

MODELING AND SIMULATION OF A MODIFIED SEPIC DC-DC CONVERTER WITH MPPT CONTROL FOR APPLICATIONS IN PHOTOVOLTAIC SYSTEMS

MODELAGEM E SIMULAÇÃO DE UM CONVERSOR CC-CC SEPIC MODIFICADO COM CONTROLE MPPT PARA APLICAÇÕES EM SISTEMAS FOTOVOLTAICOS

MODELIZACIÓN Y SIMULACIÓN DE UN CONVERTIDOR CC-CC SEPIC MODIFICADO CON CONTROL MPPT PARA APLICACIONES EN SISTEMAS FOTOVOLTAICOS

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ABSTRACT

The growing use of photovoltaic systems requires DC-DC converters capable of operating efficiently under varying load and irradiance conditions. This paper presents the modeling and simulation of a modified SEPIC converter with a voltage-multiplying cell and Maximum Power Point Tracking (MPPT) control, intended and designed for applications with an output voltage of 380 Vdc. Initially, classical converter topologies, conduction modes, and voltage-boosting techniques are studied, establishing the basis for the proposed design. Next, the components are sized, and the converter's performance is evaluated through simulations in PSIM, both under ideal conditions and when coupled to a photovoltaic module. The results showed high agreement between the analytical and simulated values for the voltages, with differences of less than 1 V, while the discrepancies observed in the currents were consistent with the switching dynamics. The implementation of MPPT, based on the Perturb and Observe (P&O) technique, significantly increased the power output under irradiance levels of 800 W/m² and 500 W/m², recovering up to

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229 W compared to fixed-cycle operation and providing a rapid response to irradiance variations. Thus, the proposed converter demonstrated high performance, greater energy efficiency, and feasibility for integration into medium-sized photovoltaic systems.

Keywords: DC-DC Converters. Modified SEPIC. MPPT. Photovoltaic Systems. Simulation.

RESUMO

O uso crescente de sistemas fotovoltaicos demanda conversores CC-CC capazes de operar eficientemente sob variações de carga e irradiância. Este trabalho apresenta a modelagem e simulação de um conversor SEPIC modificado com célula multiplicadora de tensão e controle de *Maximum Power Point Tracking* (MPPT), destinado e projetado a aplicações com tensão de saída de 380 Vcc. Inicialmente, são estudadas as topologias clássicas de conversores, os modos de condução e as técnicas de elevação de tensão, estabelecendo a base para o projeto proposto. Em seguida, são dimensionados os componentes e avaliado o desempenho do conversor por meio de simulações no PSIM, tanto em condições ideais quanto acoplado a um módulo fotovoltaico. Os resultados apresentaram elevada concordância entre os valores analíticos e simulados para as tensões, com diferenças inferiores a 1 V, enquanto as discrepâncias observadas nas correntes foram compatíveis com a dinâmica de comutação. A implementação do MPPT, baseada na técnica *Perturb and observe* (P&O), aumentou significativamente a potência extraída sob irradiâncias de 800 W/m² e 500 W/m², recuperando até 229 W em relação à operação com ciclo fixo e proporcionando resposta rápida às variações de irradiância. Assim, o conversor proposto demonstrou elevado desempenho, maior aproveitamento energético e viabilidade para integração em sistemas fotovoltaicos de médio porte.

Palavras-chave: Conversores CC-CC. SEPIC Modificado. MPPT. Sistemas Fotovoltaicos. Simulação.

RESUMEN

El uso cada vez mayor de sistemas fotovoltaicos exige convertidores CC-CC capaces de funcionar de manera eficiente ante variaciones de carga y de irradiación. Este trabajo presenta el modelado y la simulación de un convertidor SEPIC modificado con una célula multiplicadora de tensión y control de seguimiento del punto de máxima potencia (MPPT), diseñado y destinado a aplicaciones con una tensión de salida de 380 Vcc. En primer lugar, se estudian las topologías clásicas de los convertidores, los modos de conducción y las técnicas de elevación de tensión, sentando así las bases para el proyecto propuesto. A continuación, se dimensionan los componentes y se evalúa el rendimiento del convertidor mediante simulaciones en PSIM, tanto en condiciones ideales como acoplado a un módulo fotovoltaico. Los resultados mostraron una elevada concordancia entre los valores analíticos y los simulados para las tensiones, con diferencias inferiores a 1 V, mientras que las discrepancias observadas en las corrientes eran compatibles con la dinámica de conmutación. La implementación del MPPT, basada en la técnica *Perturb and Observe* (P&O), aumentó significativamente la potencia extraída con irradiaciones de 800 W/m² y 500 W/m², recuperando hasta 229 W en comparación con el funcionamiento con ciclo fijo y proporcionando una respuesta rápida a las variaciones de irradiación. De este modo, el convertidor propuesto demostró un elevado rendimiento, un mayor aprovechamiento energético y viabilidad para su integración en sistemas fotovoltaicos de tamaño medio.

Palabras clave: Convertidores CC-CC. SEPIC Modificado. MPPT. Sistemas Fotovoltaicos. Simulación.



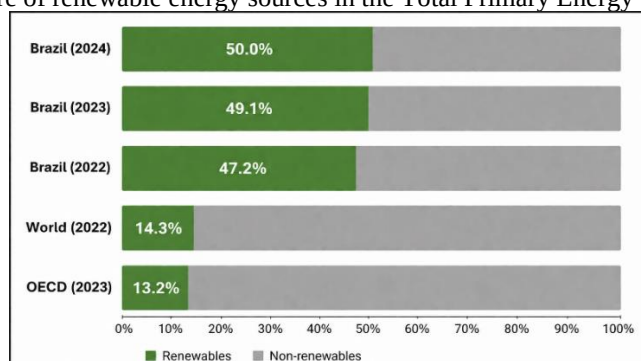
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INTRODUCTION

The growing concern over climate change, combined with the need to reduce dependence on fossil fuels, has driven the expansion of renewable energy sources worldwide. According to the REN21 report (2025), renewable sources accounted for more than 30% of the global electricity generation capacity in 2024, with solar photovoltaic (PV) energy standing out as the fastest-growing technology. This expansion has been driven by the decreasing cost of photovoltaic modules, improvements in system efficiency, and the implementation of public policies promoting distributed generation.

In Brazil, this energy transition has also progressed rapidly. According to the National Energy Balance (EPE, 2025), approximately 50% of the country's Total Primary Energy Supply (TPES) is derived from renewable sources, placing Brazil among the countries with the highest share of clean energy in its energy matrix, as shown in Fig. 1. Among these renewable sources, photovoltaic generation has experienced the most significant recent growth, mainly driven by the expansion of Distributed Microgeneration and Minigeneration (DMMG) systems, making it one of the most promising technologies for diversifying the Brazilian electricity matrix.

Figure 1. Share of renewable energy sources in the Total Primary Energy Supply (TPES).



Source: EPE (2025).

Alongside the expansion of photovoltaic energy, decentralized power generation

architectures, such as microgrids and nanogrids, have also gained increasing attention. These configurations provide greater operational flexibility, enhanced supply reliability, and improved utilization of renewable energy resources. In particular, direct current (DC) nanogrids enable the direct interconnection of photovoltaic panels, battery banks, and DC loads, thereby reducing the number of power conversion stages, minimizing energy losses, and improving overall system efficiency. These characteristics are particularly advantageous for residential, commercial, and remote-area applications (Alves et al., 2024).

Within this context, DC-DC converters play a fundamental role by conditioning the energy supplied by photovoltaic modules and adapting voltage and current levels to the requirements of the load or the DC bus. In addition to voltage regulation, these converters enable the integration of multiple energy sources and energy storage systems, making them widely employed in distributed generation, electric vehicles, embedded systems, and power electronics applications (Garcia, 2010; Tavares, 2019).

Among the various available topologies, the Single-Ended Primary Inductor Converter (SEPIC) stands out because of its ability to both step up and step down the output voltage without reversing its polarity, while also providing low input current ripple, a highly desirable characteristic in photovoltaic systems. However, applications requiring high voltage conversion ratios, such as 380-V DC buses, demand high duty cycles, which increase the electrical stress on semiconductor devices and reduce converter efficiency. To overcome this limitation, several high-gain techniques have been proposed in the literature, with particular emphasis on the use of Voltage Multiplier Cells (VMCs), which significantly increase the voltage gain without requiring extreme duty cycles, thereby reducing losses and improving the overall converter performance.

Another essential aspect for maximizing the efficiency of photovoltaic systems is the implementation of Maximum Power Point Tracking (MPPT) algorithms, which continuously adjust the operating point of the photovoltaic module to ensure maximum power extraction under varying irradiance and temperature conditions. Among the available techniques, the Perturb and Observe (P&O) algorithm stands out due to its simplicity, low computational cost, and widespread commercial adoption, making it one of the most commonly employed MPPT strategies in photovoltaic power converters (Dadkhah, 2023).

In this context, this paper proposes the modeling and simulation of a modified SEPIC converter incorporating an Up3 voltage multiplier cell and an MPPT controller based on the Perturb and Observe algorithm for photovoltaic applications with a 380-V DC output. First, the

theoretical background related to DC-DC converters, the conventional SEPIC converter, high-voltage-gain techniques, and the MPPT algorithm is presented. Subsequently, the design procedure of the converter components and the modeling of the proposed topology are carried out, and its performance is evaluated through computer simulations using the PSIM software.

Finally, the obtained results are compared with the analytical predictions to validate the proposed model and to assess the impact of the MPPT strategy on the extracted power, system stability, and energy conversion efficiency in photovoltaic applications.

Voltage Multiplier Cells (Capacitor-, Inductor-, and Diode-Based Cells)

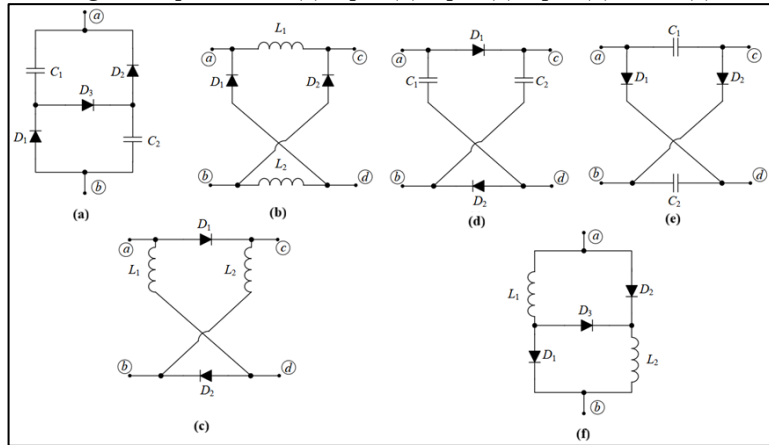
As previously discussed, photovoltaic applications employing high-voltage DC buses require converters capable of achieving high voltage conversion ratios without compromising efficiency. Although conventional converters, such as the Boost, Buck-Boost, Ćuk, SEPIC, and Zeta topologies, theoretically provide unlimited voltage gain as the duty cycle approaches unity, operating under this condition substantially increases conduction and switching losses, thereby reducing their practical efficiency (Schmitz, 2020).

To overcome this limitation, several high-voltage-gain techniques have been proposed, including switched-capacitor structures, voltage multiplier cells, switched inductors, magnetic coupling, and multistage converter architectures, all of which enable high voltage gains without requiring extreme duty cycles (Forouzesh et al., 2017). Among these approaches, Voltage Multiplier Cells (VMCs) have attracted considerable attention because they enable the development of high-gain converters while maintaining a relatively simple structure and eliminating the need for transformers.

Voltage Multiplier Cells consist of arrangements of capacitors, diodes, inductors, and/or switching devices that store and transfer energy throughout the switching cycle, thereby increasing the converter output voltage. According to Ioinovici (2012), these cells can be classified into step-up structures (Up1, Up2, and Up3) and step-down structures (Dw1, Dw2, and Dw3), as illustrated in Fig. 2(a)–(f), respectively. These cells can be integrated into the main DC-DC converter topologies to form hybrid high-gain configurations. Their main advantages include transformerless operation, reduced weight, high power density, and ease of integration with conventional converter topologies. However, the increased number of components may lead to higher conduction and switching losses. In this work, the Up3 voltage multiplier cell is integrated

into the SEPIC converter to achieve a higher voltage gain while maintaining high efficiency for photovoltaic applications.

Figura 2. Dw3 Voltage multiplier cells: (a) Up1, (b) Up2, (c) Up3, (d) Dw1, (e) Dw2, and (f) Dw3.

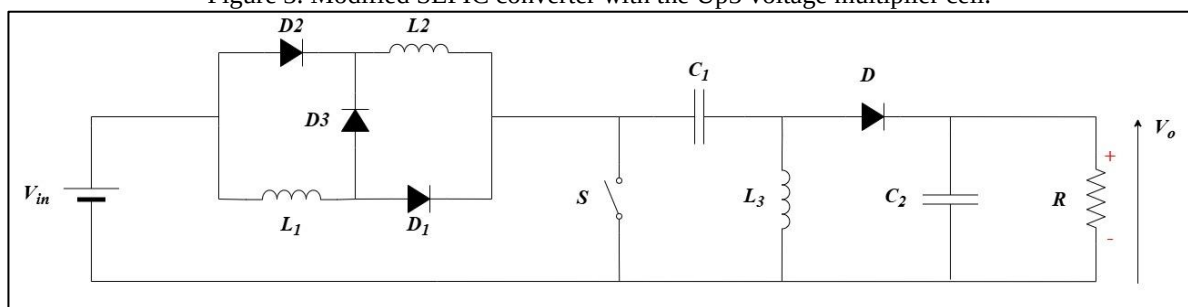


Source: Adapted from Ioinovici (2012).

QUALITATIVE ANALYSIS

Based on the theoretical background presented in the previous section, a modified SEPIC converter incorporating an Up3 voltage multiplier cell is proposed, as shown in Fig. 3. The insertion of the Up3 cell replaces the input inductor of the conventional SEPIC converter by adding two inductors and three diodes to the topology. This modification significantly increases the voltage conversion ratio, enabling output voltages close to 380 VDC to be achieved with lower duty cycles than those required by the conventional SEPIC converter.

Figure 3. Modified SEPIC converter with the Up3 voltage multiplier cell.

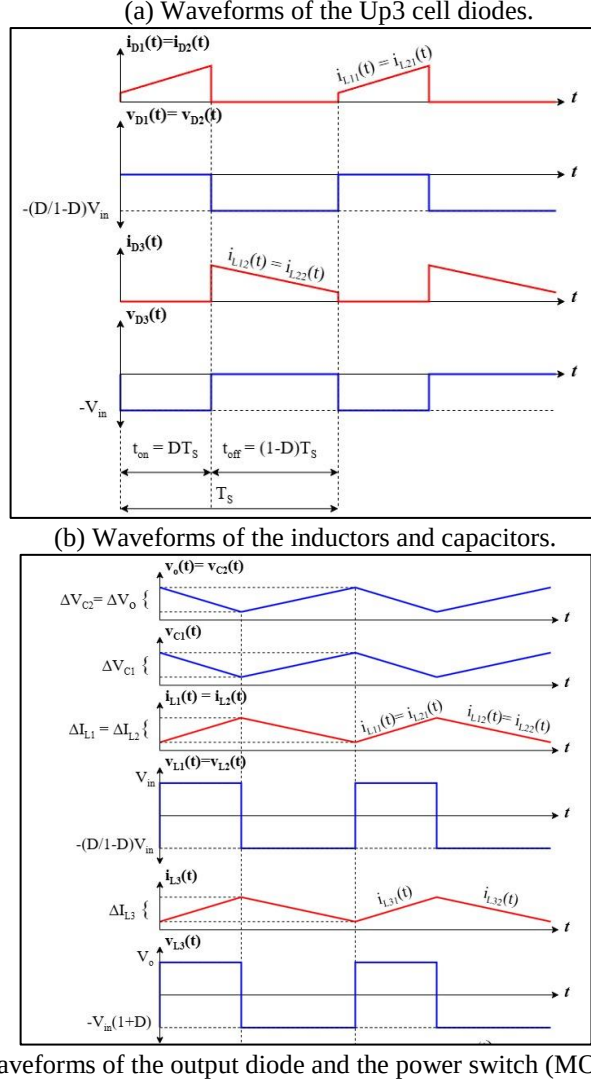


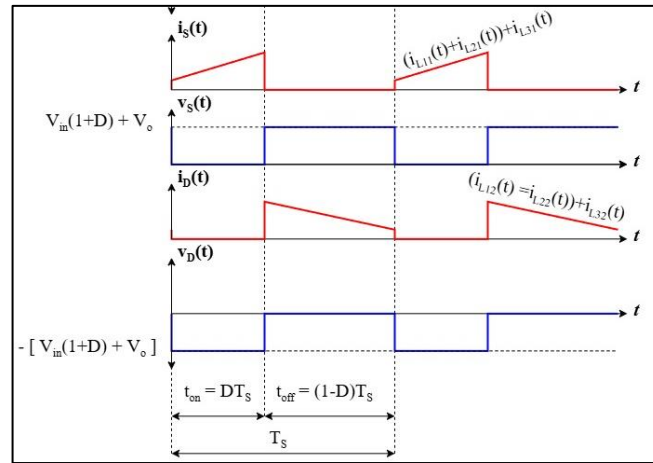
Source: Author (2026).

For the converter analysis, the following assumptions are adopted: operation in Continuous Conduction Mode (CCM) under steady-state conditions, ideal components, and

negligible voltage ripple across the capacitors. Under these assumptions, the converter operates in two switching stages during each switching period, whose main voltage and current waveforms are illustrated in Fig. 4(a) – (c).

Figure 4. Theoretical waveforms of the SEPIC-Up3 converter operating in CCM.





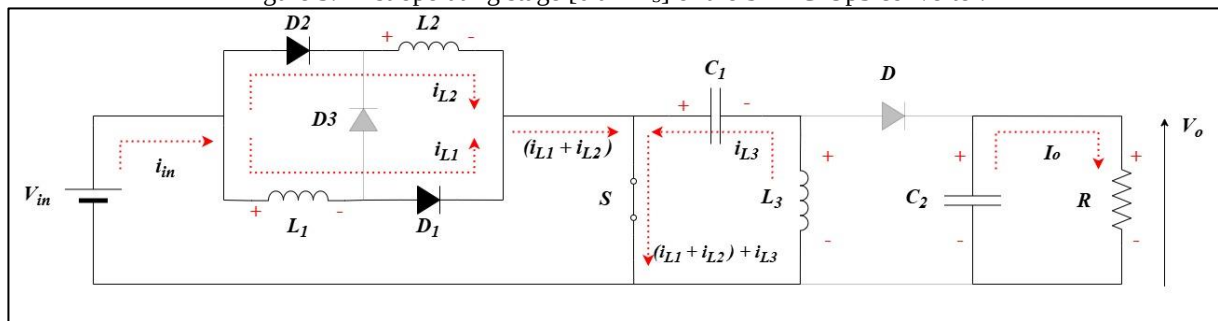
Source: Author (2026).

QUANTITATIVE ANALYSIS

First Operating Stage ($0 - DT_s$)

During the interval $0 \leq t \leq DT_s$, illustrated in Fig. 5, switch S remains turned on while the output diode is reverse-biased. Diodes D_1 and D_2 conduct, whereas D_3 remains reverse-biased, allowing inductors L_1 and L_2 to be charged in parallel from the input voltage V_{in} . Simultaneously, the coupling capacitor C_1 stores energy, while the output capacitor C_2 supplies the load.

Figure 5. First operating stage $[0 \text{ à } DT_s]$ of the SEPIC-Up3 converter.



Source: Author (2026).

The inductor voltages during this interval are given

$$V_{L1} = V_{L2} = V_{in} \quad (1)$$

$$V_{L3} = V_{C1} \quad (2)$$

Since $L_1 = L_2$, the equivalent parallel inductance is defined as

$$L_{eq} = \frac{L_{1,2}}{2} \quad (3)$$

Applying the fundamental inductor equation,

$$v_L(t) = L \frac{di_L(t)}{dt} \quad (4)$$

the inductor current ripples are obtained as

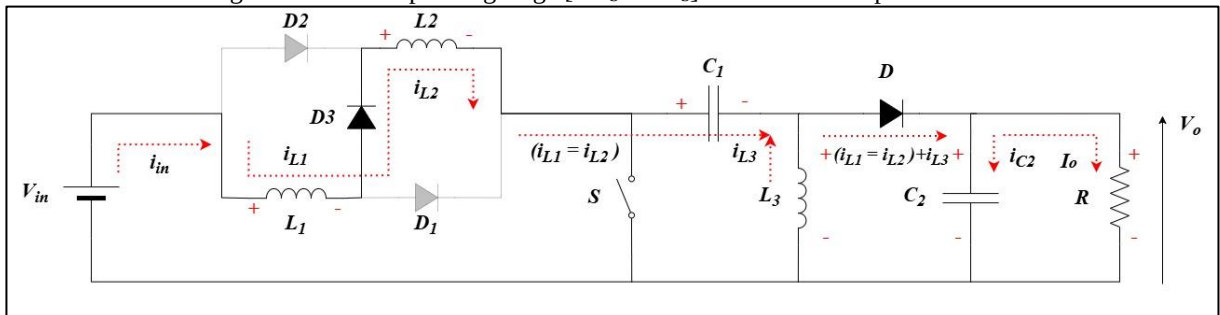
$$\Delta I_{Leq} = \frac{DV_{in}}{f_s L_{eq}} \quad (5)$$

$$\Delta I_{L3} = \frac{DV_{C1}}{f_s L_3} \quad (6)$$

Second Operating Stage ($DT_s - T_s$)

During the second operating stage, shown in Fig. 6, switch S is turned off and the output diode becomes forward-biased. Under this condition, the energy stored in inductors L_1 , L_2 and capacitor C_1 is transferred to inductor L_3 and the load, while capacitor C_2 is recharged to maintain the output voltage.

Figure 6. Second operating stage [DT_s 0 à T_s] of the SEPIC-Up3 converter.



Source: Author (2026).

Applying Kirchhoff's Voltage Law (KVL) yields

$$V_{Leq} = \frac{V_{in} - V_{C1} - V_o}{2} \quad (7)$$

$$V_{L3} = V_o \quad (8)$$

The current ripples during the off-state interval are

$$\Delta I_{Leq} = \frac{(1-D)(V_{in} - V_{C1} - V_o)}{2f_s L_{eq}} \quad (9)$$

$$\Delta I_{L3} = \frac{(1-D)V_o}{f_s L_3} \quad (10)$$

Voltage Conversion Ratio

The voltage conversion ratio of the converter is obtained by applying the volt-second balance principle to the inductors, considering that the average voltage across each inductor is zero under steady-state conditions.

For the equivalent inductor L_{eq}

$$V_{Leq(méd)} = \frac{1}{T_s} \left[\int_0^{t_{on}=DT_s} (V_{in}) dt + \int_{t_{on}=DT_s}^{T_s} \frac{(V_{in} - V_{C1} - V_o)}{2} dt \right] = 0 \quad (11)$$

which results in

$$V_{C1} = \frac{V_{in}(1+D) - V_o(1-D)}{(1-D)} \quad (12)$$

For inductor L_3 ,

$$V_{L3(méd)} = \frac{1}{T_s} \left[\int_0^{t_{on}=DT_s} (V_{C1}) dt + \int_{t_{on}=DT_s}^{T_s} (-V_o) dt \right] = 0 \quad (13)$$

resulting in

$$V_{C1} = \frac{V_o(1-D)}{D} \quad (14)$$

By equating the two expressions for V_{C1} , the converter voltage conversion ratio is obtained as:

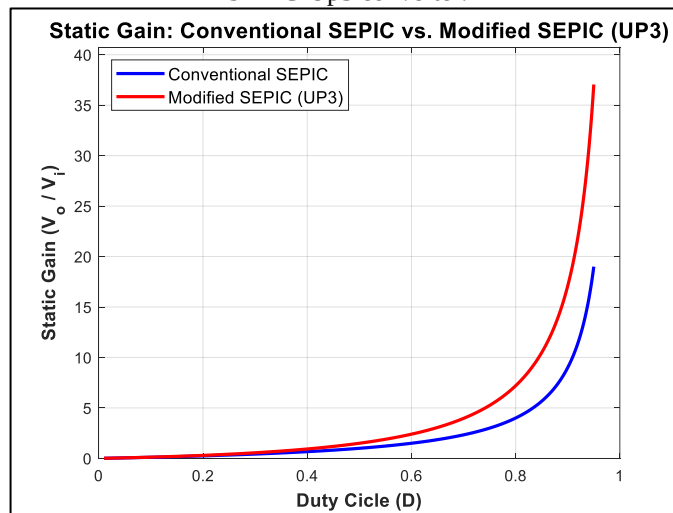
$$G = \frac{V_o}{V_{in}} = \frac{I_{in}}{I_o} = \frac{(1+D)D}{(1-D)} \quad (15)$$

Fig. 7 compares the voltage conversion ratio of the conventional SEPIC converter with that of the proposed SEPIC-Up3 topology.

Similarly, to the conventional Buck-Boost, Ćuk, Zeta, and SEPIC converters, (15) indicates that the proposed converter exhibits both step-down and step-up operating characteristics:

- $D < 0,5 \rightarrow V_o < V_{in}$ (step-down operation);
- $D = 0,5 \rightarrow V_o = V_{in}$;
- $D > 0,5 \rightarrow V_o > V_{in}$ (step-up operation).

Figure 7. Comparison between the voltage conversion ratio of the conventional SEPIC converter and the proposed SEPIC-Up3 converter.



Source: Author (2026).

It can be observed that the incorporation of the Up3 voltage multiplier cell significantly enhances the voltage conversion ratio, particularly for duty cycles above 0.5, allowing high output voltages to be achieved with lower duty-cycle values. This feature reduces the electrical stress on semiconductor devices and contributes to improving converter efficiency in high-gain photovoltaic applications.

Summary of the Converter Equations

Table 1 summarizes the main average voltage and current equations for the modified SEPIC converter incorporating the Up3 voltage multiplier cell.

Table 1. Average voltages and currents of the SEPIC-Up3 converter.

Component	Average Voltage (V)	Average Current (A)
V_{in}	$\frac{(1-D)V_o}{(1+D)D}$	$\frac{(1+D)DI_o}{(1-D)}$
R	$\frac{(1+D)DV_{in}}{(1-D)}$	$\frac{(1-D)I_o}{(1+D)D}$
L_1	0	$\frac{I_{in}}{2}$
L_2	0	$\frac{I_{in}}{2}$
L_3	0	I_o
C_1	$\frac{V_o(1-D)}{D}$	0
C_2	V_o	0
S	$V_{in}(1+D) + V_o$	$\frac{DI_o}{1-D}$
D	$-(V_{in}(1+D) + V_o)$	$I_{D(méd)} = I_o(2D^2 + D + 2)$
D_1	$-\left(\frac{D}{1-D}\right)V_{in}$	$D\frac{I_{in}}{2}$
D_2	$-\left(\frac{D}{1-D}\right)V_{in}$	$D\frac{I_{in}}{2}$
D_3	$-V_{in}$	$(1-D)\frac{I_{in}}{2}$

Source: Author (2026).

PROPOSED DESIGN

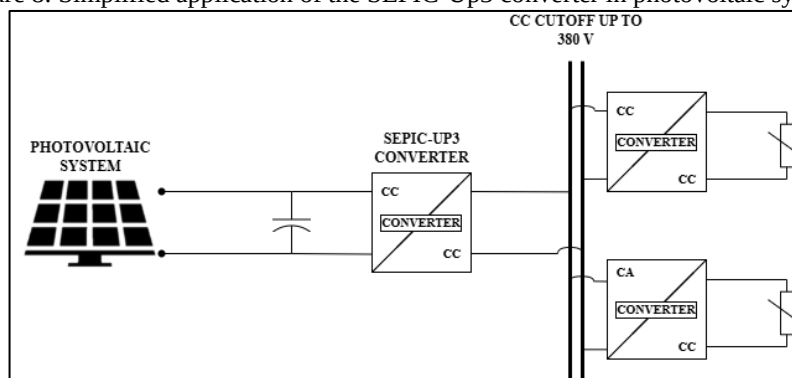
System Configuration and Simulation Setup

The design specifications were established based on the theoretical calculations of the proposed SEPIC-Up3 converter and validated through simulations performed in the PSIM software. In this work, the system consists of a photovoltaic (PV) array connected to the SEPIC-Up3 converter controlled by a Maximum Power Point Tracking (MPPT) algorithm, allowing the evaluation of the system behavior under irradiance variations and the controller's ability to maintain operation at the maximum power point.

Figure 8 presents the simplified configuration of the proposed application, in which the converter boosts the voltage supplied by the photovoltaic array to approximately **380 VDC**,

providing power to a DC bus.

Figure 8. Simplified application of the SEPIC-Up3 converter in photovoltaic systems.



Source: Author (2026).

The theoretical voltage and current waveforms used as references for validating the proposed model were presented in the previous section, allowing a comparison between the analytical predictions and the simulation results.

Converter Design Parameters

The converter was designed under ideal operating conditions by neglecting component losses, thus assuming that the input power is equal to the output power. The main design specifications adopted in this study are summarized in Table 2.

Table 2. Converter design specifications.

Converter Parameter	Value
Input voltage	84,6 V
Output voltage	380 V
Maximum output power	1140 W
System efficiency	100%

Source: Author (2026).

Based on these specifications, the duty cycle, voltage conversion ratio, and electrical parameters of the converter were calculated, as summarized in Table 3.

Electrical Components

The converter components were designed to ensure operation in Continuous Conduction

Mode (CCM). Simulations performed using an ideal voltage source employed the calculated theoretical values of the inductors and capacitors, enabling validation of the analytical model.

For the simulations involving the photovoltaic module, commercially available capacitors were adopted, using a 47 μF coupling capacitor and a 100 μF output capacitor. These values are compatible with the converter voltage ratings and are readily available in the commercial market. The switching frequency and all converter operating parameters were kept unchanged throughout all simulations.

Table 3. Main electrical parameters of the SEPIC-Up3 converter.

Converter Parameter	Value
Input voltage	$V_{in} = 84,6 \text{ V}$
Output voltage	$V_o = 380 \text{ V}$
Input current	$I_{in} = 13,48 \text{ A}$
Output current	$I_o = 3,00 \text{ V}$
Converter efficiency	100%
Load at maximum power	$R = 126,62 \Omega$
Voltage conversion ratio	$G = 4,49$
Duty cycle	$D = 0,723$
Input voltage ripple (1%)	$\Delta V_{in} = 0,85 \text{ V}$
Output voltage ripple (1%)	$\Delta V_o = 3.8 \text{ V}$
Input current ripple (10%)	$\Delta I_{in} = 0,67 \text{ A}$
Output current ripple (10%)	$\Delta I_o = 0,15 \text{ A}$
Coupling capacitor	$C_1 = 64,1 \mu\text{F}$
Output capacitor	$C_2 = 24,58 \mu\text{F}$
Inductors 1 and 2	$L_1 = L_2 = 2,27 \text{ mH}$
Inductor 3	$L_3 = 8,78 \text{ mH}$

Source: Author (2026).

Photovoltaic Module Parameters

To supply the converter, two commercial RM-570W-182M/144TB photovoltaic modules connected in series were considered, providing approximately 84.6 V under maximum power conditions. The electrical characteristics of the PV modules were directly implemented in the physical model available in PSIM using the manufacturer's datasheet parameters.

Although minor discrepancies may arise due to the software's internal modeling procedures, the simulated output power remained close to the nominal array power (1140 W), which is adequate for validating the proposed converter. Table 4 summarizes the main electrical parameters of the photovoltaic array used in the simulations.

Table 4. Electrical parameters of the RM-570W-182M/144TB photovoltaic module.

Parameter	Value
Number of cells	144
Rated power, P_{max}	1140 W
Voltage at maximum power, V_{mpp}	84,58 V
Current at maximum power, I_{mpp}	13,48 A
Open-circuit voltage, V_{oc}	102,14 V
Short-circuit current, I_{sc}	14,25 A
Temperature coefficient of V_{oc}	-0,25 %/°C
Temperature coefficient of I_{sc}	0,045 %/°C
Temperature coefficient of P_{max}	-0,29 %/°C
Module efficiency	22,06 %

Source: Author (2026).

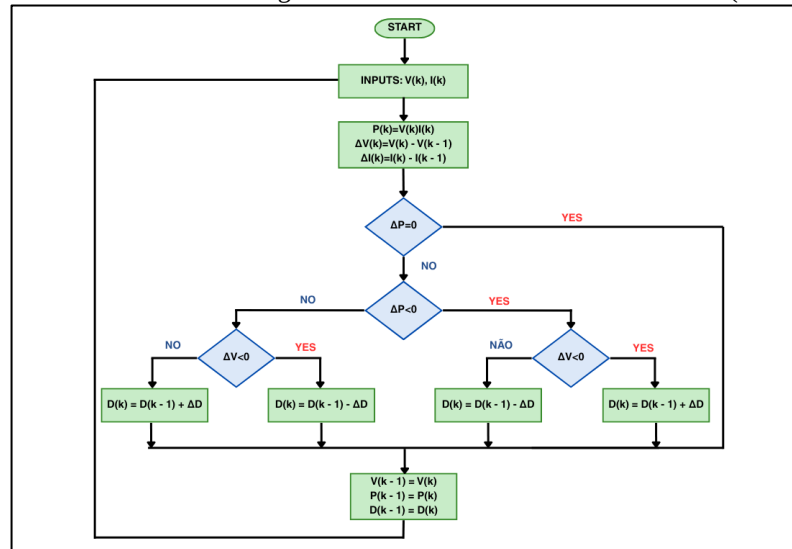
MPPT Control

To maximize the energy extracted from the photovoltaic array, a Maximum Power Point Tracking (MPPT) algorithm based on the Perturb and Observe (P&O) technique was implemented.

The algorithm continuously calculates the instantaneous power of the photovoltaic array from the measured voltage and current values. The current power is then compared with the value obtained in the previous iteration. If the output power increases, the algorithm maintains the direction of the perturbation applied to the duty cycle; otherwise, the perturbation direction is reversed, driving the operating point back toward the maximum power point (Ibrahim, 2023). The perturbation magnitude is determined by a predefined step size, which represents a trade-off between dynamic response speed and steady-state oscillation reduction.

The duty-cycle reference generated by the MPPT algorithm is converted into a PWM signal through comparison with a fixed-frequency triangular carrier waveform, thereby controlling the conduction interval of the converter semiconductor switch. The simplified flowchart of the P&O algorithm implemented in this work is presented in Fig. 9.

Figure 9. Flowchart of the MPPT algorithm based on the Perturb and Observe (P&O) technique.



Source: Author (2026).

RESULTS AND SIMULATIONS

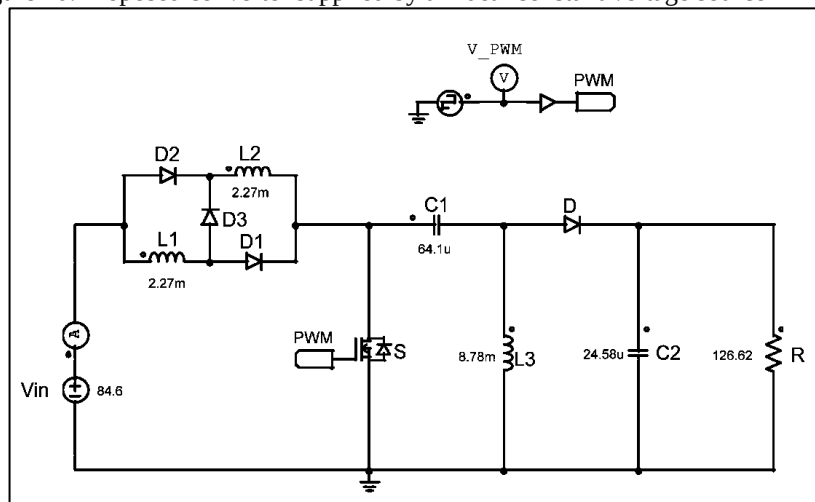
Initially, the proposed SEPIC-Up3 converter was validated under ideal operating conditions to verify the agreement between the developed analytical model and the waveforms obtained through simulation. Subsequently, simulations were carried out considering a photovoltaic power source under two operating conditions: fixed duty cycle and MPPT-controlled operation. Although both configurations were evaluated, the discussion presented in this paper focuses on the complete system—composed of the photovoltaic array, the SEPIC-Up3 converter, and the MPPT controller—as it represents the intended application of the proposed topology.

Converter Validation

As a first validation step, the converter was simulated in PSIM using an ideal 84.6 V DC voltage source, as shown in Fig. 10, allowing the operating principle of the proposed topology to be verified before its integration with the photovoltaic system. The PWM signal shown in Fig. 10 was generated using a square-wave source configured with a 1V peak amplitude, 40 kHz switching frequency, and 0.723 duty cycle. The probe labeled V_PWM was used to monitor the generated PWM voltage waveform and assist in the analysis of the converter operating waveforms.

The simulated waveforms are presented in Fig. 11 (formerly Fig. 26), including the PWM signal as well as the voltages and currents of the inductors, diodes, capacitors, and semiconductor switch.

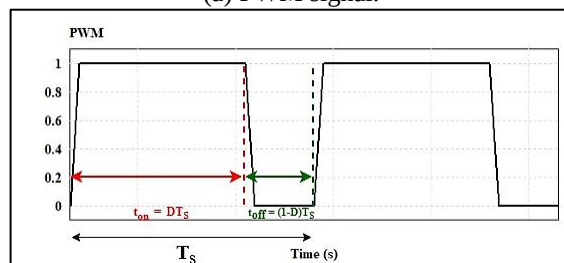
Figure 10. Proposed converter supplied by an ideal constant voltage source in PSIM.



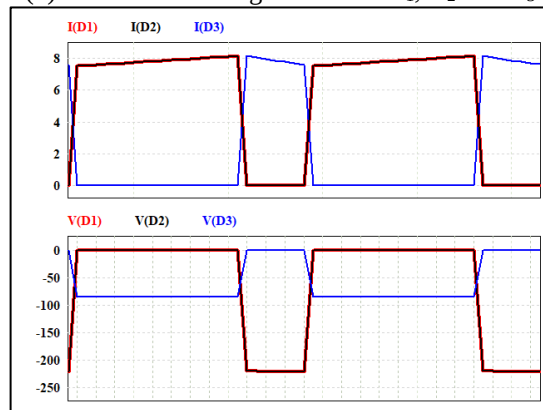
Source: Author (2026).

Figura 11. Simulated waveforms of the SEPIC-Up3 converter operating in CCM.

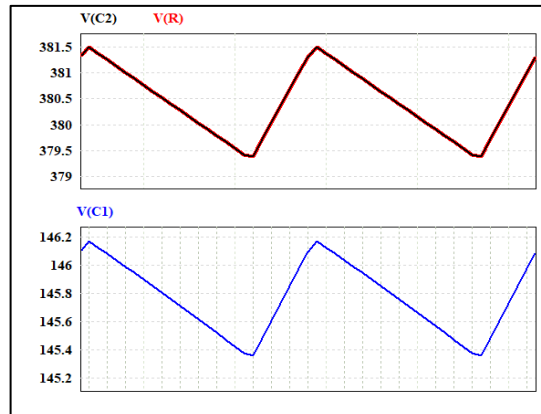
(a) PWM signal.



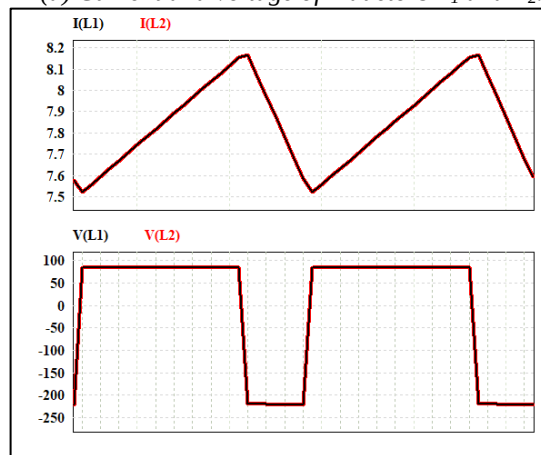
(b) Current and voltage of diodes D1, D2 and D3.



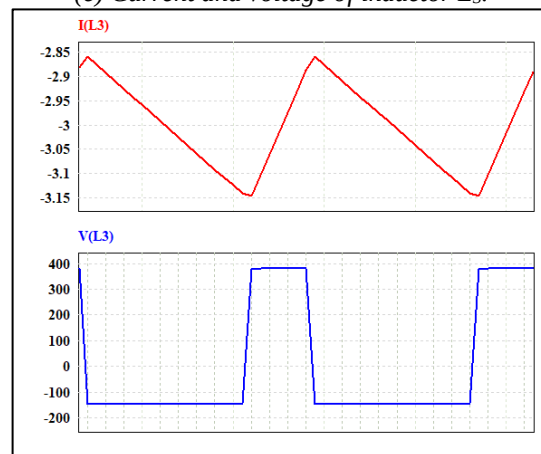
(c) Voltages across capacitors C1, C2 and VR (Vo).



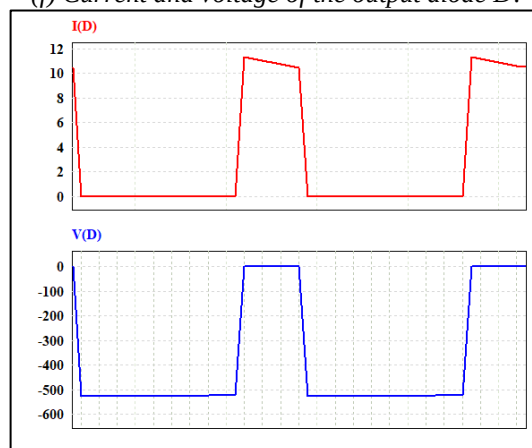
(d) Current and voltage of inductors L_1 and L_2 .



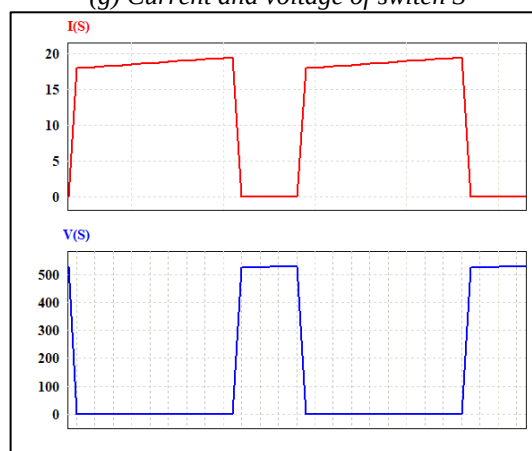
(e) Current and voltage of inductor L_3 .



(f) Current and voltage of the output diode D .



(g) Current and voltage of switch S



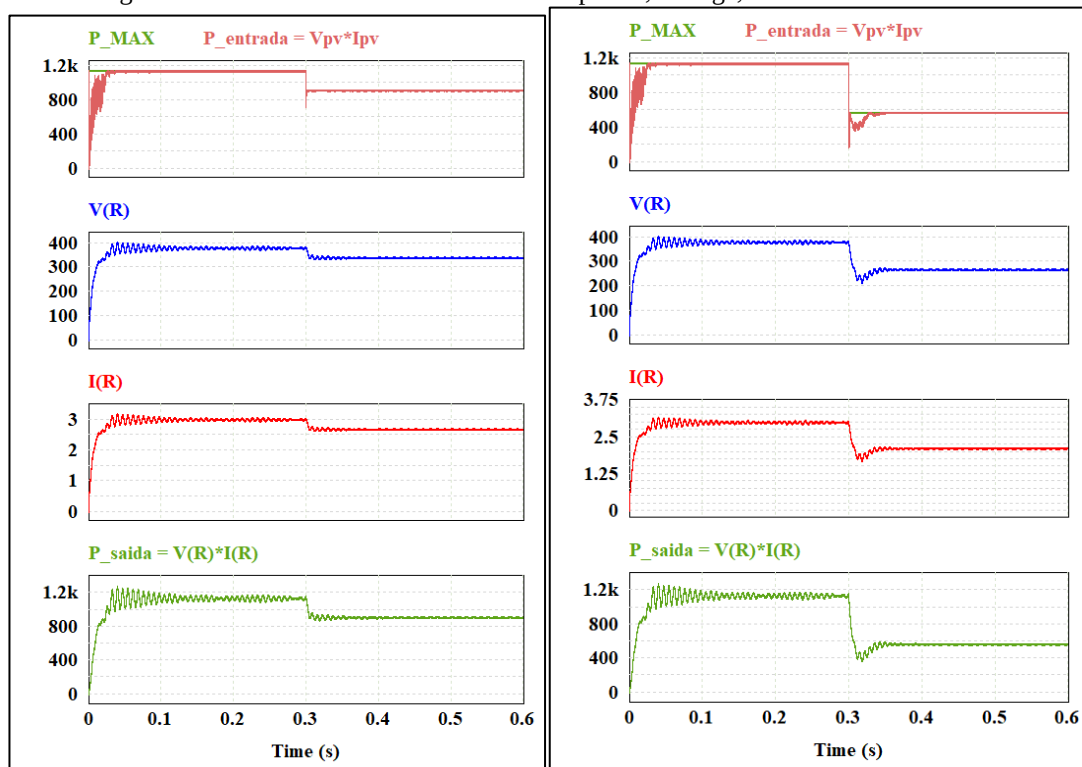
Source: Author (2026).

The simulated waveforms closely match the theoretical analysis presented in the previous section, confirming the converter operation in Continuous Conduction Mode (CCM). The inductor currents remained continuous throughout the entire switching period, while the voltages across the capacitors and the load remained nearly constant, exhibiting only small switching-induced ripple. Likewise, the diodes and the power switch operated with conduction and blocking intervals consistent with the expected operating stages of the converter.

The validity of the analytical model is further confirmed by the average values presented in Table 5, which compares the theoretical predictions with the simulation results. The voltage values differed by less than 1 V from the calculated values, whereas the small discrepancies observed in the internal currents are mainly attributed to the numerical approximations of the simulator and to the inherent ripple of the converter. Therefore, the obtained results validate both the analytical modeling and the implementation of the proposed converter topology.

The system performance was evaluated under two irradiance transition conditions: $1000 \rightarrow 800 \text{ W/m}^2$ and $1000 \rightarrow 500 \text{ W/m}^2$. The corresponding voltage, current, and power waveforms are presented in Fig. 13(a) and Fig. 13(b), while the corresponding average values are summarized in Table 6.

Figure 13. Photovoltaic module with MPPT: power, voltage, and current waveforms.



(a) Irradiance transition from 1000 to 800 W/m^2 (b) Irradiance transition from 1000 to 500 W/m^2

Source: Author (2026).

Figure 13 (a) shows that when the irradiance decreases from 1000 W/m^2 to 800 W/m^2 , the power supplied by the photovoltaic module drops instantaneously. Immediately afterward, the MPPT algorithm automatically adjusts the converter duty cycle, allowing the extracted power to rapidly converge to a value very close to the new maximum available power. During this transient, small oscillations appear in the output voltage and current before the system quickly reaches a new steady-state operating condition.

A similar behavior is observed in Fig. 13(b), corresponding to the irradiance transition from 1000 W/m^2 to 500 W/m^2 . Although the reduction in the available power is considerably greater, the controller successfully readjusts the duty cycle, enabling the converter to operate close to the new maximum power point. The small oscillations observed in the power, voltage, and current waveforms are inherent to the operation of the MPPT algorithm and demonstrate its

continuous search for the optimum operating point.

Table 6. Average simulation results of the proposed converter supplied by a photovoltaic array with MPPT.

Parameter	Solar irradiance (W/m ²)				
	1000	800	500	1000-800	1000-500
P_{MAX}	1135.03 W	908.03 W	563.46 W	1015.03 W	849.24 W
$V_{PV} * I_{PV} \approx$ $V_R * I_R$	1105.01 W	907.14 W	552.80 W	1013.90 W	828.01 W
V_o	378.19 V	339.22 V	265.70 V	357.83 V	319.22 V
I_o	2.99 A	2.68 A	2.10 A	2.83 A	2.52 A

Source: Author (2026).

The average results presented in Table 6 further confirm this behavior. Under an irradiance level of 800 W/m², the converter extracted approximately 907 W, while the maximum available power was 908 W. For the 500 W/m² condition, the extracted power was approximately 553 W, compared with a reference maximum power of 563 W, demonstrating a high tracking efficiency. Furthermore, the output voltage and current remained higher than those obtained under fixed-duty-cycle operation, indicating a more efficient utilization of the energy available from the photovoltaic array.

These results demonstrate that the MPPT algorithm responds rapidly to irradiance variations by continuously adjusting the converter duty cycle and maintaining operation close to the photovoltaic module maximum power point, thereby improving the overall efficiency of the system.

Comparison Between Operating Strategies

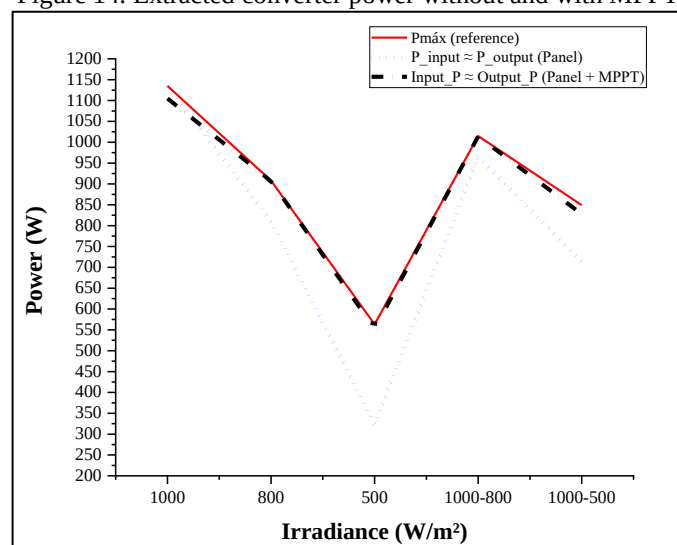
To quantify the benefits of the MPPT controller, Table 7 compares the performance of the converter operating under a fixed duty cycle with that obtained using MPPT control. The evolution of the extracted power is illustrated in Fig. 14.

Table 7. Comparison between the photovoltaic system operating with and without MPPT.

Solar intensity (W/m ²)	P_{MAX} (W)			$V_{PV} * I_{PV} \approx V_R * I_R$ (W)			V_o (V)			I_o (A)		
	Module			Module			Module			Module		
	Module	Module + MPPT	Gain	Module	Module + MPPT	Gain	Module	Module + MPPT	Gain	Module	Module + MPPT	Gain
1000	1135.03	1135.03	0	1134.23	1105.01	-29.22	378.93	378.19	-0.74	2.99	2.99	0
800	908.03	908.03	0	810.34	907.14	96.8	320.95	339.22	18.27	2.53	2.68	0.15
500	563.46	563.46	0	323.52	552.8	229.28	204.83	265.7	60.87	1.62	2.1	0.48
1000-800	1015.03	1015.03	0	965.94	1013.9	47.96	348.66	357.83	9.17	2.75	2.83	0.08
1000-500	849.24	849.24	0	712.77	828.01	115.24	288.28	319.22	30.94	2.28	2.52	0.24

Source: Author (2026).

Figure 14. Extracted converter power without and with MPPT.



Source: Author (2026).

It can be observed that both operating strategies exhibit similar performance under 1000 W/m², since the fixed duty cycle was originally designed for this operating condition. However, as the irradiance decreases, the fixed-duty-cycle converter operates progressively farther from the maximum power point, leading to a significant reduction in the extracted power.

With the automatic duty-cycle adjustment provided by the MPPT algorithm, the extracted power remains very close to the maximum available power under all irradiance conditions considered. The observed improvements reach approximately 97 W at 800 W/m² and 229 W at 500 W/m², accompanied by corresponding increases in the output voltage and current.

Therefore, the obtained results demonstrate that the integration of the photovoltaic array, the SEPIC-Up3 converter, and the MPPT controller provides improved energy harvesting capability and greater adaptability to irradiance variations, validating the proposed topology for photovoltaic power conversion applications.

CONCLUSION

This paper presented the development, modeling, and simulation of a modified SEPIC DC-DC converter incorporating an Up3 voltage multiplier cell for photovoltaic applications. The study provided a comprehensive understanding of the proposed topology and evaluated its performance under both ideal operating conditions and realistic photovoltaic operating scenarios.

The theoretical analysis established the basis for sizing the converter components and determining the main voltage and current stresses, resulting in a design capable of operating in Continuous Conduction Mode (CCM) while providing an output voltage close to 380 VDC. Simulations performed in PSIM validated the analytical model, with voltage deviations of less than 1 V between the calculated and simulated values. The small discrepancies observed in the internal currents were mainly attributed to the numerical discretization associated with the switching process implemented by the simulator and did not compromise the consistency of the obtained results.

When integrated with the photovoltaic module, the converter maintained stable operation under all analyzed operating conditions. The implementation of the Perturb and Observe (P&O) MPPT algorithm significantly improved the utilization of the available solar energy, recovering approximately 97 W under an irradiance level of 800 W/m² and approximately 229 W under 500 W/m². This improvement was reflected in higher output voltage and current levels while enabling rapid adaptation to irradiance variations, maintaining operation close to the photovoltaic module maximum power point.

Overall, the integration of the proposed SEPIC-Up3 converter, the photovoltaic array, and the MPPT controller demonstrated high efficiency, stable operation, and effective adaptation to varying environmental conditions, highlighting the potential of the proposed topology for high-gain photovoltaic applications requiring improved energy harvesting.

As future work, the following research directions are recommended: (i) investigating additional high-voltage-gain techniques to reduce the required duty cycle and improve overall converter efficiency; (ii) implementing PI-based or more advanced control strategies to regulate the output voltage; and (iii) developing an experimental prototype to validate the simulation results and evaluate the robustness of the proposed topology under real operating conditions.

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