

MODELING AND SIMULATION OF A MODIFIED ZETA DC-DC CONVERTER WITH MPPT CONTROL FOR PHOTOVOLTAIC SYSTEM APPLICATIONS

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

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

Nadson Daniel de Oliveira¹, Caellison Bezerra Morais², Randres Cides Lopes de Oliveira³, João Victor Praxedes Nunes⁴, Thiago Praxedes Amorim⁵, Rodrigo de Almeida Coelho⁶, Antônio Alisson Alencar Freitas⁷

DOI: 10.54899/dcs.v23i92.5547

Recibido: 16/05/2026 | Aceptado: 20/05/2026 | Publicación en línea: 09/07/2026.

ABSTRACT

This work addresses the development and evaluation of a modified Zeta DC-DC converter incorporating an Up2 voltage multiplier cell, intended for photovoltaic systems. The central issue lies in the need to boost the low voltage of photovoltaic panels to levels suitable for DC bus operation, while maintaining high efficiency even under irradiance variations. The justification stems from the growing adoption of solar generation and the demand for converters with higher static gain and better dynamic performance. Thus, the main objective of this study is to design, model, and simulate the proposed converter, analyzing its behavior under ideal conditions and in scenarios with and without MPPT. The methodology consisted of: mathematical modeling of the topology; sizing of inductors, capacitors, and semiconductor devices; implementation of the model in PSIM software; detailed modeling of the photovoltaic array; application of the maximum power point tracking technique based on the Perturb and Observe algorithm; and execution of two simulation scenarios: ideal DC source feeding the converter and photovoltaic array feeding the converter with MPPT. The main results show that the converter operates according to the theoretical model, presenting errors below 3% in the ideal scenario. With MPPT

¹ Bachelor's Degree in Electrical Engineering, Universidade Federal Rural do Semi-Árido (UFERSA), Caraúbas, Rio Grande do Norte, Brazil. E-mail: nadson.oliveira@alunos.ufersa.edu.br

² Bachelor of Science and Technology, Universidade Federal Rural do Semi-Árido (UFERSA), Caraúbas, Rio Grande do Norte, Brzsil. E-mail: caellison10@gmail.com Orcid: <https://orcid.org/0000-0002-6971-6061>

³ Bachelor of Science and Technology, Universidade Federal Rural do Semi-Árido (UFERSA), Caraúbas, Rio Grande do Norte, Brazil. E-mail: randreycides@gmail.com

⁴ Bachelor of Science and Technology, Universidade Federal Rural do Semi-Árido (UFERSA), Caraúbas, Rio Grande do Norte, Brazil. E-mail: victorpraxedes3.0@gmail.com

⁵ Undergraduate student in Science and Technology, Universidade Federal Rural do Semi-Árido (UFERSA), Caraúbas, Rio Grande do Norte, Brazil. E-mail: thiago.amorim@alunos.ufersa.edu.br

⁶ Ph.D. in Electrical Engineering, Universidade Federal de Campina Grande (UFCG), Caraúbas, Rio Grande do Norte, Brazil. E-mail: rodrigo.coelho@ufersa.edu.br Orcid: <https://orcid.org/0000-0002-3486-5307>

⁷ Ph.D. in Electrical Engineering, Universidade Federal do Ceará (UFC), Caraúbas, Rio Grande do Norte, Brazil. E-mail: alisson.freitas@ufersa.edu.br Orcid: <https://orcid.org/0000-0002-2484-0990>

enabled, the system extracted nearly all available power, reaching 550.91 W at the same irradiance level. The results confirm the efficiency of the modified topology and highlight the importance of MPPT control to maximize energy extraction in photovoltaic systems.

Keywords: DC-DC Converter. Modified Zeta. Up2 Cell. Photovoltaic Systems. MPPT.

RESUMO

O trabalho aborda o desenvolvimento e avaliação de um conversor CC-CC Zeta modificado com célula elevadora Up2, destinado a sistemas fotovoltaicos. A problemática central está na necessidade de elevar a tensão de painéis de baixa tensão para níveis adequados a barramentos CC, mantendo boa eficiência mesmo sob variações de irradiância. A justificativa decorre do crescimento da geração solar e da demanda por conversores de maior ganho estático e melhor desempenho dinâmico. Assim, o objetivo geral do estudo é projetar, modelar e simular o conversor proposto, analisando seu comportamento em condições ideais e em cenários com e sem MPPT. A metodologia consistiu em: modelagem matemática da topologia; dimensionamento de indutores, capacitores e semicondutores; implementação do modelo no software PSIM; modelagem detalhada do arranjo fotovoltaico; aplicação da técnica de rastreamento de máxima potência baseada no algoritmo Perturba e Observa; e realização de dois cenários de simulação: fonte CC ideal alimentando o conversor e arranjo fotovoltaico alimentando o conversor com MPPT. Os principais resultados demonstram que o conversor opera conforme o modelo teórico, apresentando erros inferiores a 3% no cenário ideal. Com o MPPT ativado, o sistema passou a extrair praticamente toda a potência disponível, alcançando 550,91 W no mesmo nível de irradiância. Os resultados comprovam a eficiência da topologia modificada e evidenciam a importância do controle MPPT para maximizar o aproveitamento energético em sistemas fotovoltaicos.

Palavras-chave: Conversor CC-CC. Zeta Modificado. Célula Up2. Sistemas Fotovoltaicos. MPPT.

RESUMEN

El trabajo aborda el desarrollo y la evaluación de un convertidor CC-CC Zeta modificado con celda elevadora Up2, destinado a sistemas fotovoltaicos. La problemática central radica en la necesidad de elevar la tensión de paneles de baja tensión hasta niveles adecuados para buses de corriente continua, manteniendo una buena eficiencia incluso ante variaciones de irradiancia. La justificación se deriva del crecimiento de la generación solar y de la demanda de convertidores con mayor ganancia estática y mejor desempeño dinámico. Así, el objetivo general del estudio es diseñar, modelar y simular el convertidor propuesto, analizando su comportamiento en condiciones ideales y en escenarios con y sin MPPT. La metodología consistió en: modelado matemático de la topología; dimensionamiento de inductores, capacitores y semiconductores; implementación del modelo en el software PSIM; modelado detallado del arreglo fotovoltaico; aplicación de la técnica de seguimiento del punto de máxima potencia basada en el algoritmo Perturbar y Observar; y realización de dos escenarios de simulación: una fuente CC ideal alimentando el convertidor y un arreglo fotovoltaico alimentando el convertidor con MPPT. Los principales resultados demuestran que el convertidor opera conforme al modelo teórico, presentando errores inferiores al 3 % en el escenario ideal. Con el MPPT activado, el sistema pasó a extraer prácticamente toda la potencia disponible, alcanzando 550,91 W para el mismo

nivel de irradiancia. Los resultados comprueban la eficiencia de la topología modificada y evidencian la importancia del control MPPT para maximizar el aprovechamiento energético en sistemas fotovoltaicos.

Palabras clave: Convertidor CC-CC. Zeta Modificado. Celda Up2. Sistemas Fotovoltáicos. MPPT.



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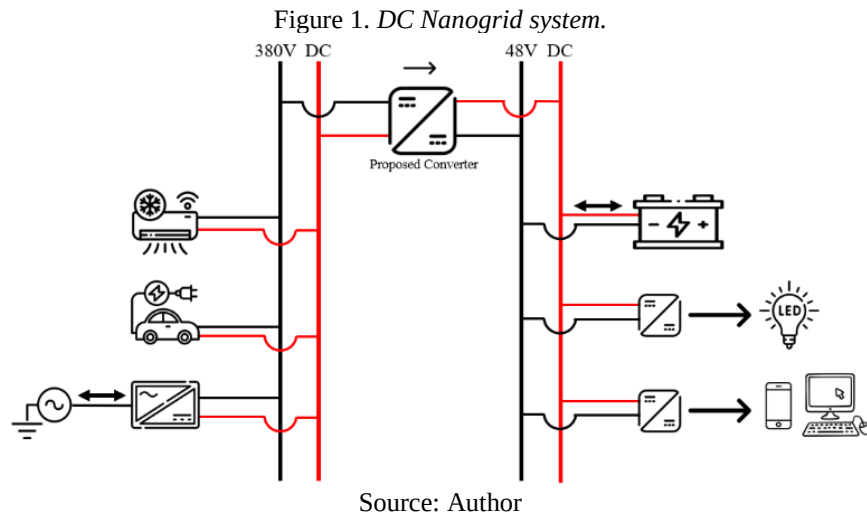
INTRODUCTION

The growing demand for clean and sustainable energy sources has driven the use of solar-based systems, requiring efficient solutions for converting and controlling the electrical energy generated. Since this energy is produced in direct current (DC) and with variable voltage levels, it is essential to use electronic converters capable of adapting the voltage to meet the needs of nanogrids, storage systems, and residential load feeding (Pontes, Silva, & Sá Junior, 2020).

DC nanogrids are establishing themselves as a promising alternative for homes and buildings in general, compared to conventional microgrids (Muthuvel, Daniel, & Yazhini, 2016). Their popularity is growing due to their simplicity of implementation in remote areas and urban environments, as well as their versatility in integrating different renewable sources into the same bus (Almasri *et al.*, 2020). In this context, power electronics play a central role in enabling the direct connection of photovoltaic generation to batteries and loads, allowing energy flow management and ensuring system stability.

However, applications focused on nanogrids often require high voltage gains and high efficiency, which demand modifications to conventional DC-DC converter topologies. To meet these needs, the use of gain cells emerges as an efficient alternative, capable of increasing static gain, reducing electrical stress on semiconductors, and improving overall system efficiency (Freitas *et al.*, 2022).

Figure 1 show a DC nanogrid system that employs a converter to process the energy generated by a photovoltaic panel, supplying it to the secondary household loads through a 380 V bus.



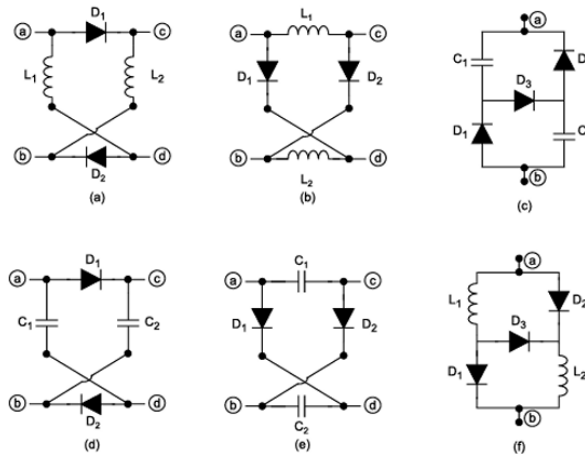
The system consists of a converter responsible for boosting the 48 V generated by the photovoltaic panel to 380 V, a battery bank for energy storage and for supplying the bus during periods of low irradiance, as well as equipment powered at 380 V, in addition to converters that step down the voltage for devices that operate at levels lower than the bus voltage (Vasconcelos Júnior *et al.*, 2025).

Thus, this work proposes the application of a gain cell in a non-isolated topology based on the Zeta converter, operating as a voltage booster, designed to process energy from photovoltaic panels and supply the necessary voltage to the DC nanogrid bus, ensuring reliable supply to residential loads.

Switched Capacitor/Inductor Cells

The voltage boost in DC-DC converters is essential in applications based on low-voltage sources, such as photovoltaic panels and battery banks. Among the available techniques, Voltage Multiplier Cells (VMCs) stand out as an efficient and relatively simple-to-implement solution (Souza *et al.*, 2024). These cells, presented in Ioinovici (2013), are incorporated into the converter structure with the aim of increasing the static gain without requiring transformers or high duty cycles, using combinations of diodes, capacitors, and inductors to multiply the output voltage and optimize the utilization of the energy stored during switching.

Figure 2. Voltage Multiplier Cells.

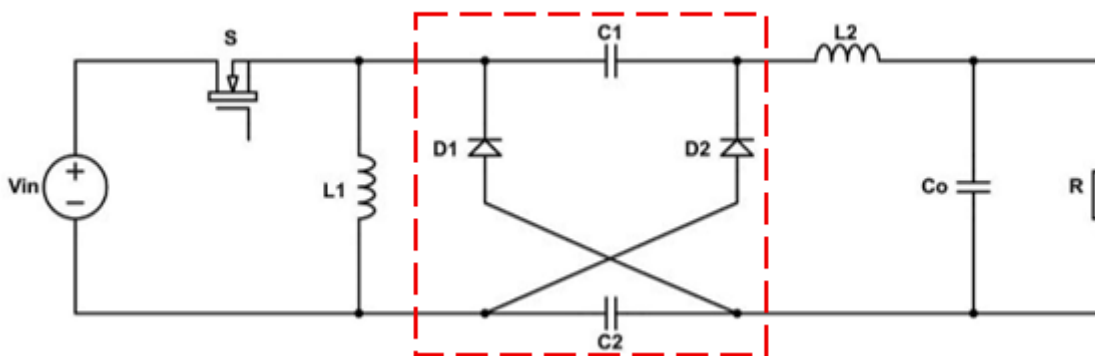


Source: Adapted from Ioinovic (2013).

QUALITATIVE ANALYSIS

Figure 3 shows the Zeta converter with a step-up 2 (Up2) cell. In this configuration, the diode and coupling capacitors from the classic topology are removed and replaced by the Up2 cell.

Figure 3. Zeta converter with Up2 Cell.



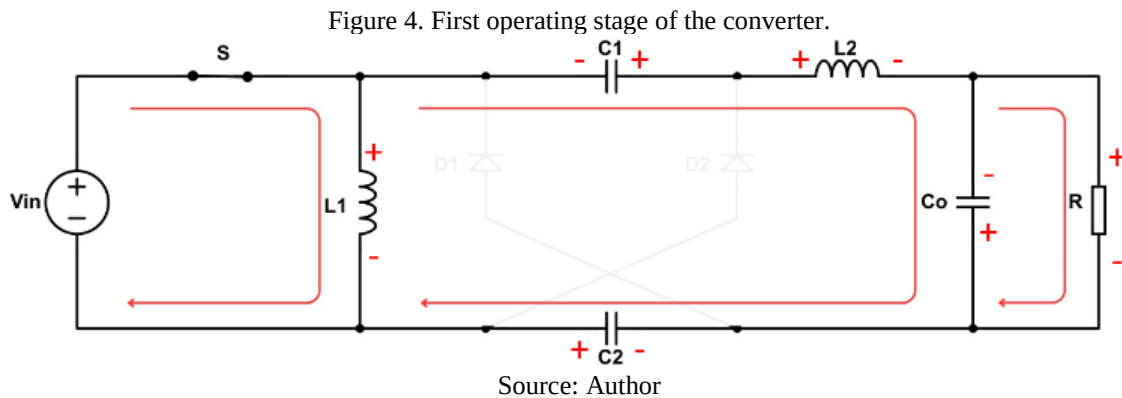
Source: Author

The topology consists of a DC voltage source, a switching switch S , two diodes $D1$ and $D2$ that are part of the cell, an input inductor $L1$, an output inductor $L2$, two capacitors $C1$ and $C2$ that make up the cell, an output capacitor C_o , and a load R .

For this analysis, the continuous conduction mode (CCM) was employed. The converter operates in two stages: the first, in which the inductors are charged, and the second, in which the capacitors are charged.

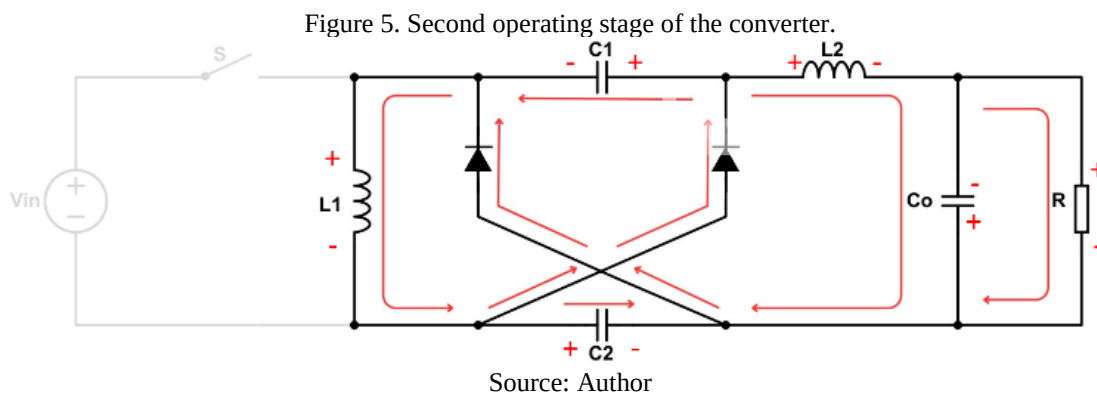
First Operating Stage

In the first operating stage, switch S is closed, as shown in Figure 4. In this stage, diodes D1 and D2 are disabled, as they are reverse-biased. The inductors store energy supplied by the DC source, while the capacitors discharge. This operating interval occurs during $0 \leq t \leq T_s$.



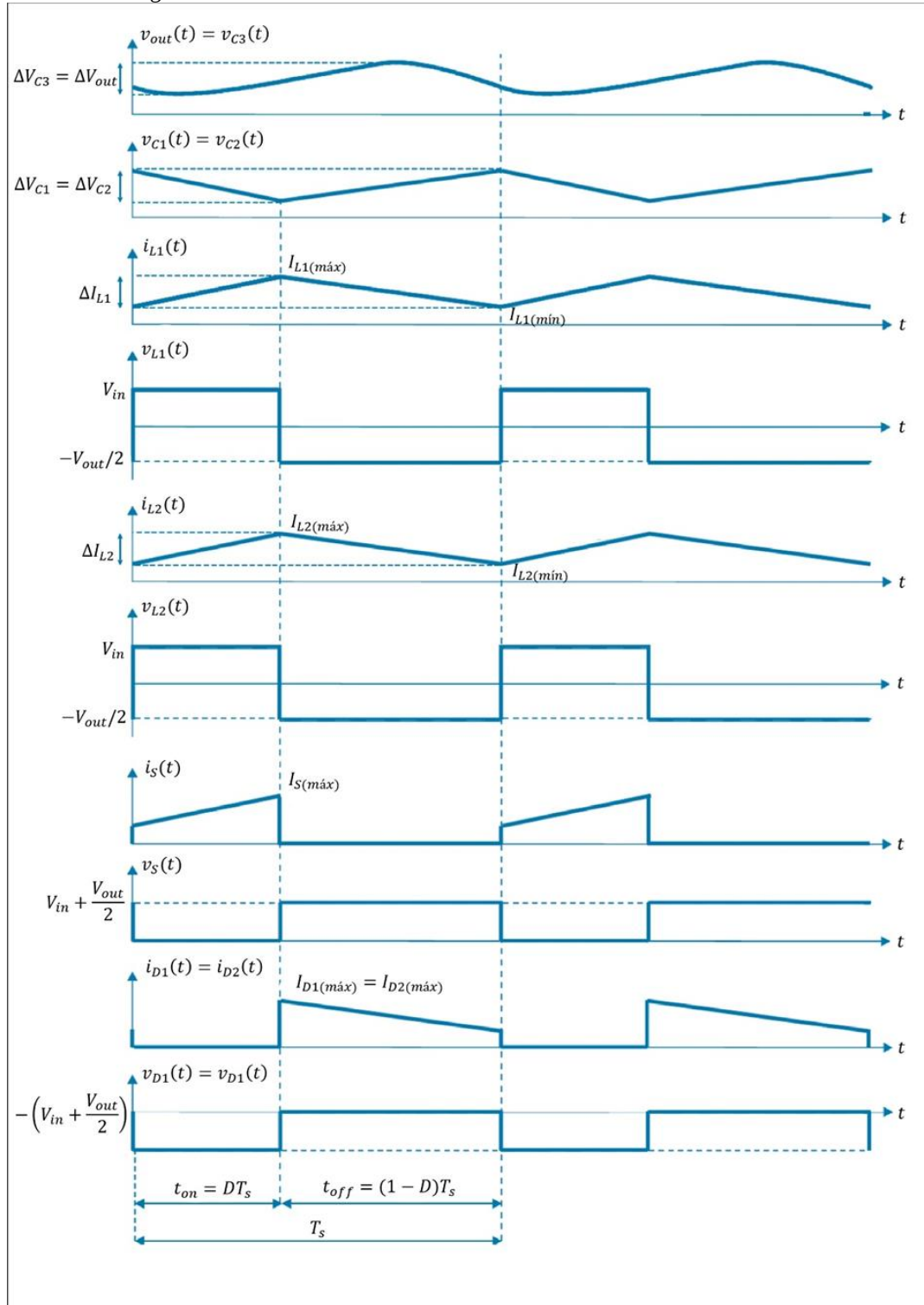
Second Operating Stage

In the second operating stage, shown in Figure 5, the switch S is open, the inductors are demagnetized and discharged, the energy stored in them during the previous stage is directed to the load, and the capacitors are charged.



In Figure 6 shown the theoretical waveforms of the modified Zeta converter.

Figure 6. Theoretical waveforms of the modified Zeta converter in CCM.



Source: Author

QUANTITATIVE ANALYSIS

Determination of the Static Gain

By analyzing Figure 4, it is possible to determine that:

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

By applying Kirchhoff's voltage law in the first operating stage, we obtain

$$-V_{C1} + V_{L2} + V_O - V_{C2} - V_{in} = 0, \quad (2)$$

and, isolating V_{L2} :

$$V_{L2} = V_{in} + V_{C1} + V_{C2} - V_O. \quad (3)$$

By analyzing Figure 5, it is possible to determine that:

$$V_{L1} = -V_{C1} = -V_{C2}. \quad (4)$$

Noting that

$$V_{C1} = V_{C2} = V_C. \quad (5)$$

By applying Kirchhoff's voltage law to the loop, we obtain

$$V_{L2} + V_O + V_{L1} = 0. \quad (6)$$

Substituting Equation (4) into (6):

$$V_{L2} + V_O - V_C = 0 \Rightarrow V_{L2} = V_C - V_O. \quad (7)$$

The static gain of a converter is defined as the ratio between the output voltage and the input voltage in steady state. By applying the steady-state condition, we have

$$V_{L1,med} = \frac{1}{T_s} \int_0^{T_s} V_{L1}(t) dt, \quad (8)$$

$$V_{L2,med} = \frac{1}{T_s} \int_0^{T_s} V_{L2}(t) dt. \quad (9)$$

Based on the analyses of the operating stages, with the switch closed and open, the expressions for the voltages across the inductors in each interval are known. For the inductor L_1 :

$$V_{in}D - V_C + V_C D = 0. \quad (10)$$

For the inductor L_2 :

$$V_{L2}D + V_{L2}(1 - D) = 0, \quad (11)$$

$$(V_{in} + 2V_C - V_O)D + (V_C - V_O)(1 - D) = 0, \quad (12)$$

$$V_C = \frac{V_O - V_{in}D}{1 + D}. \quad (13)$$

Applying Equation (13) to Equation (10):

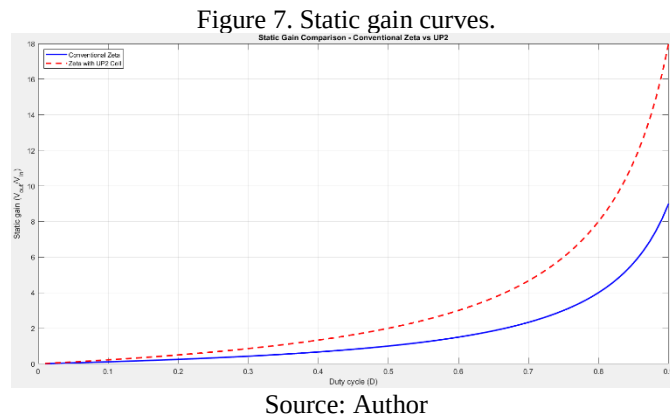
$$V_{in}D = \frac{V_O - V_O D - V_{in}D + V_{in}D^2}{1 + D}, \quad (14)$$

$$V_O(1 - D) = 2V_{in}D, \quad (15)$$

Thus, we arrive at the result:

$$\frac{V_O}{V_{in}} = \frac{2D}{1 - D}. \quad (16)$$

Equation (24) represents the static gain of the Zeta converter with the Up2 cell. This analysis is important because it shows that, with this modification to the classic topology, the converter exhibits a static gain twice as high. Figure 7 presents a comparison between the static gain of the classic Zeta converter and the gain of the converter with the Up2 cell.

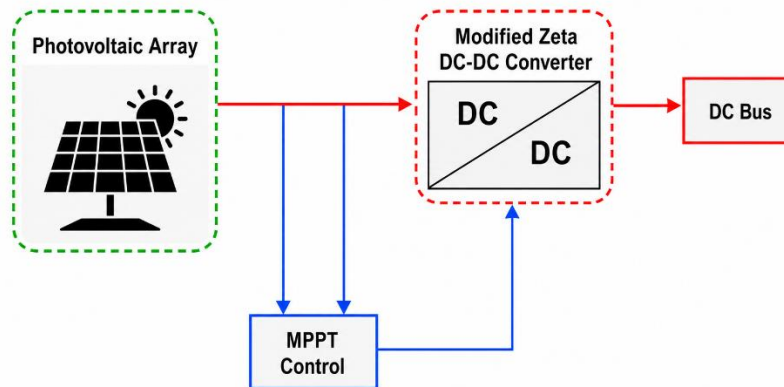


The representation above merely confirms the result obtained in the static gain calculation, where it was identified that with the step-up 2 cell, the Zeta converter's gain becomes twice as high as that of its classic topology.

PROPOSED SYSTEM

Figure 8 shows the simplified block diagram of the proposed system, consisting of three main parts: the photovoltaic panel array, the modified Zeta DC–DC converter, and the MPPT control system.

Figure 8. Simplified block diagram of the proposed system.



Source: Author

The photovoltaic array is responsible for converting solar energy into direct-current electrical energy, with its voltage and current varying according to environmental conditions, such as irradiance and temperature. This energy is applied to the input of the modified Zeta converter, whose function is to step up the voltage generated by the array to the level required to supply the DC bus, ensuring a stable and suitable voltage for applications in distributed generation systems, nanogrids, or microgrids.

The MPPT control operates by continuously tracking the maximum power point of the photovoltaic array. To this end, the system measures the panel voltage and current, calculates the instantaneous power, and adjusts the duty cycle (D) of the Zeta converter to maintain operation at the optimal energy extraction point. This action is essential to maximize the system efficiency, since the electrical characteristics of the panels vary according to environmental conditions.

In the proposed system, the datasheet parameters of the RM-570W-182M/144TB photovoltaic panel model will be used in the simulations. For the tests, the studied system was considered two panels connected in series. Table 1 shows the simulated parameters, already considering the series arrangement for values for an irradiance of 1000 W/m², module temperature of 25 °C, and AM = 1.5.

Table 1. Parameters of the RM-570W-182M/144TB photovoltaic model

Parameters	Value
Number of cells	144
Rated power – P _{max} (W)	1140
Maximum power voltage – V _{mpp} (V)	84.58
Maximum power current – I _{mpp} (A)	13.48
Open-circuit voltage – V _{oc} (V)	102.14
Short-circuit current – I _{sc} (A)	14.25
Temperature coefficient of V _{oc} (%/°C)	-0.25
Temperature coefficient of I _{sc} (%/°C)	0.045
Temperature coefficient of P _{max} (%/°C)	-0.29
Module efficiency (%)	22.06

Source: Author

Since the electrical parameters of photovoltaic modules constantly vary as a function of environmental conditions, and considering that PV cells present relatively low efficiency, it becomes necessary to apply control techniques capable of extracting the maximum instantaneous power available from the panel. This process is known as Maximum Power Point Tracking (MPPT).

Among the main methods reported in the literature are Constant Voltage, Open-Circuit Voltage, Pulsed Short-Circuit Current, Perturb and Observe (P&O), Incremental Conductance (IncCond), Hill Climbing, Beta Method, Ripple Correlation Control, as well as more modern approaches based on artificial intelligence, among others.

Among these techniques, the Perturb and Observe (P&O) and Incremental Conductance (IncCond) methods stand out because they combine good energy efficiency, simple implementation, and low computational cost, being widely applied in DC–DC converters integrated into photovoltaic systems (Gomes *et al.*, 2016). In this work, the P&O technique was adopted due to its simple and efficient operation, as well as its ease of implementation in the simulation environment.

Table 2 summarizes all the converter parameters adopted in the simulations, consolidating the electrical quantities obtained during the design process. However, some values had to be adjusted before implementation in the simulation, either due to rounding, adequacy to commercially available values, or to improve the dynamic performance of the system. In particular, the output capacitor C_3 was significantly increased in relation to the calculated value to reduce the output voltage ripple.

Table 2. Simulation parameters of the proposed converter.

Parameter	Calculated Value	Adopted in the Simulations
Input voltage	$V_{in} = 84.58 \text{ V}$	$V_{in} = 84.6 \text{ V}$
Output voltage	$V_{out} = 380 \text{ V}$	$V_{out} = 380 \text{ V}$
Input current	$I_{in} = 13.48 \text{ A}$	$I_{in} = 13.5 \text{ A}$
Output current	$I_{out} = 3 \text{ A}$	$I_{out} = 3 \text{ A}$
Input and output power	$P_{in} = P_{out} = 1140 \text{ W}$	$P_{in} = P_{out} = 1140 \text{ W}$
Switching frequency	$f_s = 40 \text{ kHz}$	$f_s = 40 \text{ kHz}$
Equivalent load resistance	$R_{out} = 126.67 \Omega$	$R_{out} = 127 \Omega$
Duty cycle	$D = 0.692$	$D = 0.692$
Inductors L_1 and L_2	$L_1 = L_2 = 4.877 \text{ mH}$	$L_1 = L_2 = 5 \text{ mH}$
Capacitors C_1 and C_2	$C_1 = C_2 = 13.659 \mu\text{F}$	$C_1 = C_2 = 15 \mu\text{F}$
Capacitor C_3	$C_3 = 0.248 \mu\text{F}$	$C_3 = 47 \mu\text{F}$

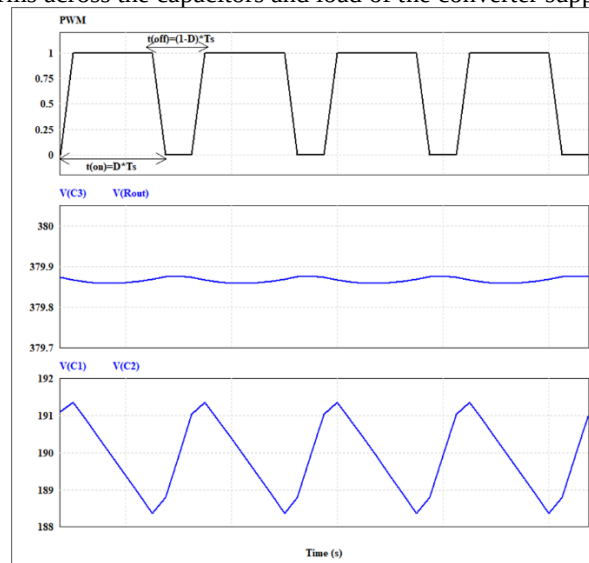
Source: Author

RESULTS AND SIMULATIONS

Figure 9 shows the voltage waveforms across the capacitors and the load, together with the PWM signal applied to the MOSFET, which serves as a reference for analyzing the other waveforms during the conduction stages. The observation of these signals, when compared with the previously discussed theoretical results, confirms the consistency of the converter dynamic behavior.

It can be observed that, during the interval in which the switch is closed, that is, when the MOSFET is conducting, the capacitors of the Up2 cell discharge, transferring energy to the inductors. When the switch is opened, the capacitors are recharged. In addition, the low ripple observed in the output voltage demonstrates that capacitor C_3 is properly performing its filtering function, providing a more stable voltage consistent with the expected behavior of the modified Zeta converter.

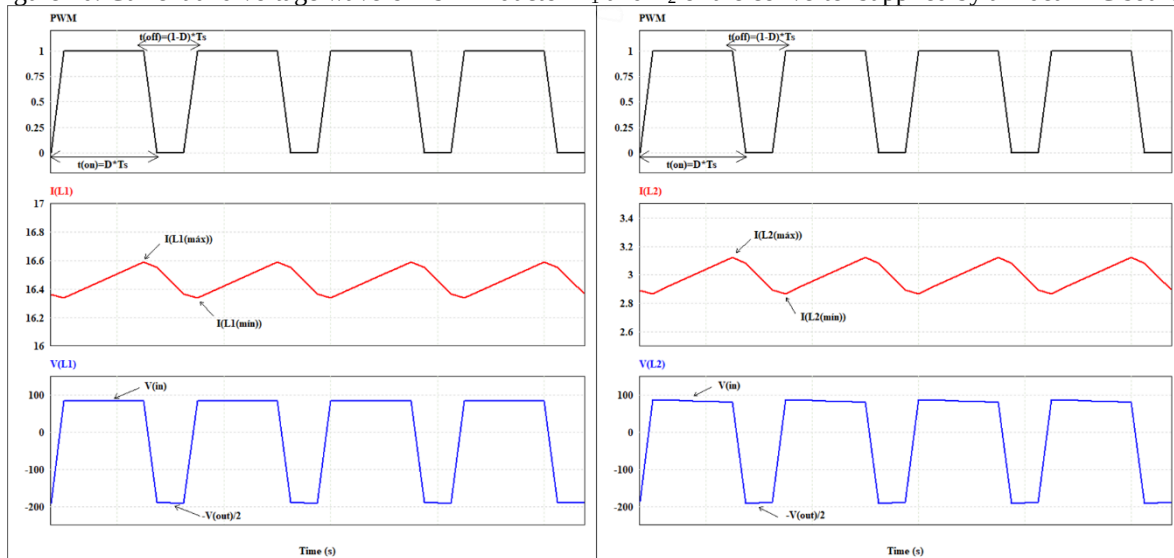
Figure 9. Voltage waveforms across the capacitors and load of the converter supplied by an ideal DC source.



Source: Author

Figures 10 show the current and voltage waveforms in inductors L_1 and L_2 , allowing for an accurate evaluation of the dynamic behavior of these elements throughout the switching period. It can be observed that the currents exhibit a triangular waveform and never reach zero, indicating operation in continuous conduction mode, as predicted by the theoretical model.

Figure 10. Current and voltage waveforms in inductor L_1 and L_2 of the converter supplied by an ideal DC source.



Source: Author

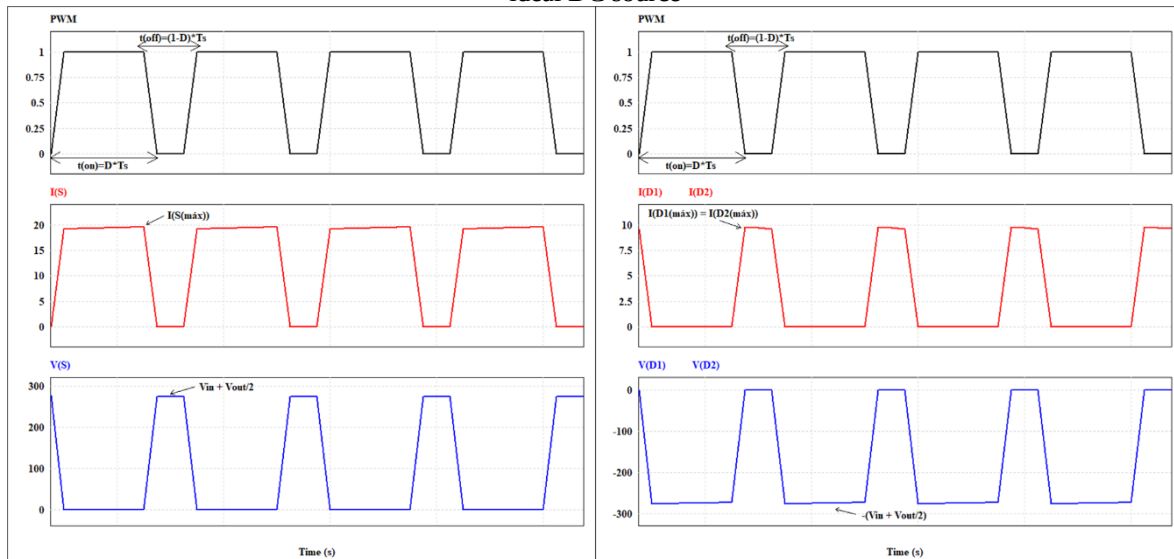
During the interval in which the MOSFET is turned on ($t_{on} = DT_s$), the voltage applied to the inductors is approximately equal to the input voltage V_{in} , causing a linear increase in the

current. In the interval in which the MOSFET is turned off ($t_{off} = (1 - D)T_s$), the voltage across the inductors becomes negative and close to $-V_{out}/2$, resulting in the current decay stage.

Figure 11 shows the current and voltage waveforms of MOSFET S and diodes D_1 and D_2 . It can be observed that the device current is different from zero only during the conduction interval t_{on} , reaching its maximum value at the end of this period, as expected, since it corresponds to the instantaneous sum of the inductor currents.

When the MOSFET is turned off (t_{off}), the current immediately drops to zero, while the voltage across its terminals rises to approximately $V_{in} + V_{out}/2$, which is a characteristic predicted for the modified Zeta converter with the Up2 cell. This behavior confirms that the switching process is being reproduced consistently with the theoretical model.

Figure 11. Current and voltage waveforms in MOSFET S and diodes D_1 and D_2 of the converter supplied by an ideal DC source



Source: Author

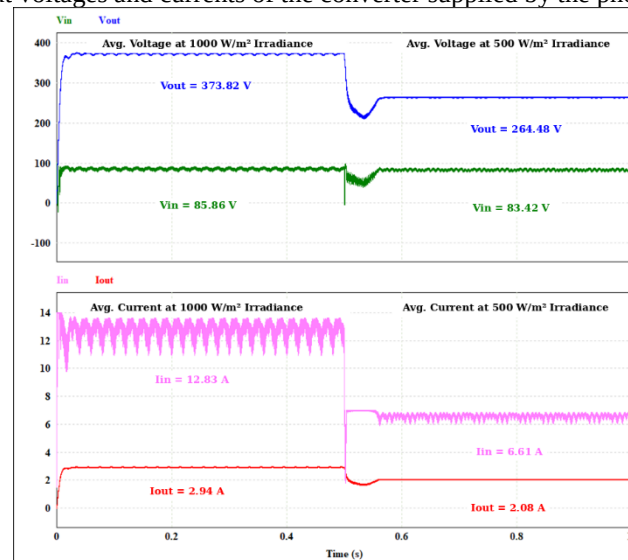
Regarding the diodes, it can be observed that both diodes conduct only during the t_{off} interval, presenting maximum currents compatible with half of the sum of the inductor currents, exactly as indicated by the theoretical equations. During t_{on} , the diodes remain reverse-biased and are subjected to a reverse voltage close to $-(V_{in} + V_{out}/2)$.

Figure 14 shows the input and output voltage and current waveforms of the converter operating with MPPT enabled.

For the initial irradiance of 1000 W/m^2 , it can be observed that the input voltage stabilizes at approximately 85.86 V , a value consistent with the maximum power point of the photovoltaic array. The output voltage, in turn, reaches approximately 373.82 V .

This behavior is expected, since the P&O method performs small continuous perturbations in the duty cycle around the maximum power point. Thus, the converter does not remain exactly at the optimal value, but oscillates within a narrow range around it, producing small variations in the output voltage. The currents follow the same pattern: the input current stabilizes at around 12.83 A and the output current at approximately 2.94 A , indicating that the converter operates very close to the ideal conditions and that the MPPT is properly driving the system toward the maximum power extraction region.

Figure14. Input and output voltages and currents of the converter supplied by the photovoltaic array with MPPT.



Source: Author

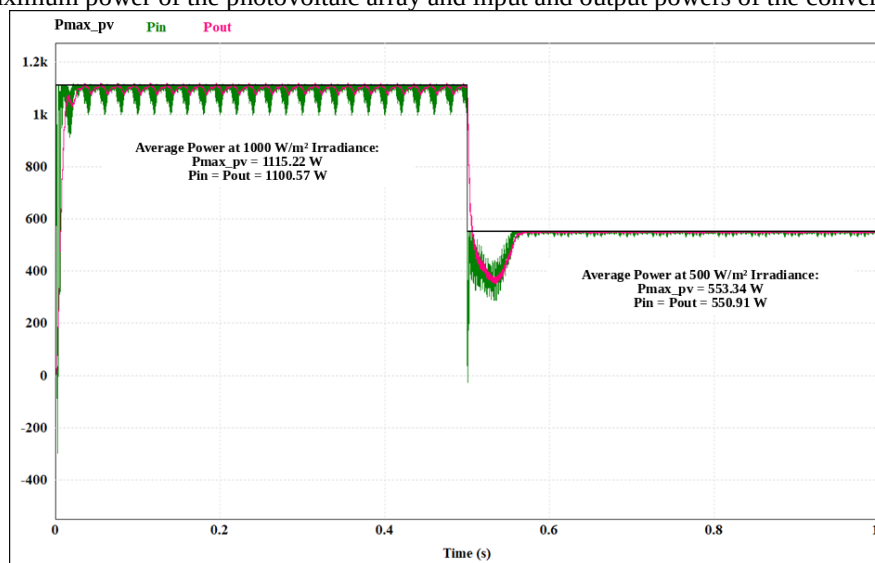
After the irradiance is reduced to 500 W/m^2 , the MPPT rapidly adjusts the duty cycle, causing the input voltage to stabilize at 83.42 V , a value consistent with the panel maximum power point under this condition. This demonstrates that, even with lower available power, the converter can use the energy more efficiently when the tracking algorithm is enabled.

Figure 15 shows the comparison between the maximum power available in the photovoltaic array ($P_{\max_pv}$) and the input and output powers of the converter with the MPPT algorithm enabled.

For an irradiance of 1000 W/m^2 , the array provides approximately 1115.22 W at its maximum power point, and the converter operates with an input and output power of approximately 1100.57 W , indicating an excellent approximation to the maximum power point.

When the irradiance is reduced to 500 W/m^2 , the photovoltaic array presents a maximum power of 553.34 W . With MPPT enabled, the converter is able to operate very close to this limit, with an input and output power of approximately 550.91 W , representing a significant gain compared with the scenario without MPPT, in which the converter captured only about 308.13 W .

Figure 15. Maximum power of the photovoltaic array and input and output powers of the converter with MPPT.



Source: Author

This difference clearly demonstrates the effectiveness of the algorithm in driving the system to the maximum energy extraction point, even under abrupt irradiance variations.

CONCLUSION

This work presented the study, modeling, and simulation of a modified Zeta DC-DC converter applied to photovoltaic systems, evaluating its behavior under two operating conditions: ideal operation and operation with MPPT. The objective was to verify the converter performance under different irradiance conditions and analyze the influence of the maximum power point tracking algorithm on the energy utilization of the photovoltaic array.

In the first scenario, using an ideal DC source, the converter exhibited behavior consistent with the theoretical model. The simulated average voltage and current values closely matched the analytical results, with relative errors below 3%, validating both the component design and the circuit implementation. In addition, the voltage and current waveforms in the inductors, capacitors, MOSFET, and diodes reproduced the expected behavior for continuous conduction mode, confirming the proper operation of the converter under ideal conditions.

In the second scenario, the use of the P&O MPPT algorithm demonstrated a positive impact on the system performance. With active tracking, the converter adjusted the duty cycle in real time, keeping the photovoltaic array operating close to its maximum power point, even after an abrupt irradiance variation. For 500 W/m², the converter extracted approximately 550.91 W, which corresponds to practically all the available power from the array. These results demonstrate the effectiveness of the MPPT algorithm and the converter's ability to operate stably and efficiently under non-ideal conditions.

Overall, the results confirm that the modified Zeta converter with the Up2 gain cell presents consistent performance, operating as expected under ideal conditions and processing energy efficiently when associated with an MPPT algorithm. Thus, the obtained results validate both the theoretical modeling and the adopted control strategy, demonstrating the robustness and functionality of the designed converter for photovoltaic applications.

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