Comparative Validation of Perturbation and Observation and Incremental Conductance MPPT Techniques for Photovoltaic Integration in Electric Vehicle Battery Using RT-LAB

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Abstract - This study presents a comprehensive validation and comparative analysis of two prominent Maximum Power Point Tracking (MPPT) techniques, Perturbation and Observation (P&O) and Incremental Conductance (INC), for the integration of photovoltaic (PV) energy into electric vehicle (EV) batteries. The validation process is conducted using the real-time simulation platform RT-LAB, following initial simulations performed with SimPower Systems in MATLAB. Through rigorous assessment, the study evaluates the output power generated by the PV system employing P&O and INC MPPT techniques. Furthermore, the study examines the duty cycle of Pulse Width Modulation (PWM) controlling the DC converter, offering insights into the efficiency and efficacy of MPPT techniques in tracking the maximum power point (MPP) of the PV panel. Additionally, parameters including current, voltage, and state of charge are analyzed to provide a comprehensive understanding of the overall performance and energy utilization of the PV-integrated EV battery system. The comparative analysis results shed light on the strengths and limitations of P&O and INC MPPT approaches, aiding in the selection of the most suitable MPPT technique for PV integration in EV batteries.

Keywords - electric vehicle (EV), efficiency, energy utilization, Maximum Power Point Tracking (MPPT), photovoltaic (PV), real-time simulation, RT-LAB, SimPower Systems, state of charge, Incremental Conductance (INC), Perturb and Observe (P&O), Pulse Width Modulation (PWM).

I. INTRODUCTION

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The integration of renewable energy sources into electric vehicle (EV) drive systems is pivotal amid the growing necessity for environmentally sustainable transportation solutions. Among these sources, photovoltaic (PV) systems stand out due to their capacity to harness solar energy, offering potential additional electricity supply for vehicles [1]. However, the successful adoption of PV-integrated drive systems in EVs necessitates precise simulation and validation [2], [3].

Integration of a PV panel into the drive system offers several advantages. It supplements the vehicle's power by generating electricity from solar energy [4], [5], thereby enhancing overall sustainability and efficiency of the EV by extending its autonomy and reducing reliance on the battery. Yet, achieving effective integration and optimal utilization of solar energy requires detailed simulation models that accurately capture the intricate interactions among the PV panel, battery system, motor, and power electronics.

To maximize energy harvesting from solar panels, the application of Maximum Power Point Tracking (MPPT) techniques is crucial. MPPT algorithms continuously adjust the operating conditions of the PV system to track the Maximum Power Point (MPP), where the panel yields the highest available power. These approaches enhance energy conversion efficiency and overall system performance by maintaining the PV system at the MPP.

This paper investigates two widely-used MPPT methods: Perturbation and Observation (P&O) and Incremental Conductance (INC). Both methods find application in PV systems, including PV energy integration into EV batteries. Perturbation and Observation perturbs the operating point of the PV system and observes resulting power changes to determine the direction for MPP tracking, while INC continuously adjusts the operating point based on the system's incremental conductance. Each method exhibits distinct advantages and disadvantages concerning tracking precision, response time, and environmental adaptability. This research aims to provide a comparative analysis and validation of these MPPT approaches specifically for PV integration in EV batteries.

The simulation model is developed using MATLAB SimPower Systems, a versatile software enabling the representation of electrical components and their dynamic behavior [6]. By incorporating realistic driving profiles, solar irradiance data, and system parameters, the simulation accurately predicts the operation of the PV-integrated drive system under diverse conditions [7], [8]. The validation of the PV integration system and comparative analysis of P&O and INC MPPT methods are conducted using the RT LAB platform. RT LAB offers a reliable real-time simulation environment. Through RT LAB validation, parameters such as output power, voltage, current, and state of charge are measured and compared for both P&O and INC MPPT methods. The accuracy and effectiveness of MPPT techniques in tracking the MPP of the PV system are evaluated based on real-time data collected from the system.

II. POWER ELECTRONICS COMPONENT LAYOUT IN A BATTERY ELECTRIC VEHICLE

The conventional configuration of the power electronics parts of a battery electric vehicle (BEV) is shown in Fig. 1. The auxiliary supply system is responsible for supplying power to various equipment within the vehicle. The auxiliary supply in modern automobiles runs at 12V; however, 48V or higher voltages may be used in future models [2], [3], [9]. The drive system of EVs can use a DC motor. The DC motor is chosen due to its simple structure and low cost, making it widely used in electromechanical systems that require movement. DC motors find applications in vehicles, industrial tools [10], and robotic manipulators[11]. Moreover, they are suitable for many applications requiring accurate operation and high precision, thanks to their natural decoupling between torque and speed, as well as their simple control[12]–[15]. For simplicity, a separately excited DC motor is used.

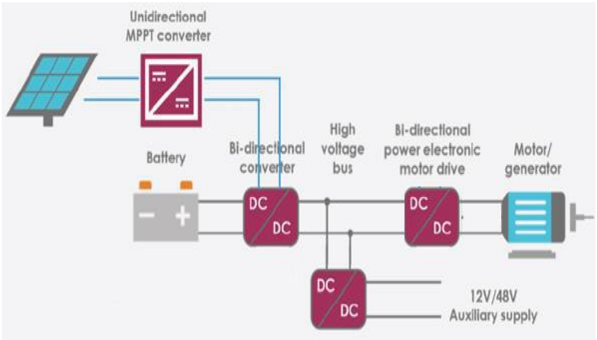

Fig. 1. Power electronics component layout in a battery electric vehicle (BEV) [9].

As the battery voltage is typically significantly lower than the voltage of the so-called high-voltage bus, the most popular DC/DC converter for power processing is a step-up (boost converter) and step-down (buck converter) converter (see Fig. 1). The device operates in buck (step-down) mode when recovering kinetic energy from the vehicle, which reduces the voltage from the high-voltage bus to a level that falls within the battery's safe voltage range [5], [16]

III. INTEGRATION OF PHOTOVOLTAIC PANELS

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The battery electric vehicle (BEV) utilizes a DC-DC converter that integrates the Maximum Power Point Tracking (MPPT) method and serves as a boost converter (see Fig. 1). The typical voltage difference between the photovoltaic (PV) panel and the vehicle's battery system determines which converter is used [17].

Since the voltage output of the PV panel is typically lower than that of the battery, a boost converter is employed to efficiently raise the voltage to the desired level. The MPPT capability of the DC-DC converter ensures that the PV panel operates at its maximum power point (MPP), maximizing the extraction of energy from the panel. The converter maximizes the amount of power transferred from the PV panel to the battery, thereby increasing overall system efficiency. It achieves this by continuously monitoring and adjusting the input voltage and current.

A) Perturbation and Observation (P&O) MPPT

In photovoltaic (PV) systems, the Perturbation and Observation (P&O) algorithm is a popular Maximum Power Point Tracking (MPPT) method. It works by continuously perturbing the operational point of the PV system and measuring the resulting change in power to determine the direction to follow the Maximum Power Point (MPP).

The P&O algorithm operates on a simple yet effective principle (see Fig. 2). It adjusts the working voltage or duty cycle of the DC-DC converter and measures the resulting change in power output. If the output power increases, the algorithm continues perturbing in the same direction until the power starts to decrease. At that point, the algorithm reverses the perturbation direction and continues tracking towards the MPP. Iteratively executing this process ensures maximal power extraction from the PV panel and dynamic adjustment of the operating point [18].

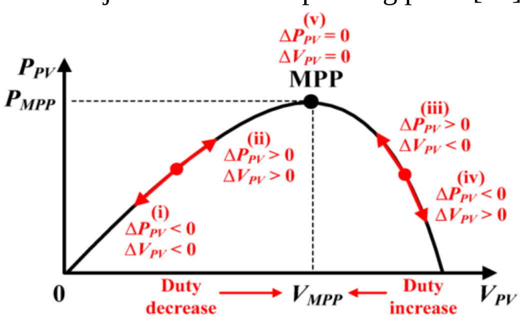

Fig. 2. Principle of operation for perturbation and observation (P&O) algorithms [18].

B) Incremental Conductance (INC) MPPT

In photovoltaic (PV) systems, the Incremental Conductance (INC) algorithm is another popular Maximum Power Point Tracking (MPPT) method. Unlike the Perturbation and Observation (P&O) technique, the INC algorithm utilizes the PV system's incremental conductance to continually adjust the operating point and monitor the Maximum Power Point (MPP).

The INC algorithm operates under the assumption that the MPP occurs when the PV system's incremental conductance is zero. Incremental conductance, the reciprocal of resistance, expresses the rate at which current changes in relation to voltage. By monitoring the incremental conductance, the algorithm determines how to adjust the operating point to track the MPP (see Fig. 3).

The algorithm compares the PV system's incremental conductance to zero and uses the result to adjust the duty cycle or operational voltage of the DC-DC converter. A positive incremental conductance indicates that the operating point is away from the MPP, prompting the algorithm to adjust the operating point accordingly. Conversely, a negative incremental conductance suggests that the operating point has passed the MPP, prompting the algorithm to adjust the operating point in the opposite direction [19].

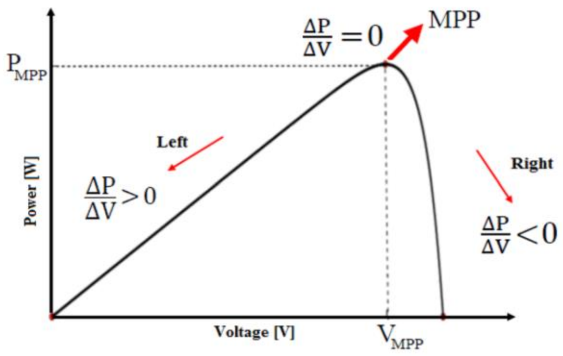

Fig. 3. Principle of operation for Incremental Conductance (INC) algorithms [19].

IV. INTEGRATION OF PHOTOVOLTAIC PANELS RT-LAB VALIDATION

RT-LAB is utilized to verify the efficiency and performance of the MPPT algorithms in the

PV-integrated system. RT-LAB offers a precise and dependable environment for real-time simulation and validation of power electronic systems. The SimPower Systems model, which simulates the PV system with MPPT algorithms, is integrated with the electrical components of the battery and DC-DC converter in the RT-LAB simulation setup. The PV panel's electrical characteristics, such as voltage, current, and power, are captured and processed by the MPPT algorithms in real-time.

The system is divided into two subsystems, SC (Speed Control) and SM (System Monitoring), to evaluate the simulation. In the SC subsystem, the reference speed is provided as an input, and the system displays parameters such as the actual motor speed, state of charge, and current. These displays are connected to the OpComm module of the RT-LAB toolbox, enabling communication and data exchange. In the SM subsystem, the system itself is integrated. The input is connected to the OpComm module, facilitating communication with external devices. The OpWriteFile module is linked to the output, which will be plotted during the remaining stages of the RT-LAB process [20], [21].

By dividing the system into these two subsystems and utilizing the capabilities of the OpComm and OpWriteFile modules within RT-LAB, the simulation can be effectively validated. The SC subsystem provides real-time monitoring of key parameters, while the SM subsystem allows for data exchange and plot generation, ensuring a comprehensive validation process.

The studied system is constructed within the SimPowerSystems environment (see Fig. 4) where the first chopper is utilized in the initial stage to stabilize the DC bus voltage. This component guarantees a steady and dependable supply of electricity to the system. By regulating the voltage, the first chopper helps ensure the stability and efficiency of the entire system. The four-quadrant chopper takes over management of the voltage needed to drive the motor. It functions throughout the entire voltage-current plane, allowing for bidirectional power flow and regenerative braking. This advanced control capability provides greater flexibility and efficiency in managing the motor's performance and energy consumption. The system consists of a 5 HP, 1750 RPM DC motor powered by a 48 V DC source (80% SOC).

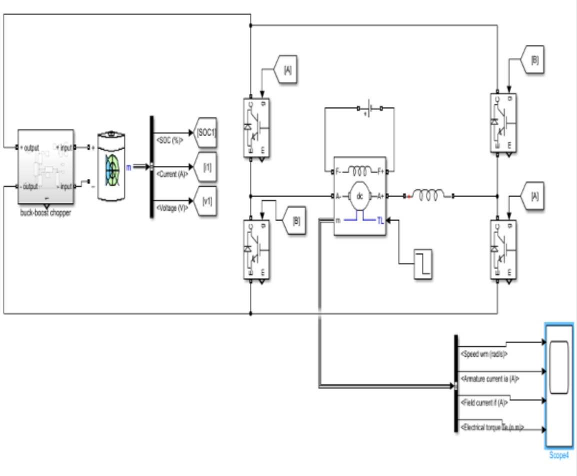

Fig. 4. Drive system EV SimPower Systems Matlab model

The simulation of the integration is achieved through a Boost chopper that ensures Maximum Power Point Tracking (MPPT) (see Fig. 5). The PV panel used in the integration has a power rating of 130 W, with an open-circuit voltage (VOC) of 21.7 V and a short-circuit current (ISC) of 8.4 A, under an irradiance level of 1000 W/m² and a temperature of 25°C.

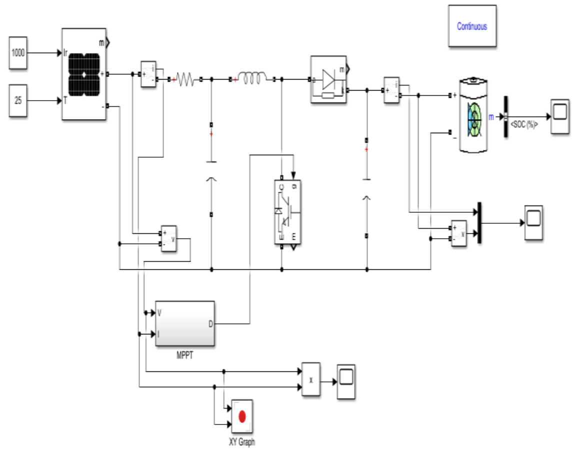

Fig. 5. PV Integration SimPower Systems Matlab model

V. RESULTS AND INTERPRETATION

The power results obtained from the RT-LAB validation of the two MPPT methods demonstrate the achievement of the maximum power output from the PV panel. The maximum power obtained is approximately 130 W, representing the maximum power that can be extracted from the PV panel (Figs. 6 and 7).

Comparing the two MPPT methods, it is observed that the Incremental Conductance (INC) MPPT method reaches the maximum power point in a shorter time, taking approximately 0.0572 s. On the other hand, the Perturbation and Observation (P&O) MPPT method takes around 0.1517 s to reach the maximum power point.

In terms of performance, the INC MPPT method exhibits less perturbation and oscillation compared to the P&O MPPT method. The maximum perturbation observed for the INC MPPT method is approximately 2.3%, while for the P&O MPPT method, it is around 8%. This indicates that the INC MPPT method provides a more stable and accurate tracking of the maximum power point.

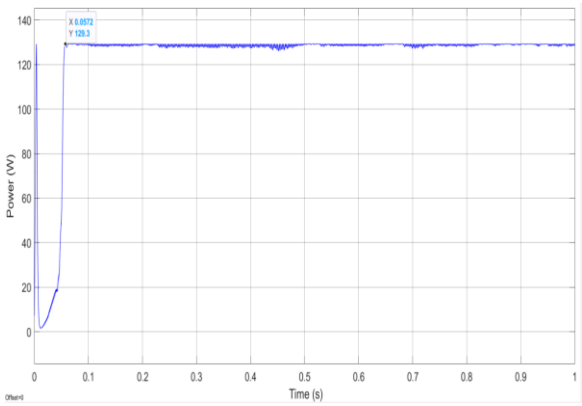

Fig. 6. Response of PV output power (W) with the Incremental Conductance (INC) MPPT algorithm

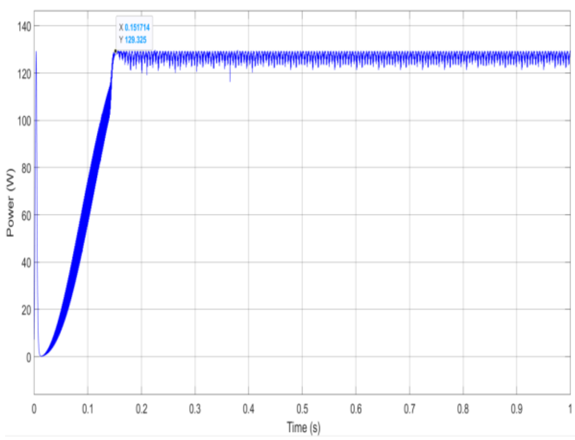

Fig. 7. Response of PV output power (W) with the perturbation and observation (P&O) MPPT algorithm

The duty cycle of the boost converter, which controls the power sent from the PV panel to the battery, is an important parameter to consider in MPPT algorithms. In the case of the Incremental Conductance (INC) MPPT method, the duty cycle reaches its maximum value at the same time as the maximum power point (Fig. 8). Similarly, for the Perturbation and Observation (P&O) MPPT method, the duty cycle reaches its maximum value around the maximum power point (Fig. 9).

Analyzing the results, it is observed that the duty cycle for the INC MPPT method oscillates around the value of 0.68, while for the P&O MPPT method, it oscillates around 0.7. This indicates that the voltage output of the boost converter does not reach its maximum value but remains stable (Figs. 10 and 11), where the output voltage is approximately 51.61 volts).

These findings suggest that both MPPT methods effectively regulate the duty cycle to maintain a stable output voltage, ensuring maximum power delivery to the load. Although the output voltage does not reach its maximum value, it remains stable for efficient operation of the system.

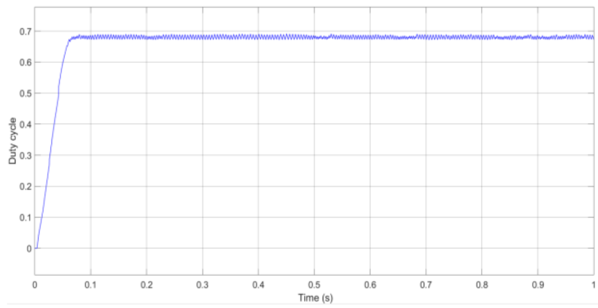

Fig. 8. Response of duty cycle with the Incremental Conductance (INC) MPPT algorithm.

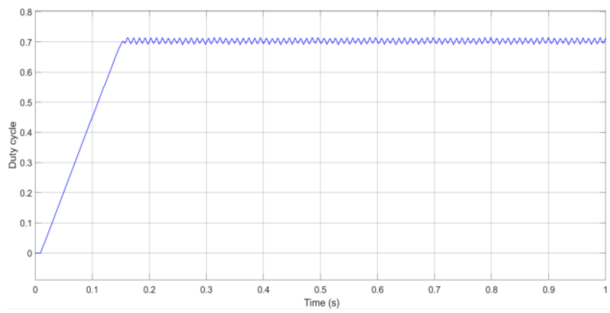

Fig. 9. Response of duty cycle with the perturbation and observation (P&O) MPPT algorithm

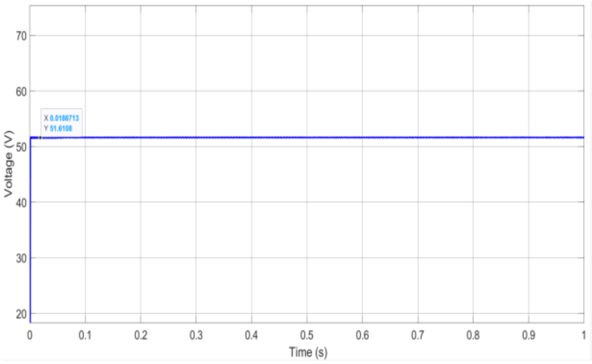

Fig. 10. Response of voltage with the Incremental Conductance (INC) MPPT algorithm

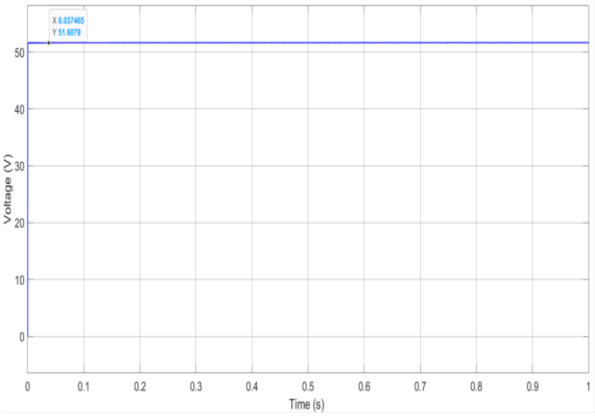

Fig. 11. Response of voltage with perturbation and observation (P&O) MPPT algorithm

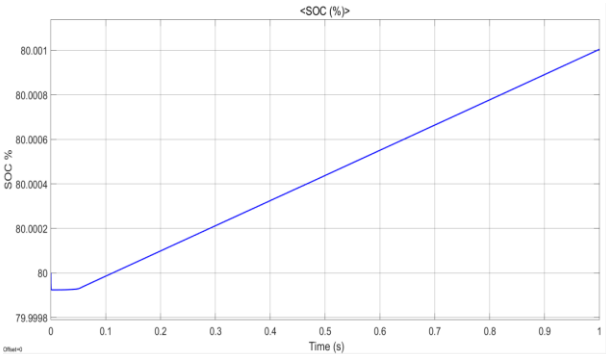

Fig. 12. Response of SOC with the Incremental Conductance (INC) MPPT algorithm.

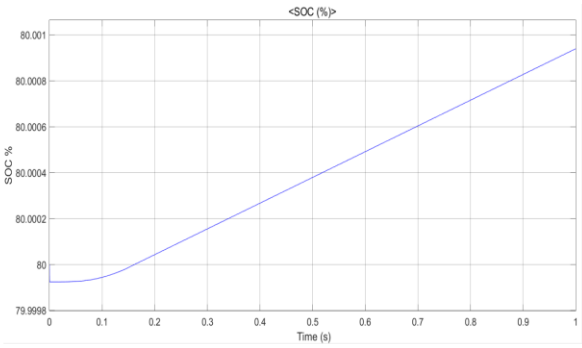

Fig. 13. Response of SOC with the perturbation and observation (P&O) MPPT algorithm

As it indicates the amount of charge held in the battery, the state of charge (SOC) of the battery is a crucial metric to monitor in PV integration systems. When using either of the MPPT methods, it is observed that the battery's SOC increases, indicating that the battery is charging (Figs. 12 and 13).

Upon analyzing the results, it is noted that the Incremental Conductance (INC) MPPT method achieves an SOC of 80.001% within one second (Fig. 12). In comparison, the Perturbation and Observation (P&O) MPPT method achieves an SOC of 80.0009% during the same period (Fig. 13).

These findings demonstrate that both MPPT methods effectively charge the battery, with the INC MPPT method slightly outperforming the P&O MPPT method in terms of SOC increment.

VI. CONCLUSION

This study utilizes MATLAB SimPower Systems and RT-LAB to validate a PV-integrated drive system for electric vehicles. The performance and efficacy of two widely utilized MPPT techniques, Perturbation and Observation (P&O) and Incremental Conductance (INC), were examined and compared.

Both MPPT methods successfully tracked the maximum power point (MPP) of the PV panel during the RT-LAB validation process, achieving the maximum power output. However, the P&O method exhibited slightly slower response times compared to the INC method.

Both MPPT techniques effectively controlled the boost converter's duty cycle, regulating power delivery. The duty cycles for the P&O and INC methods exhibited stable fluctuations around 0.68 and 0.7, respectively, ensuring correct voltage delivery to the battery.

Furthermore, both MPPT methods resulted in a gradual increase in the battery's state of charge (SOC), indicating successful battery charging. The INC method marginally outperformed the P&O method, achieving a SOC of 80.001% within one second compared to 80.0009%.

The validation results by RT-LAB confirm the accuracy and reliability of the simulation models for the PV-integrated drive system. Both MPPT methods demonstrated their effectiveness in tracking the MPP and controlling power delivery. These findings contribute to the advancement of PV integration in electric vehicles, providing insights for system design, optimization, and future research.

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NOMENCLATURE

MPPT Maximum Power Point Tracking
P&O Perturbation and observation
INC Incremental Conductance
EV electric vehicle
PV Photovoltaic

VII. REFERENCES

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