes the key components of the proposed system along with their respective functions. The overall design integrates energy generation, control, power conversion, and load utilization into a unified architecture. The solar panel serves as the primary energy source, while the Arduino-based controller executes the MPPT algorithm to ensure optimal energy extraction under varying operating conditions [3]. The interleaved boost converter performs voltage step-up with reduced ripple and improved efficiency, enabling effective energy transfer to the battery and load. In addition, sensing and display modules provide real-time monitoring, contributing to stable and reliable system operation.

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V. HARDWARE IMPLEMENTATION

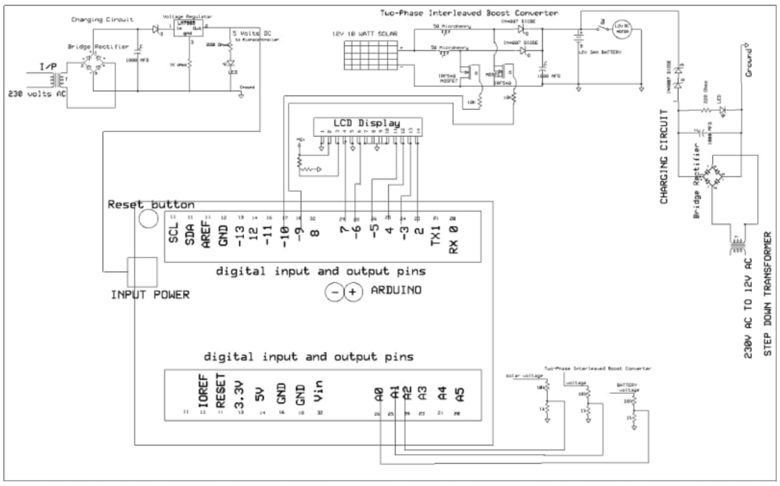

Fig. 4: Schematic diagram of Two-Phase IBC with MPPT Control for Solar PV System

The complete hardware schematic of the proposed system is shown in Fig.4. The hardware implementation of the proposed system follows a systematic process integrating sensing, control, and power conversion.
Initially, the solar panel output voltage is measured using a voltage sensor. This sensed value is fed to the Arduino, which continuously monitors the operating condition of the PV panel.
Next, the Arduino executes the MPPT (Perturb and Observe) algorithm. It calculates the instantaneous power and determines whether the operating point needs to be shifted to extract maximum power [4]. Based on this decision, the controller adjusts the duty cycle.
The Arduino then generates two PWM signals with a 180° phase shift, which are applied to the MOSFET switches (S_1 and S_2). These PWM signals control the switching operation of the interleaved boost converter [9].
During switching:

- Inductors alternately store and release energy.
- Diodes conduct during OFF states.
- Energy is transferred to the output.

As a result, the input voltage from the solar panel is boosted to a higher level with reduced ripple due to interleaving [7]. The boosted output is filtered using a capacitor and supplied to the battery, where energy is stored. Simultaneously, system parameters such as voltage are displayed on the LCD module for monitoring.
Finally, the stored energy is used to drive a DC motor load, demonstrating the practical usability of the system.

VI. RESULTS AND DISCUSSION

The performance of the proposed two-phase interleaved boost converter was experimentally validated using a digital storage oscilloscope. The gate signals of the switching devices were analyzed to verify proper interleaved operation [9].

A. PWM Gate Signals (S_1 and S_2):

Two square wave signals with identical switching frequency of approximately 10 kHz are obtained at the gate terminals of switches S_1 and S_2 as shown in Fig.5. with a phase shift of 180°, which confirms the successful implementation of interleaved switching.

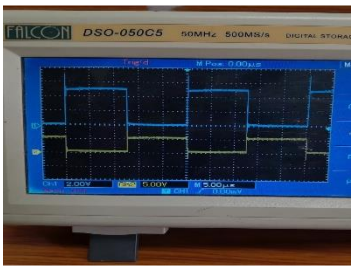

Fig. 5: PWM Gate Signals Showing 180° Phase Shift Between S_1 and S_2

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Additionally, the duty cycle of the PWM signals is observed to vary dynamically in response to the MPPT control algorithm [12]. This adaptive behavior indicates that the controller continuously adjusts the switching pattern to track the operating point of the solar panel.
Overall, the CRO results validate that the control system is capable of generating properly synchronized complementary PWM signals required for two-phase interleaved converter operation. The experimental setup used to validate the proposed system is presented in Fig.6 and the real-time voltage measurements of the system are displayed on the LCD module, as shown in Fig. 7.

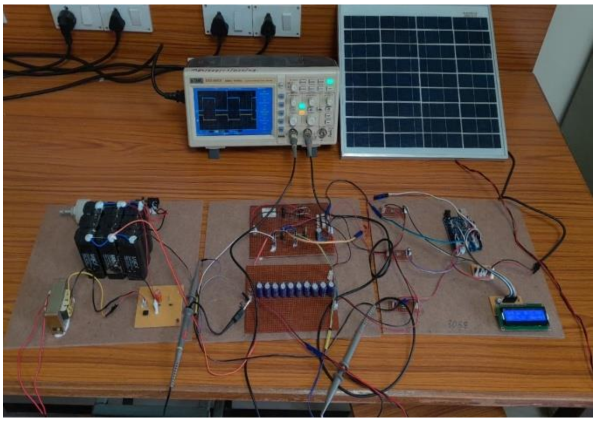

Fig. 6: Experimental Setup of Two-Phase IBC

Fig. 7: LCD Display Showing Real-Time Voltage Measurements

Table 2: Performance Evaluation of the Proposed Converter:

Parameter	Measured Range	Nominal Value
Solar Panel Voltage (V_s)	8-13V	12.6V
Boost Output (Vo)	8.2 – 13.5 V	13.1V
Battery Voltage (V_b)	12 – 12.5 V	12.1V
Switching Frequency	10 kHz	10kHz

The experimental results are summarized in Table 2, where both measured operating ranges and corresponding nominal values are presented. The observed variations in voltage are primarily due to fluctuations in solar irradiance and the continuous adjustment of the duty cycle by the MPPT control algorithm. Therefore, instead of a fixed value, a range is reported to accurately represent the dynamic operating conditions of the system. The nominal values correspond to typical steady operating points obtained during stable environmental conditions. The results indicate that the converter is actively operating and transferring energy from the solar panel to the load and battery system.

B. Output Performance Analysis:
The experimental results demonstrate that the output voltage of the converter is higher than the battery voltage, ensuring that the battery remains in a charging condition [10].
Although the theoretical voltage gain of a boost converter can produce significantly higher output levels, the observed gain in the prototype is moderate. This is primarily due to the limited input power available from the low-wattage solar panel and the closed-loop MPPT operation, which regulates the duty cycle to extract maximum power rather than maximize voltage.
The implemented Perturb and Observe (P&O) MPPT algorithm continuously adjusts the duty cycle of the converter based on the variation in input power. As a result, slight fluctuations in voltage are observed during operation. These variations are expected and indicate that the system is actively tracking the maximum power point of the solar panel [6].
Instead of forcing a higher output voltage, the controller maintains an operating point where the power extracted from the solar panel is maximized, which is the primary objective of MPPT control.
The use of interleaving between the two converter phases ensures that the input current becomes more continuous and the output voltage ripple is reduced. The phase-shifted operation of the inductors contributes to ripple cancellation, resulting in smoother overall system performance compared to a conventional single-phase boost converter.

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Practical Observations:

- The generation of 180° phase-shifted PWM signals confirms proper interleaved control.
- The system successfully transfers energy from the solar panel to the battery and load.
- The output voltage remains higher than the battery voltage, validating charging capability.
- Stable operation is maintained despite variations in input conditions.

Table 3: Performance Comparison

Parameter	Conventional Boost	Interleaved Boost
Switching Signals	Single	Dual (180° shifted)
Input Current	Pulsating	More Continuous
Output Ripple	Higher	Reduced
Thermal Stress	Concentrated	Distributed
Efficiency	Moderate	Improved

The comparative performance of the proposed interleaved boost converter with a conventional boost converter is presented in Table 3. It is observed that the interleaved configuration employs dual phase-shifted switching, resulting in a more continuous input current and reduced output voltage ripple. In addition, the distribution of power across two phases minimizes thermal stress on individual components and enhances overall efficiency. These improvements demonstrate the effectiveness of the proposed topology in achieving better performance compared to the conventional boost converter.

VII. CONCLUSION

In this work, a solar photovoltaic energy conversion system based on a two-phase interleaved boost converter integrated with MPPT control has been designed and analyzed. The proposed system effectively addresses the limitations of conventional boost converters by incorporating interleaving and intelligent control techniques. The implementation of the Perturb and Observe (P&O) MPPT algorithm ensures that the solar panel operates close to its maximum power point under varying environmental conditions. At the same time, the use of a two-phase interleaved boost topology significantly reduces input current ripple and output voltage fluctuations, resulting in smoother and more stable operation. The distribution of power across two phases also reduces switching stress on individual components, improves thermal performance, and enhances overall system efficiency. Due to the interleaving operation with a 180° phase shift, the ripple components of the two inductor currents cancel each other. The load is shared between two parallel converter phases, which reduces conduction and switching losses in individual components. Since the two phases operate alternately, at least one phase is always transferring energy to the output, ensuring continuous power delivery. Power handling is distributed across multiple components instead of a single path, reducing thermal stress on individual devices such as MOSFETs and inductors and improving reliability and lifespan of the system. The experimental and analytical results indicate that the proposed system achieves better performance when compared to a conventional single boost converter. Furthermore, the design can be extended to higher power levels with appropriate component selection and control enhancements. Overall, the proposed system provides an effective and reliable solution for efficient solar energy conversion and utilization in modern renewable energy applications.

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