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Design of a 120V, 5A SEPIC DC-DC Converter for Unipolar 120V DC Microgrid

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ABSTRACT

SEPIC is a DC-DC converter that operates in both boost and buck modes, thereby reducing voltage stress on the active power switches. It is utilized in electric vehicles, marine vessels, and aircraft to minimize dimensions, mass, maintenance, and operational expenses while enhancing efficiency, safety, and dependability. DC microgrids, characterized by their straightforward topology and economical materials, provide enhanced efficiency relative to AC microgrids. This work reviews the previous literature concerning SEPIC converters and DC-DC microgrid applications. This paper presents a SEPIC-based DC-DC converter designed for direct connection to a unipolar 120V DC microgrid and capable of delivering 600W of DC power. It is outfitted with a current sensor and a protective switch to provide self-protection against microgrid disturbances, such as brief short circuits. The converter has been designed and evaluated using PSpice. The simulation results indicated that during a sudden disturbance in the DC microgrid, the current sensor detected an excessive current, prompting the control circuit to deactivate the protective switch. This action isolated the input voltage from the converter circuit, leading to an immediate reduction of the input current to zero and a subsequent decline of the output voltage toward zero. The condition endured for approximately 50 milliseconds, anticipating a possible recovery from the disruption. Therefore, the simulation results confirmed the design methods of the proposed converter and demonstrated adequate protection against high current events.

1. INTRODUCTION

SEPIC is the abbreviation of "single-ended primary inductor converter", which is a DC-DC converter capable of functioning in both step-up and step-down modes of operation. A SEPIC converter operates in two distinct modes: continuous conduction mode (CCM) and discontinuous conduction mode (DCM). The SEPIC DC-DC converter topology reduces voltage stress on active power switches, facilitating the use of low-voltage power switches with minimal turn-on resistance [1]-[17]. A project in [1] aimed to convert direct current (DC) generated from physical exercise into alternating current (AC), thereby providing a renewable energy source. The project employed a non-isolated, PWM-switching single-ended primary inductor converter for efficient DC power production and inverter integration. A study in [2] examined the SEPIC DC-DC converter, its design for digital controllers, and associated problems such as elevated input current ripple, harmonics, and electrical stress. A system design for enhancing solar systems through the use of maximum power point tracking was presented in [3], demonstrating its efficiency through a high-efficiency converter and digital control approaches. A paper in [4] examined the design and implementation of a Maximum Power Point Tracking (MPPT) SEPIC Converter aimed at maximizing Photovoltaic (PV) power output, employing a straightforward and efficient Perturb and Observe (P&O) algorithm and integrating a soft-switching technique. A study in [5] examined the optimization of a SEPIC converter's total harmonic distortion (THD) and voltage ripple through parameter design optimization, achieving a 2.66% reduction in THD and an output power of 65 W. A study in

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[6] instructed engineering students on fundamental DC-DC converter topologies, rectifying deficiencies in the descriptions of second and advanced-fourth-order converters, and offering comprehensive equation derivations, component sizing examples, and circuit modeling. A redesigned SEPIC DC-DC converter for high-voltage gain applications was introduced in [7], which reduces costs, conduction losses, and turn-on losses while providing a compact and lightweight design. A thesis in [8] examined the efficacy of a closed-loop SEPIC converter relative to an open-loop converter, employing a PID controller and PWM modulator, alongside a novel SEPIC converter with parallel resonant capacitors.

SEPIC and LLC resonant converters for photovoltaic solar systems, utilizing PID and FLC control systems. MATLAB/SIMULINK simulations demonstrated efficiencies of 93.3% and 80.3%, respectively, along with effective output voltage regulation in [9]. Buck-boost, quadratic boost, and SEPIC converters were analyzed in conjunction with the smart grid, as referenced in [10], utilizing MATLAB Simulink to assess output voltage, power, and voltage ripple. A study in [11] introduced a design for a SEPIC converter intended for battery charging applications, examining its performance under different input voltages and presenting findings generated with MATLAB/Simulink software. The study details the design and installation of a Single-Ended Primary-Inductor Converter (SEPIC) for an LED lighting system in an electric car [12]. The converter provided a stable output voltage, enhanced voltage regulation, little input current ripple, and reduced electrical stress relative to alternative converters. A paper in [13] examined the design of a multi-input SEPIC converter circuit for hybrid energy systems utilizing wind turbines and photovoltaics, addressing the growing demand for electrical energy. A novel SEPIC-type converter model for renewable energy sources, integrating conventional SEPIC DC-DC converters with split-inductor circuits, was presented in [14]. The SEPIC DC-DC converter achieved a voltage gain of 7.5 times the supplied voltage, exhibiting reduced ripple and minimized switching stress. A study in [15] introduced a SEPIC-based solar simulator that precisely emulates the current-voltage characteristics of actual photovoltaic modules, achieving an average power conversion efficiency of 97.3%. This simulator serves as an effective instrument for the development and testing of photovoltaic systems. Designers utilize SEPIC converters in automotive electronics, portable devices, and renewable energy systems, including adaptations for high-voltage applications. A regulated DC supply mitigates high current at start-up, while the high-frequency component diminishes component size and ripple effects [16]. A study in [17] examined the integration of photovoltaic panels and bicycle dynamo renewable energy sources using a multi-input SEPIC converter, achieving an efficiency of 91.6% in a hardware field test. The objective was to support remote rural islands and areas lacking grid connectivity.

The integration of power electronic converters in electric vehicles, maritime vessels, and aircraft aims to reduce dimensions, mass, maintenance costs, and operational expenses while improving efficiency, safety, and reliability. These systems integrate alternating current (AC) and direct current (DC) loads, often requiring auxiliary systems to operate correctly. DC microgrids are more readily implementable owing to the accessibility of distributed energy resources such as photovoltaic cells and batteries. They necessitate more economical materials and offer enhanced efficiency relative to AC microgrids. DC microgrids possess a straightforward topology, are free from frequency, harmonic distortion, and reactive power issues, and do not require synchronization with the grid. Consequently, researchers are increasingly concentrating on DC microgrids to meet DC load requirements [18]-[25]. The study presented a novel SEPIC-derived hybrid converter featuring shoot-through protection and independent control, as described in reference [18] for applications in nanogrid design, smart residences, electric automobiles, hybrid fuel cells, and aircraft power distribution systems. A study in [19] examined DC-DC power converter families within MVDC grids, encompassing both isolated and non-isolated types, and their applications, with an emphasis on the scarcity of research on isolated converters. The Modified SEPIC converter (MSC) is an economical, energy-efficient, and straightforward solution for photovoltaic-driven DC microgrids [20]. It provides elevated voltage gain and sustained current, operates with a single regulated switch, and the study employed PSIM software for execution. A survey examined the viability of a novel distribution system in LVDC microgrids, its influence on social development, and technological challenges such as low inertia and voltage regulation [21]. A study in [22] introduced a speed control method for a brushless DC motor drive within a solar photovoltaic system, which was validated using Powersim software and experimental testing. A proposed DC converter, employing Cuk and SEPIC converters, was constructed in [23] for solar photovoltaic systems, offering a bipolar output and enhanced power extraction through magnetic centers. A study in [24] outlined converter specifications for decentralized DC microgrids, employed an exhaustive search technique, and presented a hardware prototype, emphasizing affordability, adaptability, and user-friendliness. A cascaded Boost-SEPIC (CBS) converter, a novel architecture for AC-DC conversion, was introduced in [25] to enhance power quality and conversion efficiency relative to conventional converters designed for high voltage output.

DC microgrids are increasingly popular due to their compatibility with renewable energy systems, energy storage, and modern electrical appliances. They offer high efficiency and reliability, but may face voltage balancing and protection issues. Despite their importance, there is a lack of focus on power flow analysis methods in DC microgrid and hybrid control topologies [26]-[31]. Many researchers explored hybrid DC microgrids, power-electronic solutions for renewable energy, AC-DC systems, interlinking converters, stability evaluation, potential imbalances, distributed energy access, and simulation models [32]-[36]. New backup fault protection schemes and shared energy storage systems were proposed in [37]-[41] for low-voltage direct current DC microgrids, improving bus voltage regulation and the performance of load sharing. DC microgrids are gaining broad popularity due to their ease of use, solar power capabilities, and lack of concerns regarding frequency and reactive power. Challenges include voltage fluctuations, power flow management, and the distribution of distributed generation. To ensure stability, maintaining proper DC bus voltage levels and effectively managing power flow are crucial. Safety aspects, such as series arc detection and touch safety voltage control, are also essential [42]-[45]. Novel multi-input DC-DC converters for grid-independent hybrid electric vehicles powered by solar photovoltaic panels and fuel cells were designed and analyzed. The high-reliability SEPIC converter combines basic converters with extended units for redundancy and reduced input current ripple. Solar energy is a renewable and environmentally friendly solution for meeting electricity demand [46]-[50].

The stability of microgrid bus voltage is a challenging issue due to the load sharing of its individual power feeders and the variations in DC load, as well as sudden disturbances such as temporary short circuits. Therefore, the protection of DC microgrids represents an urgent need. Adaptive protection systems and reliable individual DC power feeders can accomplish the goal. In this paper, a reliable, self-protected 120V, 5A SEPIC DC-DC converter is designed to operate directly connected to a 120V unipolar microgrid.

The structure of this article is as follows: Chapter 2 presents the proposed method, Chapter 3 discusses the results and draws conclusions, and Chapter 4 provides a summary of the conclusions.

2. THE PROPOSED SEPIC CONVERTER

Figure 1 illustrates the schematic design of the proposed SEPIC DC-DC converter comprising four energy storage components: two inductors, two capacitors, a MOSFET, a diode, and a resistor. The system directly connects to a 120V unipolar DC microgrid at a rated DC of 5A. The designated voltage gain (V_0/V_i) is 5, with a DC input voltage V_i of 24V. This configuration includes protection circuitry against excessive output current [26]. A current sensor (CS) detects the output current I_0. When the output current exceeds its rated value by 20%, the controller sends a control signal to the protective switch (PS) to isolate Vi from the converter circuit. The SEPIC converter can raise or lower the output voltage levels. This feature enables the regulation of changes in DC levels in photovoltaic farms. In a SEPIC converter, the maximum duty cycle D_{max} is given by [14][17].

$$D_{max} = \frac{V_0}{V_0 + V_{i(min)}} \tag{1}$$

Where V_0 is the output voltage and $V_{i(min)}$ represents the minimum input voltage. In this design, V_i is constant, thus $V_{i(min)}$ and V_i are equal. The permissible peak-to-peak ripple current (ΔI_L) flowing in the inductor L_1 constitutes approximately 20-40% of the maximum input current at the minimal input voltage. It can be given by [14][17].

$$\Delta I_L = I_0 \frac{V_0}{V_i} \tag{2}$$

Where ΔI_L refers to the permissible peak-to-peak ripple current flowing in the inductors L_1 and L_2, I_0 represents the load current. The inductors L_1 and L_2 are of equal value and can be given by [14][17].

$$L_1 = L_2 = \frac{V_i}{\Delta I_L f_S} D_{max} \tag{3}$$

Where, f_S is the converter's switching frequency. Engineers calculate C1 according to its peak-to-peak ripple voltage (ΔVC1). Therefore, researchers can compute it as follows [14][17].

$$C_1 = \frac{I_0 D_{max}}{\Delta V_{C1} f_S} \tag{4}$$

Where, ΔV_{C1} is the peak-to-peak ripple voltage appearing on the voltage profile of the capacitor C_1. The output capacitor, C_2, is responsible for producing a smooth output voltage, V_0. Engineers calculate it according to its peak-to-peak ripple voltage (ΔV_{C2}). It can be given by [14][17].

$$C_2 = \frac{I_0 D_{max}}{\Delta V_{C2} f_S} \tag{5}$$

Where, ΔV_{C2} is the peak-to-peak ripple voltage appearing on the voltage profile of the capacitor C_2.

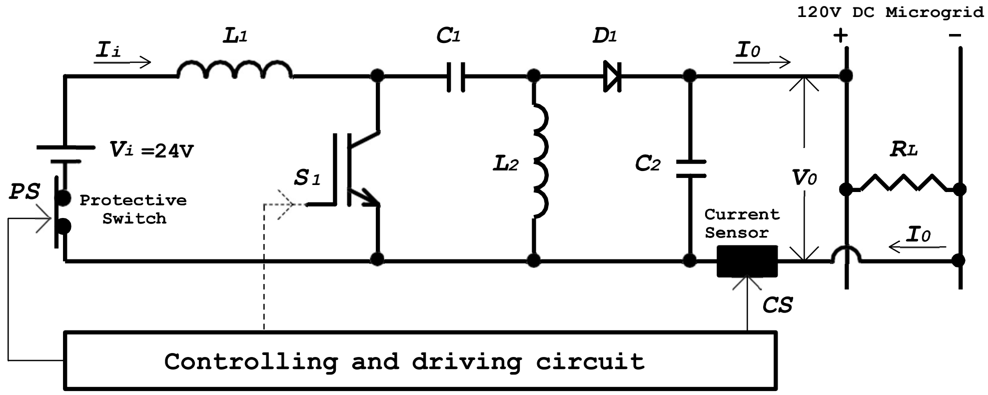

Figure 1. The schematic design of the proposed SEPIC converter

2.1. Circuit Design of the Proposed Converter

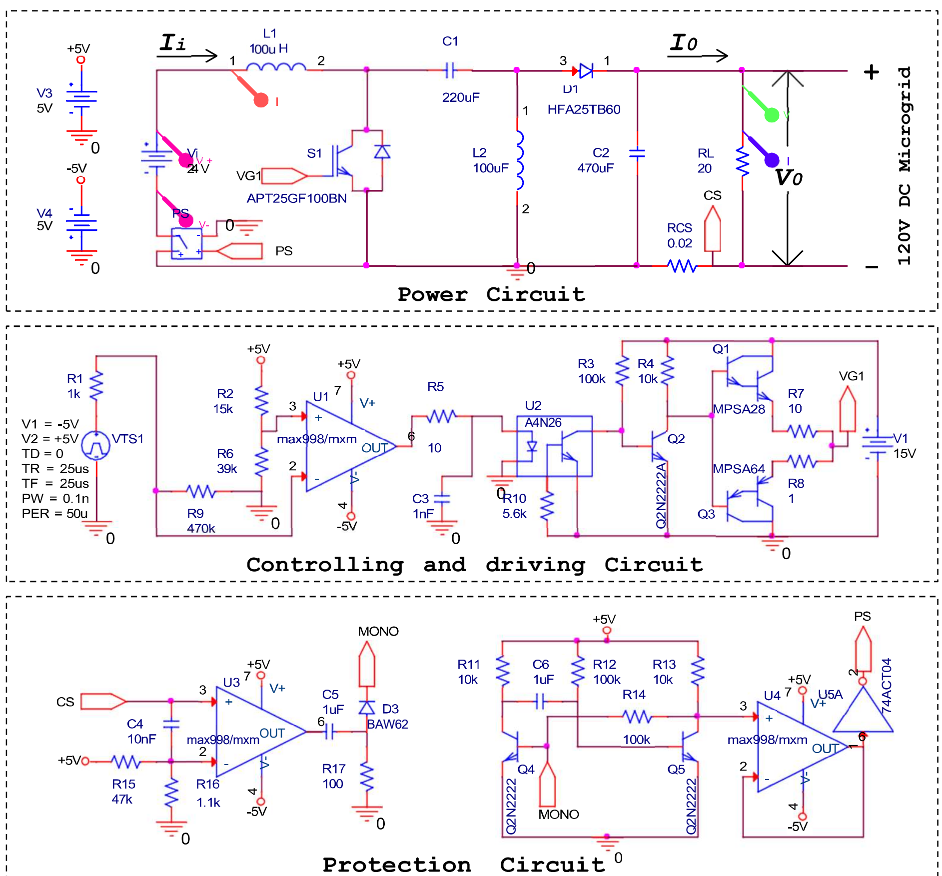

Figure 2. The circuit design of the proposed SEPIC converter

The designer chose the switching frequency f_S of this converter to be 20 kHz, provided by a triangular wave generator. For a specified DC input voltage V_i of 24V and an output voltage V_0 of 120V, the maximum duty cycle D_{max} is calculated according to equation (1) as 0.833. For a ΔIL of 30%, the designer computed the converter inductors L1 and L2 using equation (3) to be 100 µH each. For peak to peak ripple voltage of 1V, equation (4) calculates the capacitor C1 as 208 µF. The chosen value is 220µF. For peak-to-peak ripple of 0.5V in the output voltage, equation (5) calculates the capacitor C2 as 416.65 µF. Table 1 shows the design parameters of the proposed converter. The selected value is 470µF. The designer used PSpice to design the proposed SEPIC converter and utilized the available libraries to ensure the component ratings met the design requirements. Figure 2 shows the complete circuit design of this converter. The designer selected a 0.02 Ω resistor as the current sensor (CS), which produces a 0.1 V voltage drop at the rated load current of 5 A. Suppose the load current exceeds its rated value by 20% due to a particular disturbance in the microgrid voltage. In that case, the voltage across CS will increase beyond 0.1V, resulting in a controlling pulse leading the protective switch to isolate V_i from the converter circuitry.

Table 1. The design parameters of the proposed converter

Parameter	Value and unit
Input voltage, V_i	24V
Output voltage, V_0	120V
Output Current, I_0	5A
Inductors (L_1 and L_2)	100µH
Capacitor, C_1	220µF
Capacitor, C_2	470µF
Load resistance, R_L	24Ω
Switching frequency, f_S	20 kHz

3. RESULTS AND DISCUSSION

The researchers tested the circuit shown in Figure 2 on PSpice to investigate its performance. The measured parameters were the input DC voltage V_i, the input current Ii, the output voltage V_0, and the output current I_0. Figure 3 shows the transient and steady-state responses of the converter during delivery of the its rated current to the 120V unipolar microgrid.

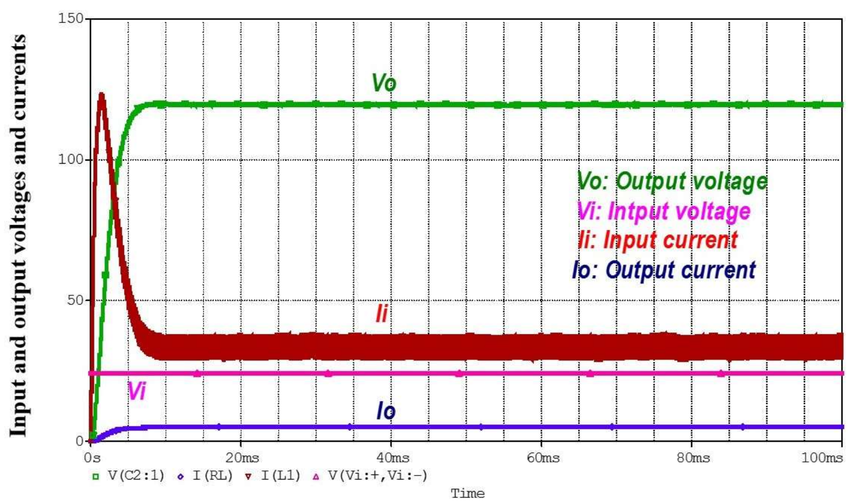

Figure 3. The transient and steady state responses of the proposed SEPIC converter

Figure 3 indicates that the proposed converter reached its steady state within a time of less than 10 milliseconds. The that the proposed SEPIC converter exhibited a significant inrush current resulting from the initial charging of the input and output capacitors, as well as the inductors in the circuit. Upon first energization of the converter, the input and output capacitors should be charged to their operational voltages resulting, in a substantial initial current demand. Furthermore, the inductors within the circuit store energy during magnetization, and this energy might lead to the inrush current. In addition, the proposed SEPIC converter may exhibit a variable output voltage during transient conditions due to the dynamic interaction of its components, particularly the inductors, capacitors, and switching element, as it transitions between various working modes. Figure 4 shows the steady state response of the converter while delivering its rated output current. The input current is the current flowing in the inductor L_1. The ripple current represents approximately 30% of the average input current I_{iavg} which is 33A. The output voltage is of 120V.

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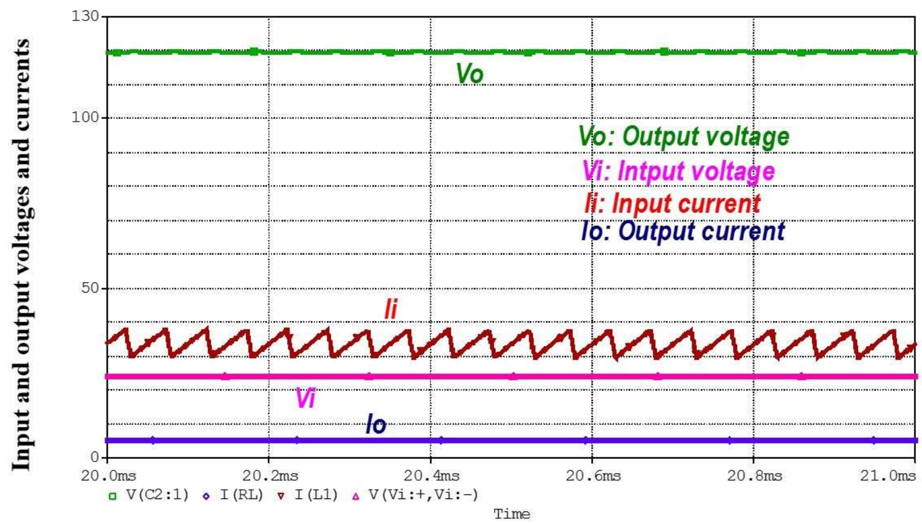

Figure 4. The steady state response of the proposed SEPIC converter

When the DC microgrid encounters a disturbance, such as a temporary short circuit, resulting in an increased current drawn from the converter, the current sensor identifies the excessive current by displaying a voltage drop surpassing 0.1V. The detected fault condition prompts the control circuit to generate a signal to switch off the protective switch, thereby isolating the input voltage from the converter circuit, as illustrated in Figure 5.

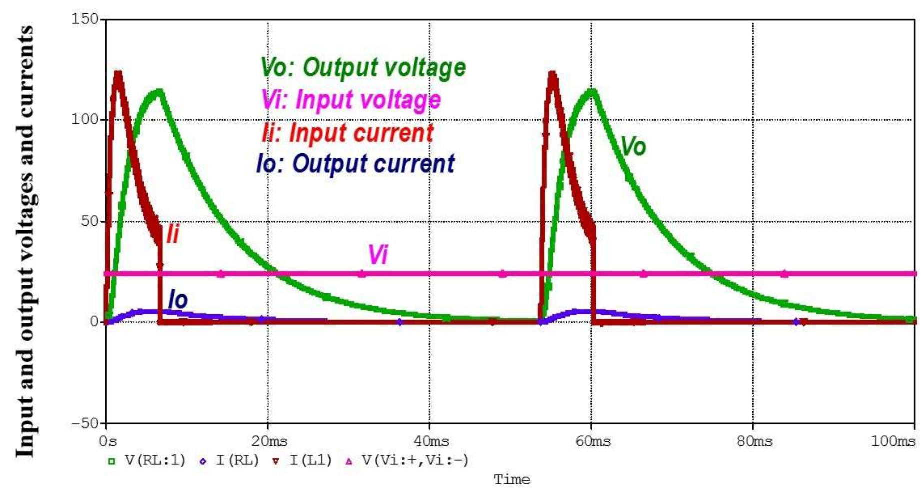

Figure 5. The behaviour of the proposed SEPIC converter against excessive load current due to a particular disturbance in the DC microgrid

The disturbance occurred within a duration of less than 7 milliseconds, prompting the converter to promptly isolate the input voltage, which resulted in an instantaneous reduction of the input current to zero and a subsequent decay of the output voltage toward zero. This situation persisted for about 50 milliseconds, anticipating a potential recovery from the disturbance. If the disturbance does not recover within this timeframe, the protection switch reactivates, and the procedure continues until the disturbance completely resolves.

Upon analyzing Figure 5, it is evident that when the protective switch disconnects V_i from the converter circuitry, the input inductor L_1 ceases to be powered, causing its current I_i to decline rapidly to zero. Consequently, there is no power transfer from the input side of the converter to the output side. The load is supplied solely by the energy stored in the output capacitor C_2, which diminishes to zero, as indicated by the converter's output voltage profile V_0. This process lasts approximately 50 milliseconds.

Although the proposed converter ensures reliable and safe operation in a unipolar microgrid, the designer must also evaluate its performance under abnormal conditions. Further tests were conducted on the proposed converter to evaluate its performance under variable input voltage, with the protective switch maintained in its original position. Figure 6 shows the converter's steady-state performance during a DC input voltage V_i of 12V. The system maintains the load resistance at 24 Ω. The produced output voltage V_0 is 55.3V, and the average input current I_{iavg} is 16.25A. The duty cycle in this test is 0.86.

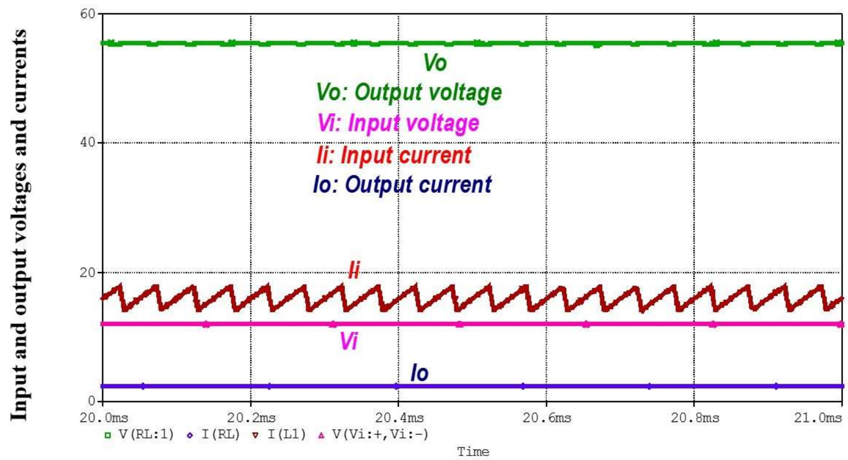

Figure 6. The steady state response of the proposed SEPIC converter during an input voltage of 12V, load resistance of 24Ω, and a duty cycle of 0.86

Figure 7 shows the converter's steady-state performance during a DC input voltage V_i of 36V. The load resistance is changed to 36Ω to keep the load current within the vicinity of 5A. The produced output voltage V_0 is 196V and the average input current I_{iavg} is 37.5A. The designer sets the duty cycle at 0.86.

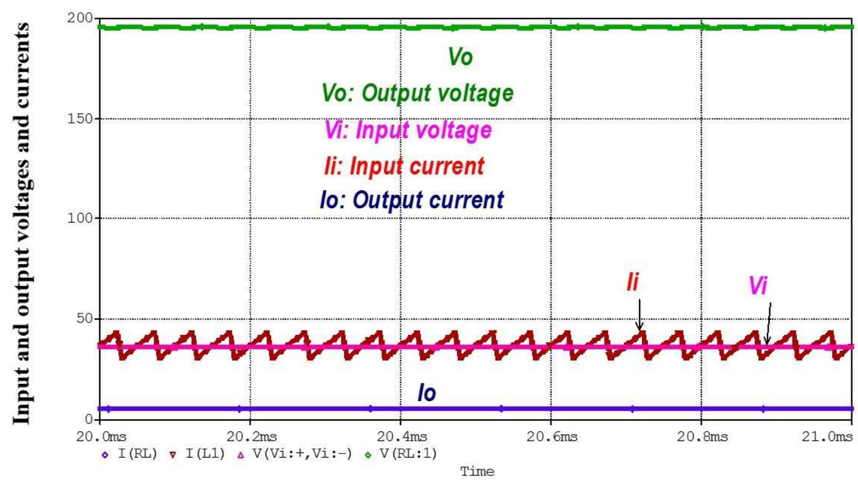

Figure 7. The steady state response of the proposed SEPIC converter during an input voltage of 36V, load resistance of 36Ω, and duty cycle of 0.86

The study conducted a final test with a different duty cycle of 0.78 and raised the input DC voltage to 48V. The researchers maintained a load resistance of 36 Ω, and Figure 8 displays the results of this test. The generated output voltage V_0 is 155.4V, and the average input current I_{iavg} is 16.2A.

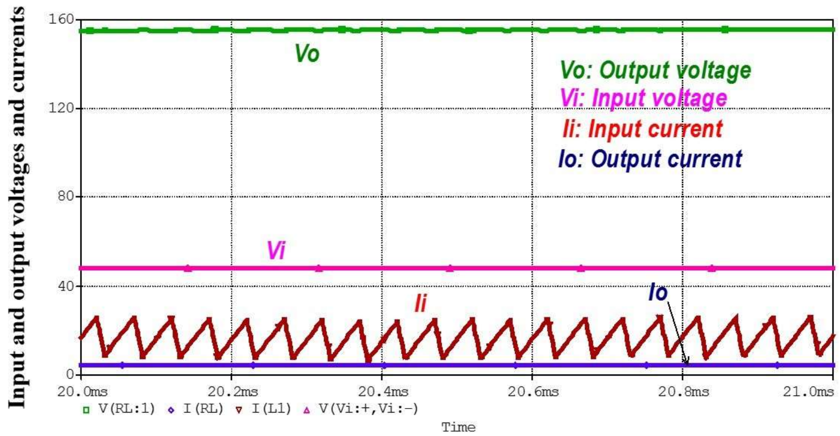

Figure 8. The steady state response of the proposed SEPIC converter during an input voltage of 36V, load resistance of 36Ω, and duty cycle of 0.78

The researchers exploited the results of the steady-state tests in Figures 4 and 6–8 to calculate the converter's input power, output power, and efficiency. Table 2 reveals the measured and calculated parameters. The that the efficiency of the converter depends on the load resistance and duty cycle. The maximum efficiency for a particular duty cycle occurs at an optimal load resistance. At this resistance, the power loss of the switching device is very much less than the output power supplied by the converter.

Table 2. The measured and calculated simulation parameters

Measured and adjusted parameters					Calculated parameters		
Input voltage, V_i	Output voltage, V_0	Average input current, I_{iavg}	Duty cycle, D	Load resistance, R_L	Input power, $P_i=V_i \times I_{iavg}$	Output power, $P_0=V_0^2/R_L$	Efficiency, $\eta=P_0/P_i$
12V	55.3V	16.25A	0.86	24Ω	195W	127.42W	65.34%
24V	120V	33A	0.86	24Ω	792W	600W	75.75%
36V	196V	37.5A	0.86	36Ω	1350	1067	79%
48V	155.4V	16.2A	0.78	36Ω	777.6	670.81	86.2%

4. CONCLUSION AND LIMITATION

A SEPIC converter is one of the DC-DC converters that operate in both step-up and step-down modes. It typically alleviates voltage stress on active power switches. It has, to some extent, a high voltage gain. This study introduces a SEPIC-based DC-DC converter engineered for direct integration into a unipolar 120V DC microgrid, capable of supplying 600W of DC power at constant output voltage. The proposed converter is equipped with a current sensor and a protective switch to ensure self-protection against microgrid disruptions, including transient short circuits. This study designs and assesses the converter using PSpice. The simulation results revealed that after a sudden disruption in the DC microgrid, the current sensor identified an excessive current, leading the control circuit to turn off the protection switch. This action disconnects the input voltage from the converter circuit, causing an instantaneous reduction of the input current to zero and a continuing decrease of the output voltage toward zero. The state continued for roughly 50 milliseconds, anticipating a potential recovery from the disturbance. During of testing the proposed converter under variable operating conditions, including input voltage, load resistance, and duty cycle, the converter demonstrated an efficiency dependence on both duty cycle and load resistance. The simulation outcomes validated the design methodologies of the proposed converter and demonstrated its effectiveness in protecting against high current incidents.

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