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AN IMPROVED CLOSED-LOOP DC-DC CONVERTER FOR VOLTAGE STABILIZATION

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Abstract: This study focuses on developing and deploying a closed-loop SEPIC (Single-Ended Primary Inductor Converter) configuration to achieve stable voltage regulation within power electronics. The SEPIC architecture is uniquely capable of producing a consistent output voltage regardless of input fluctuations whether the input is lower or higher than the required level. Through a feedback mechanism, the control loop continuously fine-tunes the switching duty cycle to maintain voltage stability across varying input and load conditions. The design process incorporates careful selection of inductors and capacitors, optimal switching frequency settings, and a responsive digital control system. Performance assessments via simulation and physical prototypes reveal strong results in terms of efficiency, dynamic behavior, and *reliability, making the system highly applicable to domains such as renewable energy, portable devices, and automotive electronics.*

Keywords: SEPIC (Single-Ended Primary Inductor Converter), photovoltaic (PV), DC-DC converter.

I. INTRODUCTION

Smart grid systems utilize advanced control technologies and digital communication to enhance the efficiency, reliability, and security of modern power networks [1-2]. These systems seamlessly integrate various renewable energy sources, including wind turbines, fuel cells, and photovoltaic (PV) systems, with PV technology emerging as a highly promising solution for sustainable energy generation [3-4]. PV systems can operate as standalone units or be connected to the grid. In grid-connected applications, a high DC voltage is required, typically achieved through three-phase inverters [5-7]. However, since PV panels inherently produce lower voltage, a step-up converter becomes necessary to boost it to the required levels. The ideal step-up converter should provide high voltage gain, superior efficiency, and minimal ripple in voltage and current to prevent power losses. Several studies have explored methods to improve step-up converter efficiency in PV applications. The Boost converter is a widely used topology that achieves high voltage gain through a large duty cycle [8]. However, this approach can lead to voltage stress on switching components, reducing overall efficiency. An alternative solution, the Quadratic Boost Converter, connects two Boost converters in series using a single switch [9-10]. While it offers higher voltage amplification, it also introduces significant current stress on the switching device, increasing conduction losses and reducing efficiency [11-13]. To address these challenges, researchers have investigated the use of Coupled Inductor technology which enhances voltage gain by optimizing the inductor coil configuration [14-15]. This technique improves energy conversion efficiency, ensuring stable operation and enabling more effective integration of PV systems into smart grids.

During high step-up operation, increased current ripple leads to leakage inductance, ultimately reducing efficiency. To address this issue, researchers have integrated the Coupled Inductor converter with a voltage doublers circuit, as demonstrated. While this approach minimizes voltage stress on the switching device, it results in the inductor receiving magnetizing current that is twice the switching frequency [16-17]. Another strategy presented in utilizes switched capacitor cells to achieve a high static voltage gain. The voltage multiplier cell technique enhances voltage gain while reducing switching voltage stress; however, it may increase the overall cost of the converter. Various configurations have been explored to boost efficiency and voltage gain, such as combining Boost converters with Cuk converters and integrating Boost converters with SEPIC converters. Despite these advancements, switching devices in these converters still experience voltage stress equal to the sum of input and output voltage averages. To overcome these limitations, a modified SEPIC converter was developed by integrating a conventional SEPIC converter with a Boost converter and a diode-capacitor circuit, as introduced. This design achieves high voltage gain, reduced switching voltage stress, and lower conduction losses, making it well-suited for PV applications. However, its performance under varying environmental conditions such as changes in solar irradiation and ambient temperature has not been extensively studied. In this research, the modified SEPIC converter proposed and is evaluated for its adaptability to different environmental conditions. Using MATLAB/Simulink simulations, the converter's behavior is examined in a grid-connected PV system rated at 15 kW considering fluctuations in irradiance levels and ambient temperatures.

The SEPIC is a versatile DC-DC converter capable of stepping up or stepping down voltage while maintaining a non-inverting output. Its adaptability stems from the ability to regulate output voltage based on its duty cycle, making it an ideal choice for applications requiring precise voltage control. Unlike traditional buck and boost converters, SEPIC offers an unrestricted maximum power point tracking (MPPT) region, maximizing energy extraction in renewable energy systems. A key advantage of SEPIC is its simplified gate-drive circuitry, as its switch control terminal is connected to ground. This design also eliminates the need for complex circuits, such as split power supplies or Opto-couplers, which are necessary in buck-boost and Cuk converters for negative voltage feedback sensing. As a result, SEPIC enhances system response time and reliability. Another notable feature is its input inductor, which significantly reduces input current pulsation, thereby improving MPPT accuracy. SEPIC is widely used in solar photovoltaic (PV) applications, particularly in MPPT-based setups like portable solar-powered equipment and autonomous PV systems. In this study, SEPIC is employed to regulate voltage from solar panels, ensuring seamless integration with the electrical grid. The system operates at 600 volts and facilitates the export of up to 50 kilowatts of power. Additionally, a reflector is incorporated to convert direct current into alternating current, while filters refine the waveform to ensure stable grid connectivity.

II. ANALYSIS OF SEPIC CONVERTER

The SEPIC is an efficient DC-DC converter capable of both stepping up and stepping down voltage while maintaining a non-inverting polarity. This feature simplifies circuit design and eliminates the need for additional components to correct voltage inversion, making SEPIC well-suited for a wide range of applications requiring precise voltage regulation. A key advantage of SEPIC is its ability to enhance energy storage and maintain a steady current flow within the circuit, ensuring reliable performance. The converter operates in two distinct states, as depicted in Fig. 1 when the switch is open, allowing energy storage in the inductors, and (2) when the switch is closed and facilitating energy transfer to the output. These operational phases enable efficient voltage control and stable power delivery.

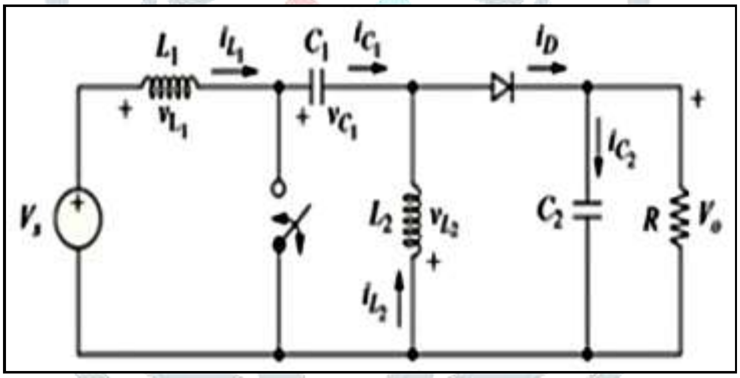

Figure.1 Single-Ended Primary Inductor Converter Circuit

Figure. 2 illustrates the operational state of the SEPIC converter when the IGBT switch is closed. During this phase, current flows through inductor **L1**, allowing energy transfer from the voltage source **Vs**. Simultaneously, inductor **L2** is energized via the capacitor **C1**, ensuring efficient power regulation and energy storage within the circuit. This stage is crucial for maintaining stable voltage conversion and optimizing the system's overall efficiency.

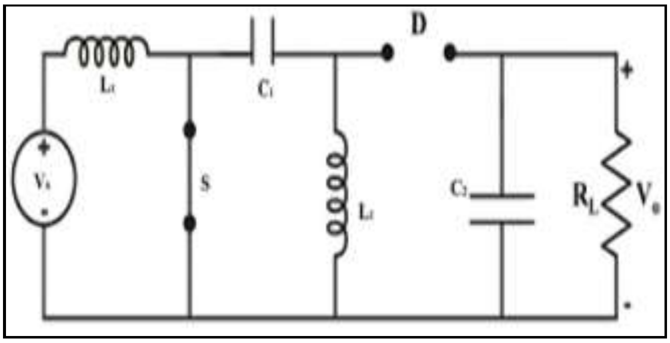

Figure. 2 SEPIC Circuit when switch is closed

Figure 3 illustrates the operation of the SEPIC converter when the IGBT switch is open. In this state, the inductors discharge their stored energy, directing current through the diode to supply the load. Meanwhile, the capacitors accumulate charge, supporting voltage stabilization. Due to the extended charging period of the inductors, the output voltage in this mode tends to be higher, ensuring efficient power delivery. This phase plays a critical role in maintaining stable voltage conversion and optimizing energy transfer.

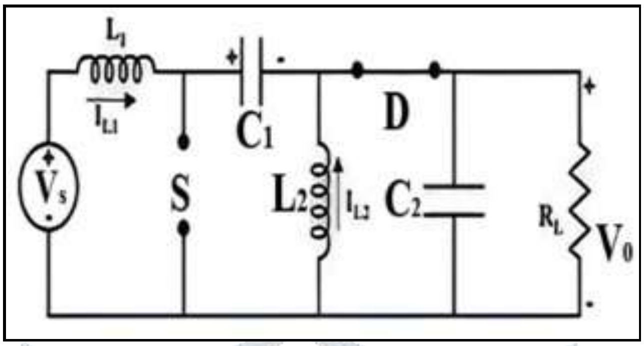

Figure. 3 SEPIC Circuit when switch is open

III. SEPIC CONVERTER DESIGN AND CONTROL STRATEGY

This study explores the design and optimization of SEPIC converters across multiple operational stages, considering various control methodologies. Initially, PID control was implemented to regulate SEPIC's performance, followed by adjustments for reverse connection scenarios. Additionally, maximum power point tracking (MPPT) control was integrated to enhance efficiency when interfacing the SEPIC converter with solar PV panels and the electrical grid. The upcoming sections provide a detailed analysis of the system's different operating conditions. To achieve optimal performance, precise determination of circuit components is essential. The selection of these parameters is guided by specific equations, assuming continuous conduction mode (CCM) operation. The key variables include **V**, representing ripple voltage; **D**, the duty cycle; **IL**, the ripple current; and **Fs**, the switching frequency. By carefully calculating these values, the efficiency and stability of the SEPIC converter can be significantly improved.

$$D = \frac{Vout}{Vin + Vout} \quad (1)$$

$$L1 = \frac{D*Vin}{\triangle IL1*Fs} \quad (2)$$

$$L2 = \frac{D*Vin}{\triangle IL2*Fs} \quad (3)$$

$$C1 = \frac{D*Iout}{\triangle VC1*Fs} \quad (4)$$

$$C2 = \frac{D*\mathrm{Iout}}{\triangle \mathrm{VC2}*Fs} \quad (5)$$

Then maximum duty cycle,

$$Dmax = \frac{Vout + Vd}{Vin + Vout + Vd} \quad (7)$$

$$\cong \frac{600 + 0.5}{298 + 600 + 0.5} = 0.66$$

IV MAT LAB/SIMULINK MODEL OF PROPOSED CLOSED LOOP SEPIC CONVERTER

The schematic representation of the open-loop SEPIC (Single-Ended Primary Inductor Converter) configuration is illustrated in Figure 4, while Figures 5 and 6 display the corresponding output voltage and current waveforms. In an open-loop system, the control strategy lacks feedback, meaning the converter operates with a pre-determined and fixed duty cycle based on theoretical estimates. Because there is no mechanism to monitor or regulate real-time variations in output voltage or current, the system cannot respond to changes in load conditions or input fluctuations, which results in unstable or inconsistent output. To mitigate this issue and enhance regulation, a closed-loop control strategy is employed. In this setup, the output voltage is continuously measured and compared against a predefined reference voltage. When a discrepancy between the actual output and the desired set point is detected, the controller actively adjusts the duty cycle to minimize the error. This dynamic feedback mechanism allows the converter to maintain a constant output voltage despite variations in operating conditions. As a result, the closed-loop SEPIC converter becomes more reliable and efficient for applications that demand stable voltage regulation.

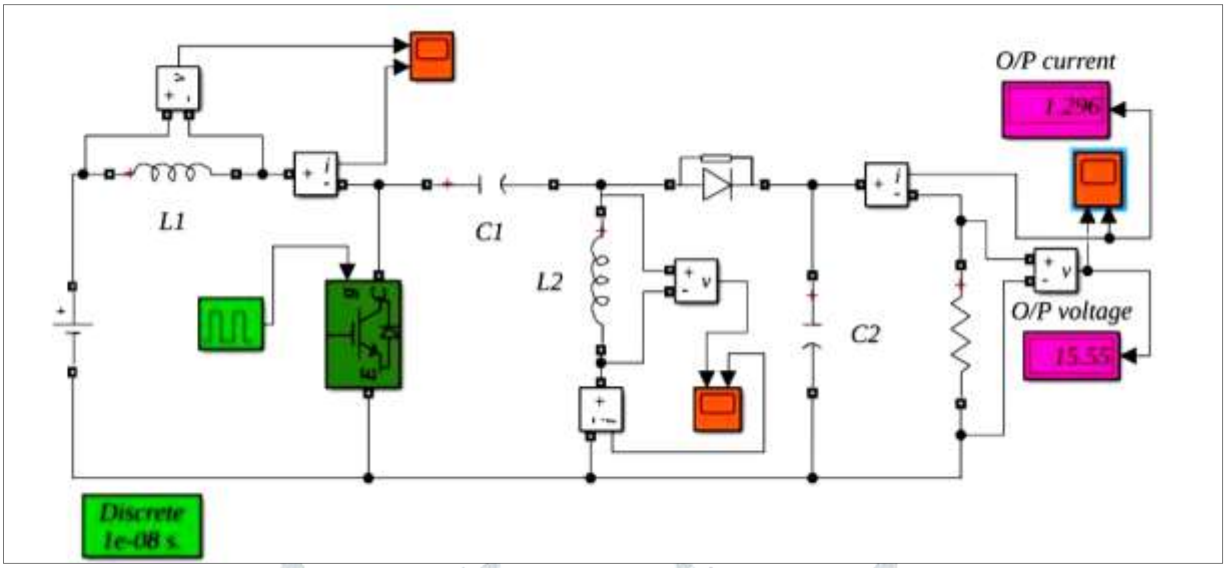

Figure. 4 Mat lab/Simulink model of basic open loop SEPIC converter

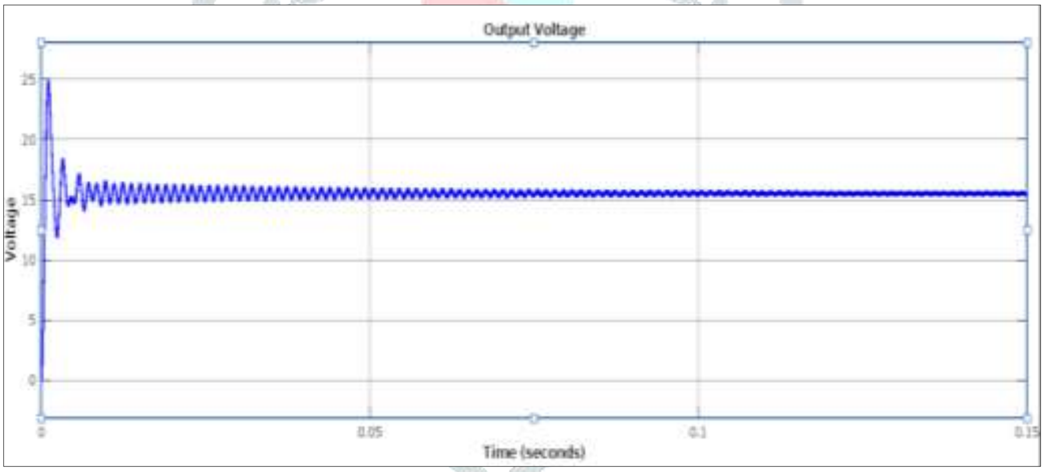

Figure. 5 Output voltage of SEPIC converter

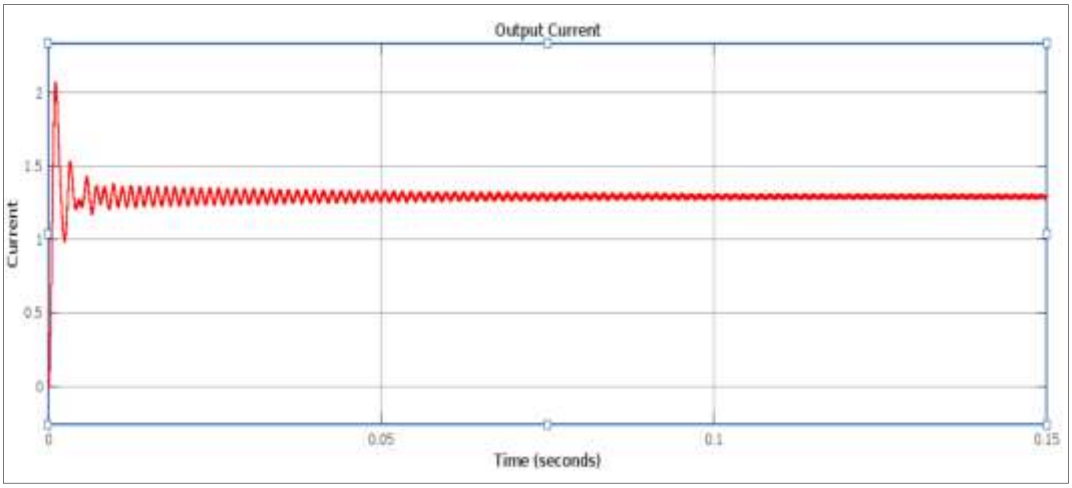

Fig.6 o/p current of SEPIC converter

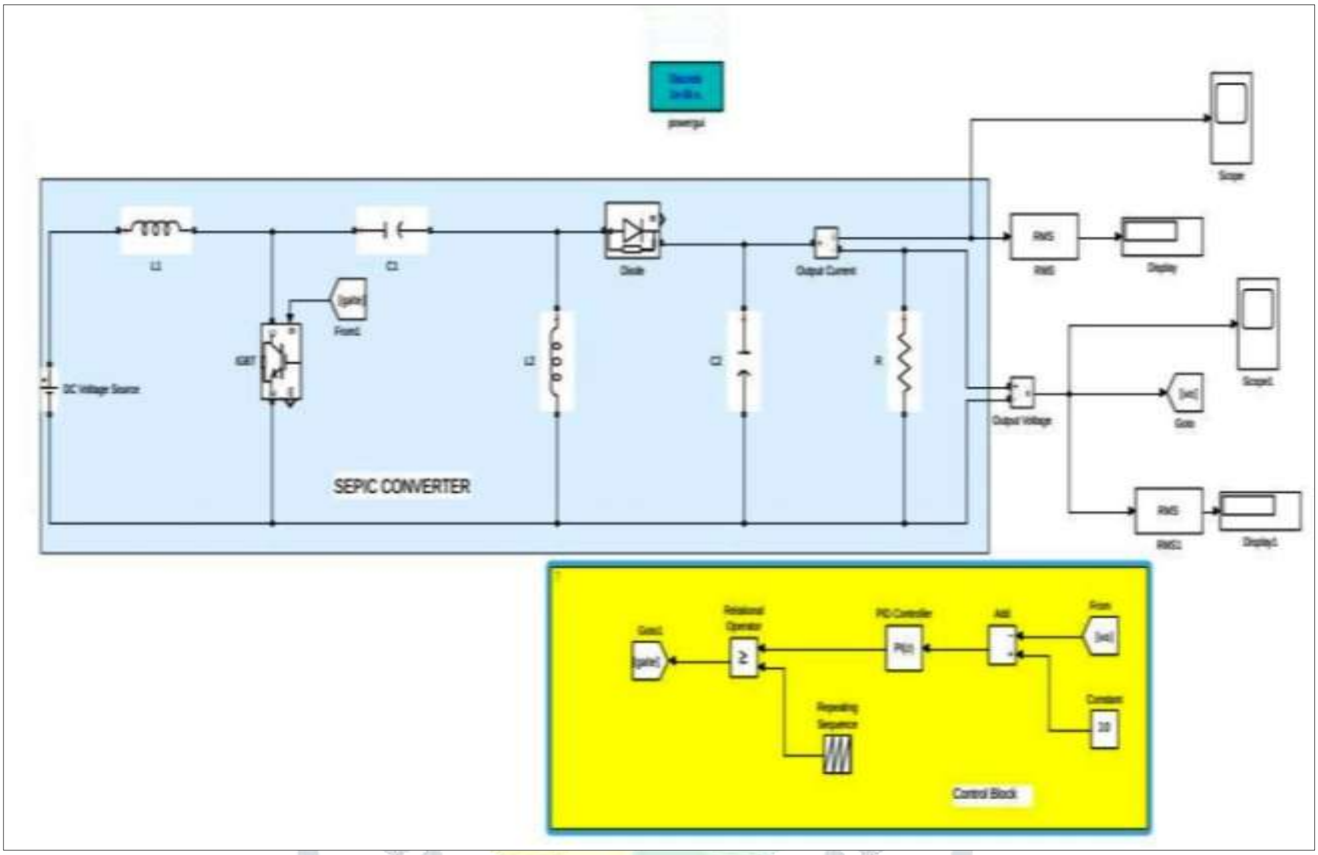

Figure. 7 Mat lab/Simulink model of basic closed loop SEPIC converter

Figure 7 illustrates the closed-loop operation of the SEPIC (circuit model, showcasing its ability to regulate output under varying conditions. In this configuration, a feedback mechanism continuously monitors the output voltage and compares it with a predefined reference value. Based on this comparison, the controller dynamically adjusts the duty cycle of the switching device to maintain a consistent output. This allows the converter to adapt to changes in input voltage or load, enhancing overall performance and stability. The resulting waveforms, representing the output voltage and current under closed-loop control, are presented in Figures 8 and 9. These plots demonstrate the converter's capacity to maintain steady operation with reduced ripple and faster response time compared to its open-loop counterpart.

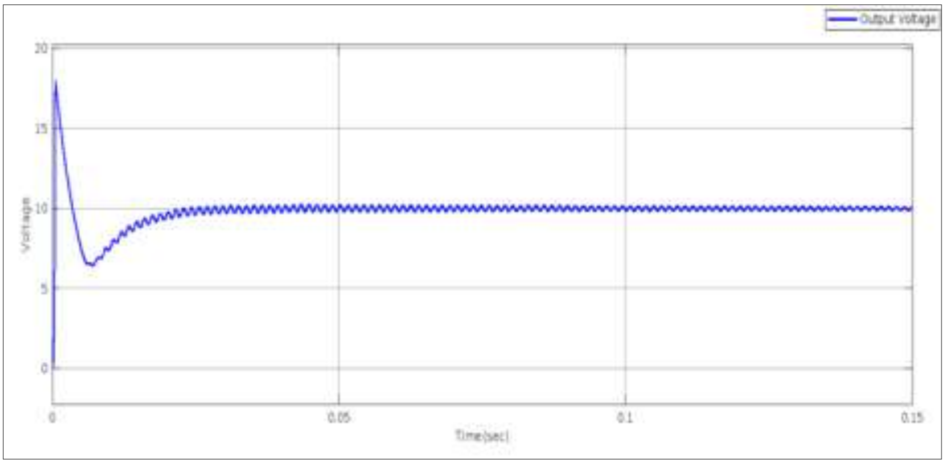

Figure. 8 Output voltage of closed loop SEPIC converter

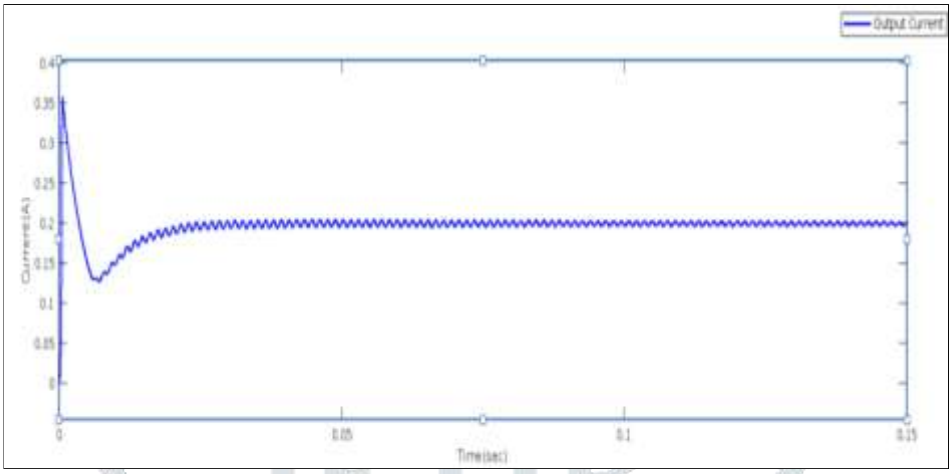

Figure. 9 Output current of closed loop SEPIC converter

V. CONCLUSION

An analysis of both open-loop and closed-loop configurations of the SEPIC (Single-Ended Primary Inductor Converter) converter is presented to demonstrate its operational behavior and advantages. A key benefit of the proposed SEPIC converter is its ability to produce an output voltage that retains the same polarity as the input voltage which simplifies system design and minimizes the need for additional circuitry. As a result the hardware implementation becomes more cost-effective compared to other converter topologies that deliver similar output performance but often require more complex arrangements. Experimental results and simulations clearly illustrate that the output voltage of the converter is highly dependent on the duty cycle of the switching element. In open-loop operation, where the duty cycle remains fixed, the output varies significantly due to the lack of feedback control. However in closed-loop control technique the duty cycle is dynamically adjusted allowing precise regulation of the output voltage. This modulation enables the SEPIC converter to perform both buck (step-down) and boost (step-up) operations, making it highly versatile for applications where the input voltage fluctuates or where both lower and higher voltage levels are required at the output.

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