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Analysis of DC-DC Converters for Integrated Photovoltaic Solar-Powered Electric Bus Charging Systems

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***Abstract*—This article presents a theoretical study and validation of the feasibility of integrating photovoltaic (PV) systems to charge electric vehicles, with a focus on an electric bus as the model for analysis. The work further explores the design of an energy conversion system employing DC-DC converters, analyzing various converter types and configurations to maximize energy transfer efficiency. The study identifies optimal converter topologies and control strategies to enhance system performance. Finally, the proposed models are validated through simulations in Matlab/Simulink, incorporating lithium-ion batteries as the energy storage system. The article aims to demonstrate how integrating photovoltaic energy into electric vehicle charging can serve as a sustainable and environmentally friendly solution, offering practical insights for improving energy efficiency in public transportation systems.**

***Keywords*—Photovoltaic systems, electric bus, solar energy, DC-DC converters, MPPT, lithium-ion batteries, public trans-portation.**

I. INTRODUCTION

The global transition towards sustainable transportation has intensified interest in Electric Vehicles (EVs) as a critical strategy to reduce greenhouse gas emissions and reliance on fossil fuels. Among the various EV applications, electric buses have emerged as pivotal in minimizing the environmental footprint of public transportation systems. However, ensuring the operational efficiency of electric buses presents challenges, particularly in developing reliable and efficient charging systems that reduce downtime and enhance energy management.

Photovoltaic (PV) solar energy offers a promising avenue for addressing these challenges by providing a renewable and sustainable energy source for EV charging infrastructure. Integrating PV systems into the charging process for electric buses has the potential to lower operational costs, improve energy independence, and support environmental sustainability. This study investigates the feasibility and optimization of integrating PV systems specifically for charging electric buses.

Furthermore, the study delves into the design of energy conversion systems using DC-DC converters, optimizing converter topologies and control strategies to maximize charging efficiency.

To validate the proposed approach, simulations are conducted using Matlab/Simulink, incorporating lithium-ion batteries as the energy storage system. By demonstrating the viability of PV solar energy as a complementary solution for charging electric buses, this work contributes to advancing eco-friendly public transportation networks and fostering sustainable urban mobility.

II. STATE OF ART

A. Solar Energy

Solar energy is a key renewable source with vast potential due to its abundance and sustainability. Over the years, advancements in photovoltaic (PV) technology have significantly improved efficiency, making solar power an increasingly competitive alternative to fossil fuels. However, its intermittency and dependence on climatic factors require detailed studies to ensure its viability and integration into energy systems.

This study focuses on Curitiba, Paraná, analyzing its solar potential and seasonal variations. While Paraná exhibits high solar irradiation levels, Curitiba's metropolitan region has one of the state's lowest averages (1,492 kWh/m².yr). Despite this, it still surpasses many European benchmarks, reinforcing its feasibility for PV applications. By leveraging computational simulations and strategic investments, Curitiba can enhance solar energy adoption and contribute to a more sustainable energy matrix [1], [2].

B. Innovations in Sustainable Transportation

Recent advances have significantly expanded the integration of renewable energy, smart monitoring, and energy optimization in electric mobility systems:

- **Smart EV Charging**: Ilahi et al. [3] developed a cost-effective e-bike charger enhanced with an IoT-based real-time monitoring system. This innovation improves small-scale EV infrastructure with intelligent energy management.

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- **Hydrogen Hybrid Vehicles**: Mansouri et al. [4] proposed a GPS-based speed estimation method to optimize energy use in hydrogen hybrid electric vehicles (HHEVs), demonstrating enhanced control strategies for sustainable transport.
- **PV Integration in Microgrids**: Gulraiz et al. [5] evaluated how photovoltaic penetration affects the performance and stability of low-voltage microgrids, reinforcing the role of solar integration in EV charging networks.
- **Resilient Microgrids for Disaster Scenarios**: Ali et al. [6] designed microgrid systems to support energy access in remote and islanded communities during natural disasters. Their findings emphasize the value of resilient, decentralized energy systems in electric mobility.

These innovations align with the goals of this study by offering insights into real-time control, decentralized systems, and hybrid energy integration—all essential for sustainable public transportation networks.

C. Electric Buses

Electric buses (EBs) reduce emissions and operating costs, and are categorized as Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Battery Electric Vehicles (BEVs). BEVs operate solely on battery power and are more suitable for sustainable public transportation, despite challenges such as limited range and charging infrastructure [7].

While all these models present viable solutions for sustainable public transportation, the Volvo BZL Electric stands out as the most suitable for Curitiba's needs [8], as summarized in Table I. Its combination of robust battery technology, extended range, and sufficient passenger capacity positions it as a key contributor to the city's effort to modernize its public transit network and reduce environmental impact [9]–[11].

D. DC-DC Converters

DC-DC converters are fundamental in managing and converting electrical energy in DC systems, using semiconductor switches controlled by PWM and passive components to ensure efficient and stable operation [12], [13]. They can be classified as non-isolated—like Boost and Buck converters, which are simpler—and isolated, which use transformers for galvanic isolation, improving safety and flexibility [13], [14].

The Boost converter is commonly used to increase voltage, operating by storing energy in an inductor when a switch is closed and releasing it when open, with output voltage depending on the PWM duty cycle. For higher voltage gains, advanced topologies such as Interleaved, Cascade, and Multilevel Boost converters are applied [14].

The Quadratic Boost Converter is a high-gain topology featuring two Boost stages in series, offering a quadratic increase in output voltage at the same duty cycle compared to a conventional Boost converter. It achieves higher efficiency and lower component stress but requires precise control [15].

These converters are key in renewable energy systems, especially for photovoltaic integration with electric vehicles, enhancing overall energy efficiency and supporting sustainable transport solutions.

E. MPPT Techniques

In photovoltaic (PV) systems, maximizing energy extraction is crucial for improving efficiency and system performance. MPPT techniques are employed to ensure that the PV system operates at its optimal power point, adapting dynamically to environmental variations such as solar irradiance and temperature [16].

Early approaches to optimizing solar energy capture relied on mechanical tracking systems that adjusted panel orientation to maximize sunlight exposure. However, these systems were later complemented by electrical tracking techniques, which continuously adjust the operating point of the PV system to match the Maximum Power Point (MPP). Since directly connecting a PV generator to a load may result in an operating point far from the MPP, an electronic converter is typically introduced between them. This converter regulates the voltage and current to maintain operation at peak efficiency.

MPPT algorithms work by monitoring input voltage and current and adjusting the duty cycle of the power converter to minimize deviations from the MPP. Various algorithms have been developed, each with specific advantages and trade-offs. In this study, four MPPT techniques are analyzed: Fixed Duty Cycle, Constant Voltage, Perturb and Observe (P&O), and Incremental Conductance (IC) [18], [23].

Each MPPT technique presents trade-offs between efficiency, complexity, and responsiveness to environmental variations. The choice of an appropriate algorithm depends on the specific application and operational requirements of the PV system.

III. METHODOLOGY

The methodology adopted in this study aims to evaluate the connection between the photovoltaic panel and the battery, optimizing energy transfer through different converter topologies and Maximum Power Point Tracking (MPPT) strategies.

A. Photovoltaic Module Under Study

To ensure accurate modeling and simulation of the photovoltaic system, the HG-L530-72CW solar panel was selected for this study. This module, manufactured by Wattstunde [19], provides a maximum power output of 530 W and consists of 144 solar cells arranged in a 6×24 configuration. The choice of this panel is based on its high efficiency and suitability for energy conversion in standalone and grid-connected photovoltaic systems. The main electrical and physical specifications of the selected module are summarized in Table II.

B. DC-DC converters

In photovoltaic systems, DC-DC converters are crucial for optimizing energy transfer between solar panels and batteries, adjusting input and output voltages as needed. This study focuses on two types of converters: the boost converter and the quadratic converter, which stand out for their efficiency in voltage elevation without isolation, reducing energy losses.

TABLE I.
COMPARISON OF ELECTRIC BUS SPECIFICATIONS

	Volvo	BYD	Mercedes	Higer
Model	VOLVO BZL ELECTRIC	D9W	eO500 U 2134/59	AZURE PADRON
Length	12 m	12.265 m	up to 13.2 m	12.5 m
Weight	19,500 kg	20,500 kg	21,200 kg	21,000 kg
Passenger Capacity	80 people	80 people	80 people	80 people
Battery Technology	Lithium-ion, NCA	BYD LifePO4	Lithium-ion, NMC	Lithium Iron Phosphate
Electric Motor	200/400 kW	150 kW*2	250 kW	260 kW
Battery Capacity	470 kWh	344 kWh	up to 588 kWh	385 kWh
System Voltage	600 V	380 V	665 V	637.56 V

TABLE II.
PHOTOVOLTAIC PANEL SPECIFICATIONS

Parameter	Value
Maximum Power (Pmax)	530 W
Length (C)	2282 mm
Width (L)	1137 mm
Reference Temperature (Tref)	25°C
Reference Irradiance (Gref)	1000 W/m²
Max Power Current (Imp)	12.83 A
Max Power Voltage (Vmp)	41.35 V
Short Circuit Current (Isc)	13.76 A
Open Circuit Voltage (Vco)	49.90 V
Solar Cells	144 (6*24)

Parameters of the HG-L530-72CW panel

C. Boost Converter

To raise the low voltage supplied by the photovoltaic panel to a suitable level for charging, a boost converter was selected, as illustrated in Figure 1, which shows the schematic implemented in Simulink. This converter operates in two distinct phases.

In the first phase, when the switch is closed and the transistor conducts, current flows through the inductor, accumulating magnetic energy. The inductor thus temporarily stores energy in preparation for transfer to the load.

In the second phase, the switch opens, stopping transistor conduction, and the energy stored in the inductor is transferred to the load via the diode and capacitor. At this point, the inductor pushes the output voltage to a level higher than the input to ensure adequate system power.

A key feature of the *boost* converter is its voltage gain—the ratio between the output and input voltages. This gain is controlled by the duty cycle (δ), representing the portion of the switching period when the control signal keeps the switch closed. Typical duty cycle values range from 0 to 1, providing flexibility in voltage regulation. By adjusting this duty cycle, the converter can increase or decrease output to match the system's power demands. This adjustable control over voltage gain is essential for optimizing energy use in photovoltaic applications, where available power fluctuates with sunlight conditions.

The voltage gain of the boost converter is directly related to the duty cycle (δ), which determines how long the switch remains closed. The duty cycle is given by [12]:

$$\delta = 1 - \frac{V_{in}}{V_{out}} \tag{1}$$

D. Quadratic Converter

The quadratic boost converter is a DC-DC step-up converter that increases voltage through two cascaded boost stages. This configuration achieves a quadratic voltage gain compared to a traditional single-stage boost converter, enabling significantly higher output voltages with the same duty cycle, as depicted in Figure 2.

Its operation is defined by two alternating phases, depending on whether the mosfet is conducting (*ON*) or not conducting (*OFF*).

In the ON phase, the mosfet conducts, causing diodes D_1 and D_3 to be reverse-biased, while D_2 is forward-biased. During this stage, capacitor C_0 supplies energy to the load, and C_1 charges inductor L_2. Simultaneously, inductor L_1 accumulates energy due to the applied input voltage V_{in}.

In the OFF phase, the mosfet turns off, and D_1 and D_3 become forward-biased, while D_2 turns off. Inductor L_1 maintains its current flow through D_1, ensuring continuous magnetic energy transfer, while the capacitors recharge, preparing for the next switching cycle.

The duty cycle (δ) of the quadratic boost converter, which governs its voltage gain, is given by [15]:

$$\delta = 1 - \sqrt{\frac{V_{in}}{V_{out}}} \tag{2}$$

E. MPPT

To maximize energy extraction from the photovoltaic panel, three Maximum Power Point Tracking (MPPT) techniques were implemented and analyzed: Perturb and Observe (P&O), Incremental Conductance (IC), and Constant Voltage (Vcte). These techniques were chosen due to their widespread use in the literature and their efficiency under different environmental conditions.

Fixed Duty Cycle (D)

This is the simplest MPPT approach, where the duty cycle of the converter is kept constant, regardless of environmental conditions. While easy to implement, it does not adapt to variations in irradiance or temperature, leading to suboptimal energy extraction. It is primarily used as a reference for comparison with more advanced methods [20], [21].

Constant Voltage (Vcte)

The Constant Voltage method maintains the PV module's operating voltage near a predefined reference, typically the voltage at the MPP under standard test conditions. It requires only voltage sensing, simplifying implementation. However, it assumes that the MPP voltage remains relatively constant, making it less effective in rapidly changing environmental conditions [20], [22].

Perturb and Observe (P&O)

The P&O algorithm periodically perturbs the PV voltage and observes the corresponding power variation. If the power increases, the perturbation continues in the same direction; otherwise, the direction is reversed. This method is widely used due to its simplicity but may cause oscillations around the MPP, especially under fluctuating irradiance [23], [22].

Incremental Conductance (IC)

The IC algorithm calculates the derivative of power with respect to voltage and adjusts the duty cycle accordingly. When the derivative is positive, the system is below the MPP and increases the duty cycle; when negative, it reduces the duty cycle. IC offers better accuracy than P&O, particularly in dynamic conditions, but is more complex to implement [24].

F. Energy Storage System

For the analysis of the battery system in this study, the Lithium-Ion HE341440 NCA cell from EAS Batteries GmbH was selected [25]. This choice was based on the technical specifications of the Volvo BZL Electric, the vehicle under consideration, which utilizes NCA (Nickel Cobalt Aluminum) battery chemistry. While the HE341440 NCA cell is not identical to the exact cells used in the Volvo BZL Electric, it serves as a representative model with similar chemistry, allowing for a relevant and detailed analysis of the battery behavior in a comparable application.

Table III presents the nominal characteristics of the selected NCA cell, including voltage, capacity, and current ratings. These parameters are fundamental for the accurate modeling and simulation of the energy storage system.

TABLE III.
NOMINAL CHARACTERISTICS OF NCA CELL

Parameter	Value
Nominal Voltage	3.6 V
Nominal Capacity	10 Ah
Nominal Current	5 A

To approximate the energy storage system used in the Volvo BZL Electric, a battery pack configuration of 181s14p (181 cells in series and 14 in parallel) was selected. This configuration ensures a nominal voltage of approximately 651.60 V and a total energy storage capacity of 91.22 kWh, which closely matches the real-world application. The detailed electrical characteristics of this battery pack are summarized in Table IV.

TABLE IV.
PACK CHARACTERISTICS OF NCA MODULES (181S14P)

Parameter	Value
Pack Configuration	181s14p (181 cells in series, 14 cells in parallel)
Nominal Voltage	651,60 V
Nominal Capacity	140 Ah
Energy Storage	91,22 kWh
Total Number of Cells	2534 cells

This battery configuration was chosen to align with the operational requirements of large electric vehicles, ensuring compatibility in terms of voltage, capacity, and energy storage. The model used in this study allows for a precise evaluation of the battery's charge and discharge cycles, efficiency, and overall performance under different operating conditions.

The mathematical modeling of the battery is based on a simplified approach, where key dynamic parameters are extracted directly from the manufacturer's discharge curve. This method eliminates the need for additional experimental testing and enables the determination of essential parameters such as fully charged voltage, nominal voltage, and internal resistance.

By implementing this model in MATLAB/Simulink, the battery system's performance is evaluated under different charging and discharging scenarios, considering the impact of variations in operating conditions. The insights obtained from these simulations contribute to the optimization of the energy management strategy and overall system efficiency.

IV. RESULTS

This chapter presents the simulation results for Boost and Quadratic converters in photovoltaic systems, analyzing four MPPT techniques: incremental conductance, perturb and observe, constant voltage, and duty cycle control. Initially, simulations were conducted under Standard Test Conditions (STC) of irradiance and temperature to benchmark performance. After identifying the optimal converter and MPPT configuration, further simulations were performed using real irradiance and temperature data from Curitiba, Brazil, during peak and low solar incidence periods. The analysis focuses on efficiency, stability, and charging performance to determine the most effective setup for integrating photovoltaic systems into the Volvo BZL Electric bus.

A. Comparative Analysis of MPPT Techniques with DC-DC Converters

To assess the performance of different MPPT techniques, simulations were conducted for Boost and Quadratic converters under Standard Test Conditions (STC). The MPPT methods evaluated include Incremental Conductance (IC), Perturb and Observe (P&O), Constant Voltage (Vcte), and Fixed Duty Cycle (D). Figures 1 and 2 depict the Simulink schematics for both converters, highlighting their voltage regulation mechanisms. In all simulation plots, the x-axis represents time in seconds, while the y-axis represents output power in

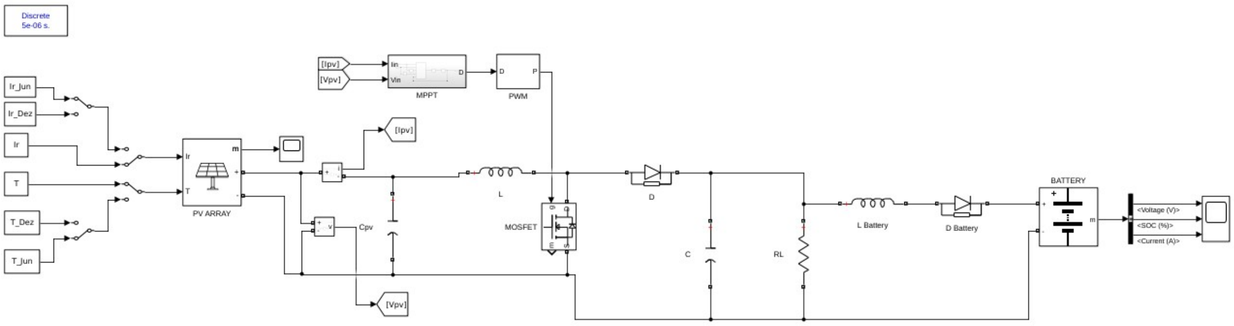

Fig. 1. Schematic implemented in Simulink for the Boost Converter

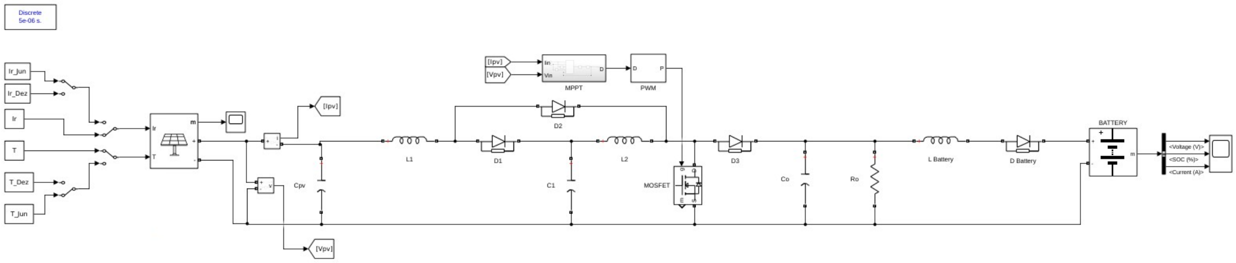

Fig. 2. Schematic implemented in Simulink for the Quadratic Converter

watts (W), allowing for a direct comparison of power tracking performance across methods.

Figures 3 and 4 compare the power extracted by each MPPT method. The IC technique demonstrated superior stability and accuracy in tracking the Maximum Power Point (MPP) for both converters. P&O exhibited larger oscillations, particularly in the Quadratic converter, while Vcte and Fixed Duty Cycle methods showed lower efficiency due to their static nature.

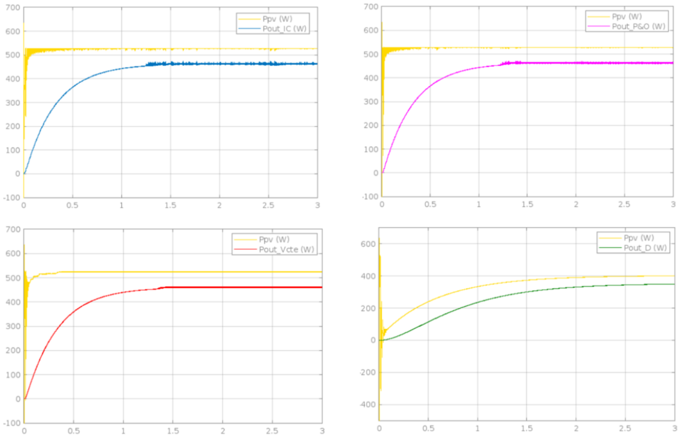

Fig. 3. MPPT Analysis for boost converter

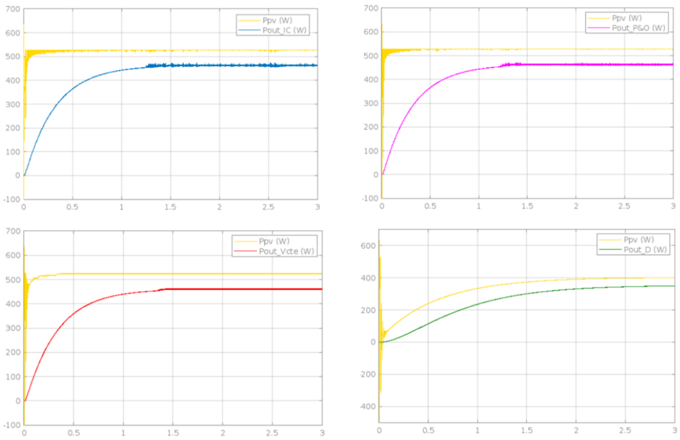

Fig. 4. MPPT Analysis for quadratic converter

In summary, the Boost converter achieved more consistent performance, whereas the Quadratic converter, despite requiring precise parameter tuning, proved beneficial for applications demanding higher voltage levels.

B. Evaluation of Converter Efficiency for Single and Panel Configurations

The efficiency evaluation of the Boost and Quadratic converters for both single-module and panel configurations is summarized in Tables V and VI, respectively. These results reveal distinct trends in performance depending on the system power level.

TABLE V.
EFFICIENCY RESULTS FOR 1 MODULE WITH BOOST AND QUADRATIC CONVERTERS (WITH CALCULATED RESISTANCE)

MPPT Method	Boost Converter Efficiency	Quadratic Converter Efficiency
Incremental Conductance	0.8735	0.6073
Perturb and Observe	0.8796	0.6040
Constant Voltage	0.8769	0.6038
Duty Cycle	0.8738	0.5924

For the single-module setup (41.35V, 530W), the Boost converter consistently outperforms the Quadratic converter, achieving efficiencies above 87% compared to around 60% for the Quadratic converter. This performance gap aligns with literature, which suggests the Quadratic converter is less efficient at lower power levels.

In contrast, for the 11-module panel configuration (454.85V, 5830W), the Boost converter reaches nearly 97% efficiency, while the Quadratic converter improves significantly, exceeding 95% efficiency. This improvement highlights the Quadratic converter's suitability for higher power outputs, where its design offers a clear advantage.

TABLE VI.
EFFICIENCY RESULTS FOR THE PANEL WITH BOOST AND QUADRATIC CONVERTERS (WITH CALCULATED RESISTANCE)

MPPT Method	Boost Converter Efficiency	Quadratic Converter Efficiency
Incremental Conductance	0.9794	0.9647
Perturb and Observe	0.9630	0.9632
Constant Voltage	0.9670	0.9552
Duty Cycle	0.9628	0.9541

Overall, the Boost converter remains the superior choice for single-module systems, but the Quadratic converter becomes competitive at panel-level power, offering a viable alternative depending on specific system requirements.

C. State of Charge Dynamics: MPPT Methods and Converter Analysis

The efficiency of energy transfer from the photovoltaic system to the battery depends on the choice of MPPT strategy and converter topology. This section presents a comparative analysis of four MPPT techniques—Incremental Conductance (IC), Perturb and Observe (P&O), Constant Voltage (Vcte), and Duty Cycle (D)—evaluating their impact on the battery's State of Charge (SoC) over time.

For the Boost converter, the IC and P&O methods showed the best performance, ensuring a steady SoC increase and efficient energy harvesting. The Vcte method also demonstrated stable performance, albeit with a slightly lower charging rate. In contrast, the D method exhibited poor energy transfer, with negligible SoC variation.

For the Quadratic converter, IC and P&O again provided optimal results, confirming their robustness across different converter topologies. The Vcte method displayed reduced effectiveness compared to the Boost configuration, indicating lower energy transfer efficiency. The D method, however, resulted in a slight decline in SoC, highlighting significant inefficiencies.

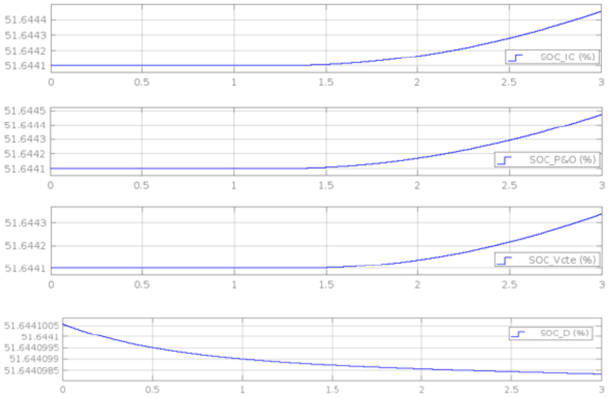

Fig. 5. SOC for differente MPPTs approach - Boost Converter

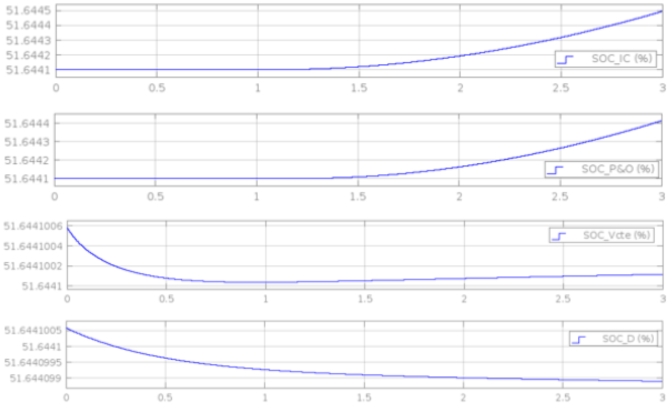

Fig. 6. SOC for differente MPPTs approach - Quadratic Converter

These results emphasize the importance of selecting an appropriate MPPT method, as it directly influences system performance, energy utilization, and battery charging efficiency.

D. System Validation: Photovoltaic Performance Under Seasonal Variations

To evaluate the real-world performance of the photovoltaic system, simulations were conducted using irradiance and temperature profiles from Curitiba, Brazil. The Boost converter combined with the Incremental Conductance (IC) MPPT method was selected for this analysis due to its superior efficiency and stability. The system was tested under two distinct seasonal conditions: June, representing the lowest solar incidence, and December, the period of highest solar availability.

Figures 7 and 8 illustrate the State of Charge (SOC) behavior of the battery during these months, highlighting the impact of seasonal variations on energy generation and storage. The results demonstrate that despite lower irradiance in June, the system maintains a stable charging process, while in December, the higher solar availability leads to improved energy capture and faster SOC increase, reinforcing the system's reliability for electric vehicle applications.

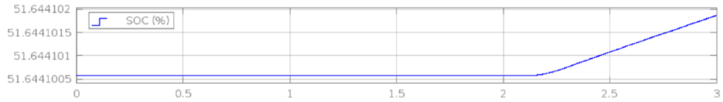

Fig. 7. State of Charge (SOC) Behavior during June

Fig. 8. State of Charge (SOC) Behavior during december

V. CONCLUSION

This study evaluated MPPT techniques for Boost and Quadratic converters in a photovoltaic system for electric buses. Simulations demonstrated that the Boost converter with the Incremental Conductance (IC) method provides the best performance, achieving efficiencies of 87.35% for a single module and 97.94% for an 11-module array. Tests under Curitiba's climatic conditions confirmed the system's reliability, maintaining stable energy transfer even in low irradiance scenarios.

The proposed solution meets the spatial and energy constraints of electric buses, offering a practical and scalable approach for solar energy integration in transportation. Future research should focus on experimental validation, integration with advanced battery technologies, and the application of AI-based MPPT algorithms to enhance efficiency and adaptability.

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