

Mathematical Modeling and Simulation of a Three-Port DC-DC Nonisolated Converter Applied to Photovoltaic Systems

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Abstract: This work presents the modeling and simulation of a three-port DC-DC nonisolated converter designed for standalone photovoltaic applications. The proposed topology integrates a solar panel, a battery, and a DC load, enabling energy transfer among these sources depending on the system's operating mode. The solar panel supplies energy unidirectionally, while the battery operates bidirectionally, being capable of both supplying and absorbing energy according to the system's demand. The converter operates in three distinct modes: SIDO (Single Input Dual Output), DISO (Dual Input Single Output), and SISO (Single Input Single Output). For each mode, the switching behavior is analyzed and described through differential equations that characterize the dynamics of the system variables. The design process includes the topology modeling, mathematical modeling for each operating mode, switching modulation strategies for each mode, and component sizing to ensure proper operation in Continuous Conduction Mode (CCM). Open-loop simulations are carried out using PSIM software, along with the development of the control system. The results confirm that the converter performs the expected energy transfer among the ports, validating both its applicability and the control system, which is currently under development.

Keywords: Three-port converter, photovoltaic systems, energy management, DC-DC converter, standalone systems.

1. Introduction

The growing demand for renewable energy sources has driven the development of power electronic topologies for the efficient integration of multiple sources and loads. In photovoltaic systems, the combination of the solar panel, energy storage unit (battery), and load requires flexible converter architectures for power flow management. Three-port DC-DC converters (TPCs) emerge as a promising alternative, reducing conversion stages and increasing efficiency [4]. This work models a TPC topology based on conventional Buck and Boost converters, recognized for their simplicity and robustness [1]. The topology, illustrated in Figure 1, consists of three ports: Ppv (unidirectional, photovoltaic panel), Pb (bidirectional, battery), and P0 (unidirectional, DC load). Different

operating modes are considered SIDO, DISO, and SISO depending on the sources' status. The modeling involves differential equations that describe the dynamics of inductor currents and capacitor voltages, allowing characterization of the performance under varying power flows. Simulations performed in PSIM and MATLAB environments confirm the operation and transitions between modes, validating the topology's applicability. The main objectives of this study include demonstrating how a compact configuration can be achieved based on simple Buck and Boost converters; mathematically modeling and proving the functionality of the three-port converter; and demonstrating the design and implementation of control strategies for such systems. The main contributions are: Model an efficient and simplified three-port

DC-DC converter topology based on buck and boost converters;

Develop the mathematical modeling, including linearization to obtain the transfer function for control purposes;

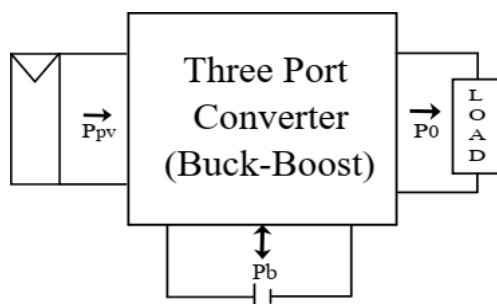
Simulate the converter in open loop across different modes to validate performance and the model;

Implement the control strategy for mode switching, including protection against adverse conditions;

Develop and validate a classical control system based on the linearized model, ensuring stability and efficiency.

representing the corresponding waveforms. The topology presented in Figure 2 represents the integrated configuration of Buck and Boost converters. The Buck converter is responsible for establishing the energy path from the photovoltaic panel to both the load and the battery, enabling unidirectional power transfer from the source to the other system elements. Meanwhile, the Boost converter creates the energy path from the battery to the load, allowing bidirectional battery operation and power supply to the load as needed. This configuration enables independent and simultaneous control of the energy sources, providing greater operational flexibility to the photovoltaic system, which can operate in different modes depending on generation conditions, load demand, and battery state of charge. The integration of these two conventional converters forms the basis of the multiport topology, facilitating the system's analysis, development, and implementation. The final configuration, shown in Figure 3, results from the optimization of the initial topology, in which redundant components were eliminated to simplify the circuit. This simplification contributes to reducing electrical losses and the overall converter volume, without compromising the essential functionalities of the topology. The final architecture preserves the main energy transfer paths among the three ports, ensuring efficient operation in SIDO, DISO, and SISO modes. Additionally, the reduced number of active components enhances the reliability and

Figure 1. general diagram of the three-port converter



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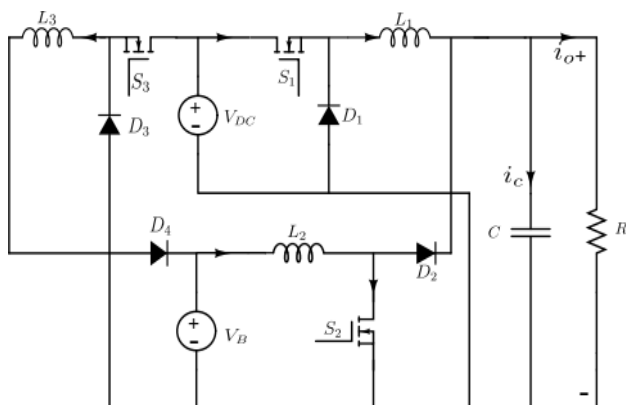
2. Derivation and Modeling of the Three-Port Converter Topology

Several studies have proposed multiport DC-DC converter topologies aiming to increase power density, reduce the number of active components, and simplify control systems ([2]–[3],[5]). Despite these advances, many of these works do not provide detailed modeling of the operating modes, such as deriving differential equations for the various switching states and clearly



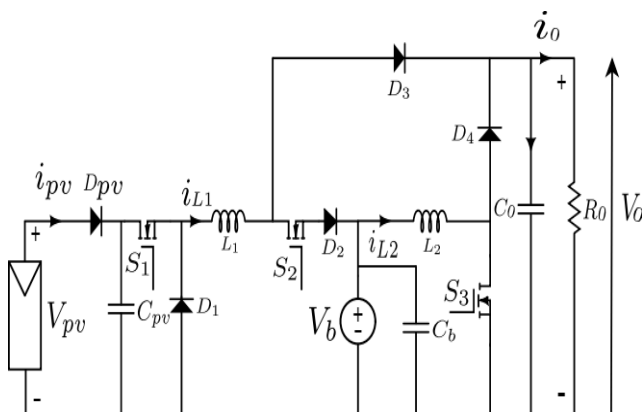
practical viability of the converter in isolated photovoltaic applications.

Figure 2. configuration of the port paths of the converter



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Figure 3. Final Converter Topology



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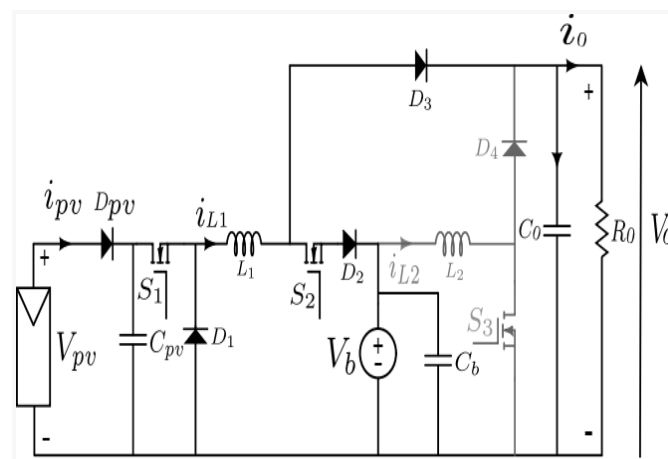
2.1. Mathematical Modeling and Dynamics by Mode of Operation

a) SIDO mode (S3–OFF):

The mathematical models of the converter in SIDO mode are based on the analysis of the equivalent circuits for the three switching states of switches S1 and S2, as illustrated in Figure 4 and the switching diagrams in Graphic 1. In this

mode, the converter operates as a Buck stage, transferring energy from the photovoltaic panel to the load and the battery. The operation occurs in three states: S1 ON with S2 OFF, where the inductor is energized by the source; S1 OFF with S2 ON, when the inductor energy is split between the load and the battery; and both switches OFF, with the inductor discharging energy only to the load. The differential equations for each state are combined using the averaging technique weighted by the duty cycles D1 and D2, resulting in the average output voltage equation V_0 .

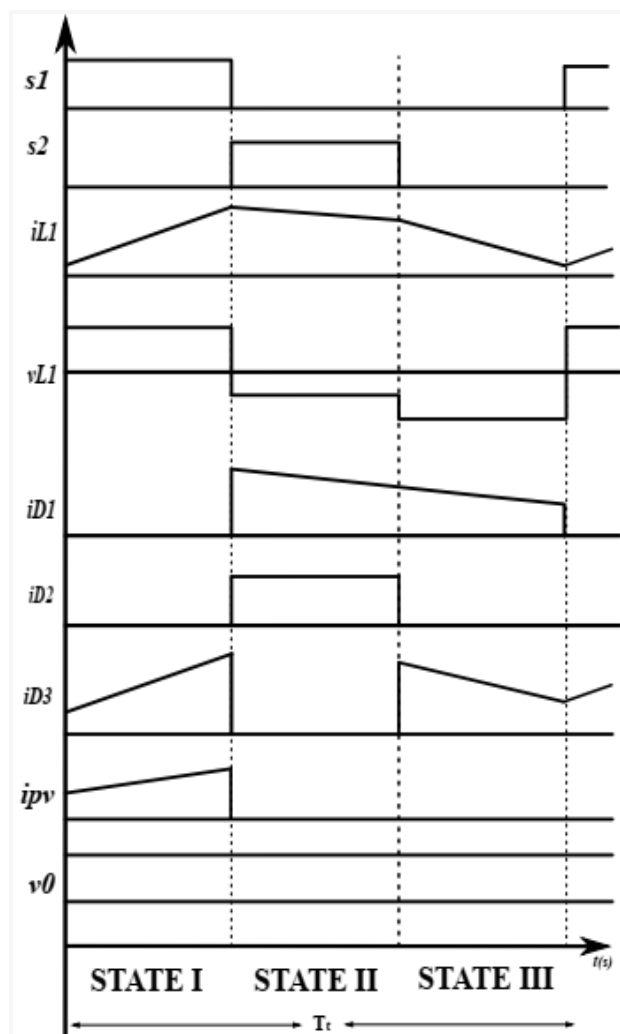
Figure 4: topology of the SIDO mode



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Graphic 1: Key waveforms of SIDO mode.



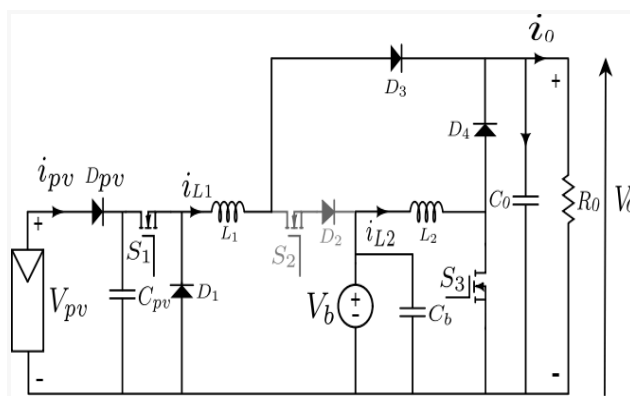
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b) DISO mode (S2–OFF):

The mathematical models of the converter in DISO mode are based on the analysis of the equivalent circuits for the three switching states of switches S1 and S3, as illustrated in Figure 5 and the switching diagrams in Graphic 2. In this mode, the photovoltaic panel remains connected, supplying partial power to the load, while the battery assists in providing energy through the converter operating as a Boost stage. The

operation occurs in three states: S1 ON with S3 OFF, where the inductor is energized mainly by the photovoltaic source and partially by the battery; S1 OFF with S3 ON, when the energy stored in the inductor is transferred to the load; and both switches OFF, with the inductor discharging energy exclusively to the load. The differential equations for each state are combined using the averaging technique weighted by the duty cycles D1 and D3, resulting in the average output voltage equation V_0 .

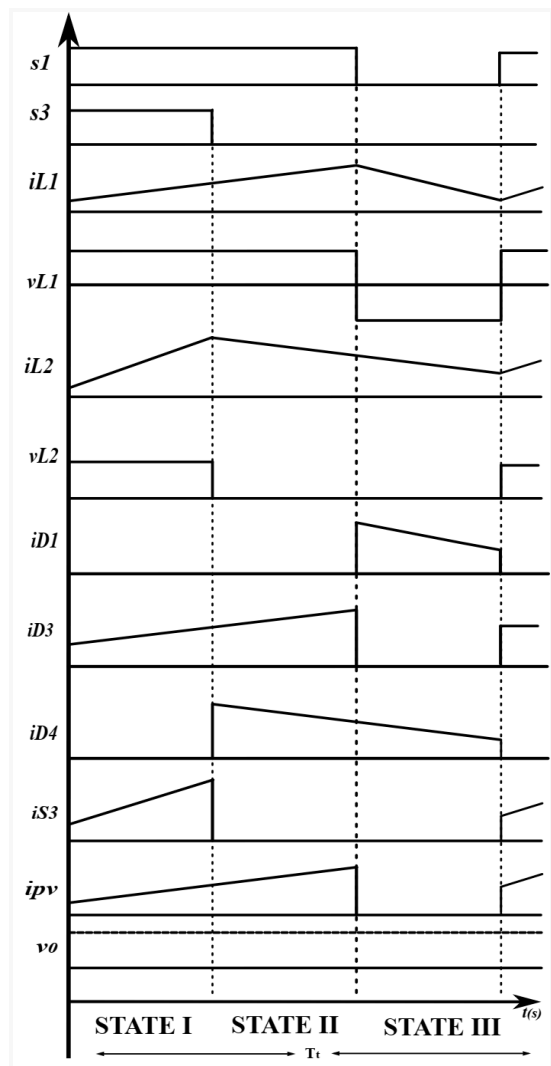
Figure 5: topology of the DISO mode



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Graphic 2: Key waveforms of DISO mode.



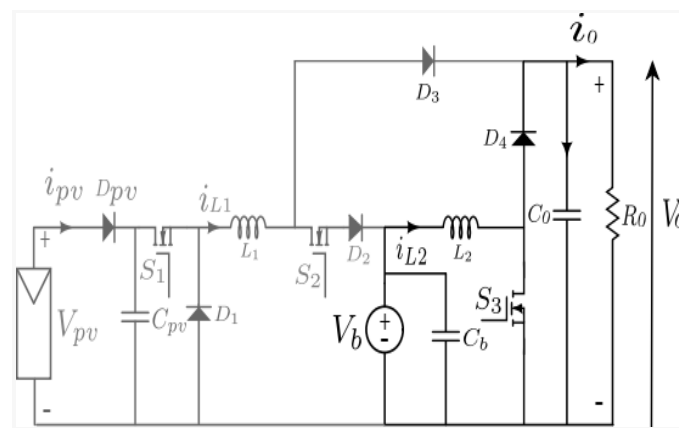
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c) SISO mode (S1-OFF, S2-OFF):

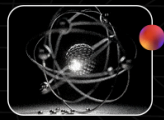
The SISO (Single Input, Single Output) operating mode is characterized by the condition in which only the battery acts as the energy source, supplying the load directly. This scenario typically occurs during periods of low irradiation or absence of photovoltaic generation, when the

solar panel does not contribute power to the system. The equivalent circuit for the SISO mode is illustrated in Figure 6, while the associated waveforms are shown in Graphic 3, highlighting the variations in the current through inductor L_2 , switch S_3 , and diode D_3 , as well as the dynamic response of the output voltage v_0 . In this mode, only the discharge path from the battery to the load is active, controlled by switch S_3 .

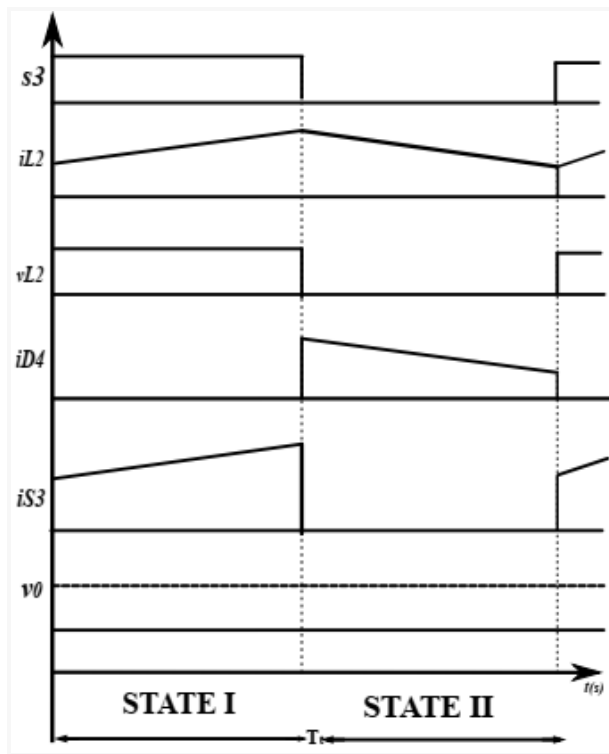
Figure 6: topology of the SISO mode



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Graphic 3: Key waveforms of SISO mode.



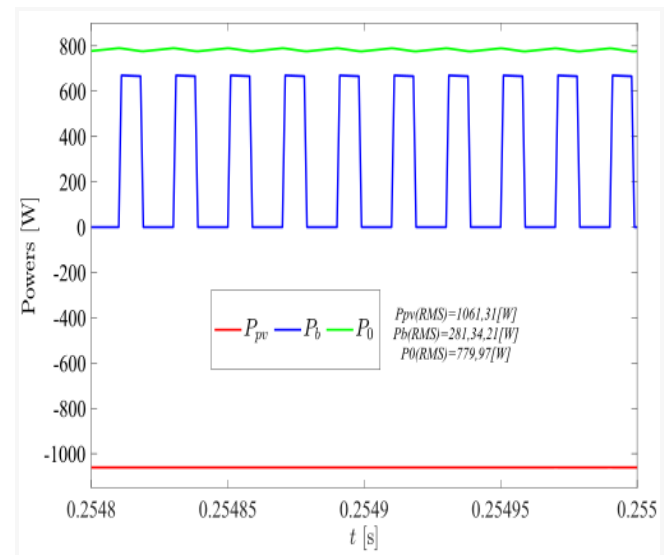
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3. Results

The functional verification of the converter was performed through open-loop simulations for the operating modes {SIDO}, {DISO}, and {SISO}. This phase aimed to validate the dynamic behavior of the proposed topology under different operating conditions, focusing on the modulation and power flow between the ports. Figure 7, 8, and 9 present the simulation results for each operating mode. The converter is shown to operate correctly in all modes, ensuring the expected energy transfer. The power flow graphs indicate the direction of energy flow between the converter ports: negative values represent power being delivered by the respective port, while positive values indicate power being received. The simulations confirmed the correct switching

behavior and the expected response of the output voltage in each operating condition. In the {SIDO} mode, the photovoltaic source delivers energy simultaneously to the load and the battery. In the {DISO} mode, the source continues supplying the load while the battery actively assists in meeting the power demand. In the {SISO} mode, the battery alone supplies energy to the load. These results validate the implementation of the open-loop modulation as well as the correct mode transition logic, demonstrating the converter's feasibility for photovoltaic systems with energy storage applications.

Figure 7: SIDO Mode – Output Power Response.



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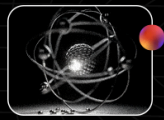
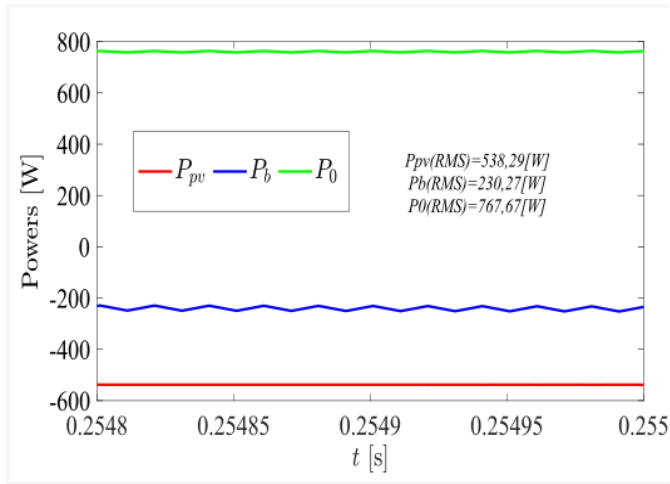
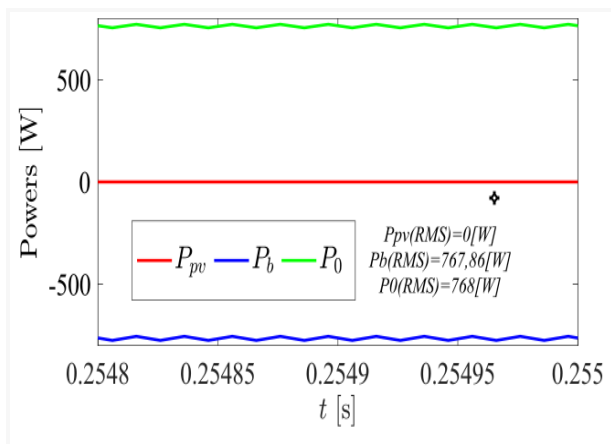


Figure 8: DISO Mode – Output Power Response



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Figure 9: DISO Mode – Output Power Response



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4. Conclusions

This work presented the development and functional validation of a three-port DC-DC nonisolated converter through simulations. The study focused on the topology modeling and the implementation of modulation strategies for the SIDO, DISO, and SISO operating modes. Simulations performed in the PSIM and MATLAB environments allowed the verification

of the converter's dynamic behavior in each mode, demonstrating proper power transfer among the ports according to the expected energy flow. The power flow graphs were consistent with theoretical models, validating the open-loop operation in all modes, including during transitions. At this stage, the closed-loop control design has not yet been implemented. However, the results obtained provide a solid foundation for the development of classical control strategies based on linearized models, aiming to ensure system stability, dynamic performance, and efficient reference tracking. The control development is in its final stage and will be presented in the final version of the article.



5. References

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