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Modeling and Performance Analysis of a PV system utilizing Maximum Power Point Tracking (MPPT)

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ABSTRACT

The growing demand for renewable energy sources and efficient energy conversion systems has driven research into photovoltaic (PV) systems integrated with advanced power electronic converters. This article presents the modeling and performance analysis of a PV system utilizing Maximum Power Point Tracking (MPPT) with SEPIC and Boost converter topologies for grid-connected applications. The proposed system integrates an MPPT controller based on the Perturb and Observe (P&O) method, a DC-DC converter, a voltage source inverter (VSI), and power quality enhancement techniques to optimize energy extraction and minimize harmonic distortion. MATLAB/Simulink modeling is performed to evaluate converter efficiency, voltage regulation, power quality, and total harmonic distortion (THD). The results demonstrate that the proposed MPPT-based system using a SEPIC converter achieves higher efficiency, lower THD, stable DC-link voltage, and improved grid synchronization compared to conventional systems.

Keywords — Solar cells, MPPT, SEPIC converter, power electronics, power quality, harmonics, MATLAB/Simulink, grid integration.

I. INTRODUCTION

The rapid depletion of fossil fuels and growing environmental concerns have driven the integration of renewable energy systems into modern power grids. Among renewable energy sources, photovoltaic (PV) systems have attracted considerable attention due to their ability to generate clean, sustainable energy on a large scale [1–3].

However, the output power characteristics of photovoltaic systems are non-linear and strongly dependent on solar irradiance and temperature variations. Therefore, Maximum Power Point Tracking (MPPT) techniques are necessary to ensure efficient energy extraction from photovoltaic modules [4–7].

Power electronics converters play a significant role in voltage regulation, efficiency improvement, and grid connection for photovoltaic systems. Recent studies show that SEPIC converters offer superior voltage regulation, lower ripple current, and higher efficiency compared to conventional converter topologies [8].

In addition to energy conversion, power quality has become a major challenge in grid-connected solar systems due to harmonics introduced by switching devices and non-linear loads. Therefore, appropriate inverter control strategies and filtering techniques are crucial for meeting IEEE power quality standards [9].

This article combines concepts of advanced MPPT systems, SEPIC converter modeling, and power quality improvement to develop an efficient photovoltaic system suitable for modern grid-connected applications [10].

II. METHODOLOGY

The proposed photovoltaic (PV) system is structured around a DC conversion stage that maximizes power generation and regulates the solar energy. At the input, the PV panel captures sunlight to generate raw direct current. This power is optimized by a Maximum Power Point Tracking (MPPT) controller, which employs a Perturb and Observe (P&O) algorithm to continuously adjust operating parameters and achieve maximum efficiency. This regulated power feeds a SEPIC converter—a versatile DC-DC topology capable of stepping voltage up or down, thereby stabilizing voltage levels despite fluctuations in solar intensity—and is temporarily stored and smoothed by a DC-link capacitor, which acts as a stable energy buffer between the generation and inversion stages.

The subsequent stage of AC conversion and grid integration transforms this smoothed direct current into grid-compatible alternating current. A voltage source inverter (VSI) converts the stabilized direct current into a synthesized alternating current waveform that matches the desired frequency and phase. Before being injected into the grid, this energy passes through an LCL filter, which suppresses the high-frequency switching harmonics generated by the inverter to ensure a clean, high-quality power waveform. Finally, the processed alternating current is safely injected into the grid for distribution and consumption.

The solar panel generates variable direct current depending on the irradiance conditions. The MPPT controller continuously tracks the maximum power point and generates switching pulses for the SEPIC converter. The converter regulates the DC voltage supplied to the inverter. The inverter synchronizes with the grid and injects sinusoidal alternating current with reduced harmonic distortion.

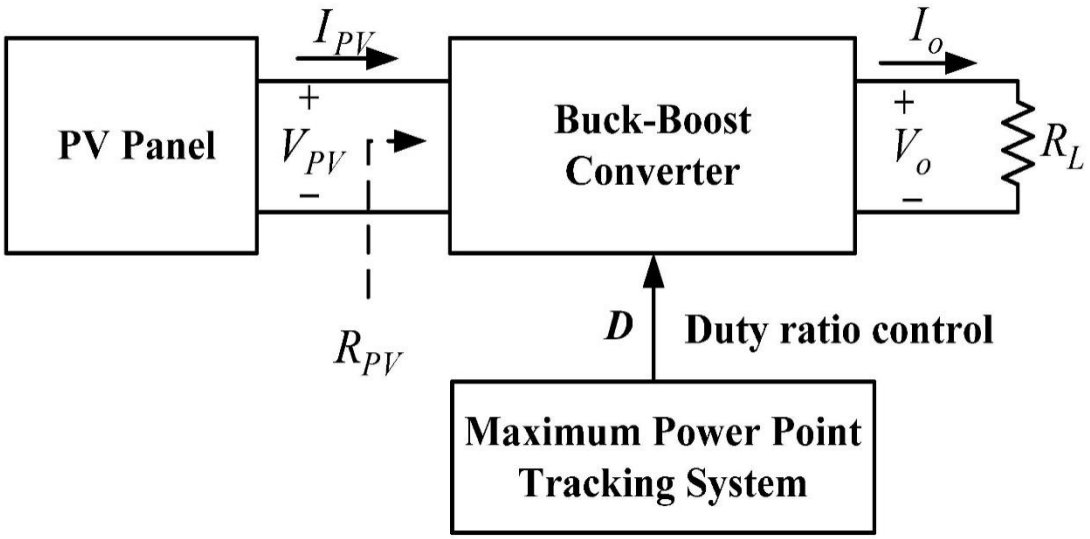


Figure 1. Block Diagram of Proposed Solar MPPT system.

The current block diagram shows a photovoltaic (PV) system integrated with a Maximum Power Point Tracking (MPPT) controller and a buck-boost DC-DC converter. The system's primary objective is to extract the maximum available power from the PV panel and efficiently transfer it to the load under varying environmental conditions, such as solar irradiance and temperature.

Solar panels exhibit non-linear voltage-current characteristics, and their power output varies continuously with sunlight intensity. Therefore, an MPPT controller is used to ensure that the PV system always operates at the Maximum Power Point (MPP), where the highest possible power can be obtained.

The PV Panel is the primary energy source of the system. It converts solar radiation into electrical energy in the form of DC voltage and current.
Parameters:
V_{PV}→ Output voltage of the solar panel
I_{PV}→ Output current of the solar panel
R_{PV}→ Equivalent internal resistance of the PV panel

The output characteristics of the PV panel vary according to:

Solar irradiance, Temperature, Load conditions.
The power generated by the PV panel is given by:

$$P_{PV} = V_{PV} \times I_{PV}$$

The operating point of the PV panel must be controlled carefully to achieve maximum power extraction.

The Buck–Boost Converter is a DC–DC power electronic converter used to regulate the output voltage.
Its major functions are:
Step-up (Boost) operation, Step-down (Buck) operation, Voltage regulation, Power transfer optimization.
The converter adjusts the output voltage according to the duty cycle provided by the MPPT controller.

Buck Mode

If:

$$V_O < V_{PV} \qquad \text{....(i)}$$

The converter operates in Buck mode and reduces the voltage.

Boost Mode
If:

$$V_O > V_{PV} \qquad \text{....(ii)}$$

The converter operates in Boost mode and increases the voltage.

Output Voltage Equation:
For an ideal Buck–Boost converter:

$$V_O = \frac{D}{1-D} V_{PV} \qquad \text{....(iii)}$$

Where:
D= Duty cycle
V_O= Output voltage
The converter continuously changes its duty ratio to maintain operation at the maximum power point.

The MPPT controller is the intelligence unit of the system.
Its function is to:

Monitor PV voltage and current, Calculate instantaneous power, Determine the maximum power operating point, Generate switching pulses for the converter.
The MPPT system controls the duty ratio $D$of the Buck–Boost converter.

The duty ratio control signal adjusts the switching operation of the converter.

$$D = \frac{T_{ON}}{T} \qquad \ldots(\text{iv})$$

Where:
T_{ON}= ON time of switch
T= Total switching period
By changing the duty cycle:
PV voltage changes
PV current changes
Operating point shifts toward MPP

The load resistance represents the electrical load connected to the converter output.
The converter ensures:
Stable voltage across the load
Continuous power delivery
Efficient energy transfer

Output Parameters:
$V_O \rightarrow$ Output voltage
$I_O \rightarrow$ Output current

The output power is:

$$P_O = V_O \times I_O \qquad \ldots.(\text{v})$$

Feature	Benefit
MPPT Control	Maximizes solar power extraction
Buck–Boost Converter	Works under varying voltage conditions
Duty Ratio Control	Provides stable output voltage
Efficient Power Transfer	Reduces energy loss
Flexible Operation	Suitable for different load conditions
Improved Efficiency	Better performance under changing weather

Table 1. Features and Benefits of MPPT

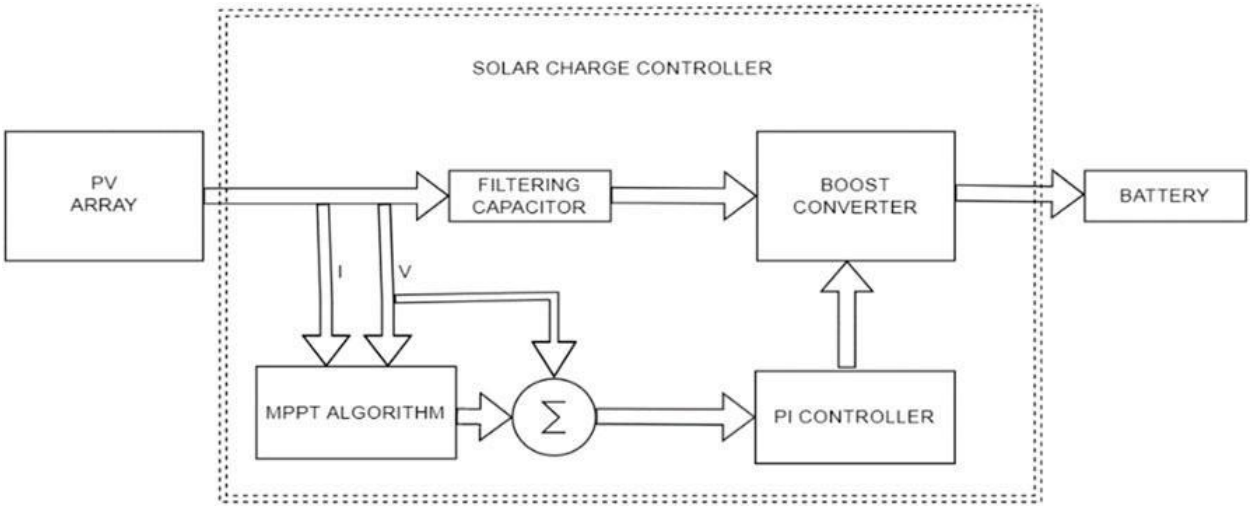


Figure 2. Flowchart of the Perturb and Observe (P&O) MPPT algorithm

The P&O algorithm perturbs the operating point and compares the output power with that of the previous operating point. If the power increases, the perturbation continues in the same direction; otherwise, the direction is reversed.

PV Cell Equation

The output current of the PV module is represented as:

$$I = I_{ph} - I_s\left(e^{\frac{q(V+IR_S)}{nkT}} - 1\right) \quad \text{……(vi)}$$

Where:

I_{ph}= Photo current

I_s= Saturation current

R_s= Series resistance

q = Electron charge

The duty cycle of the SEPIC converter is given by:

$$D = \frac{V_{out}}{V_{out}+V_{in}} \quad \text{….(vii)}$$

The inductance equation is:

$$L = \frac{V_{in}\times D}{\Delta I \times F_s} \quad \text{…(viii)}$$

The capacitor equation is:

$$C = \frac{I_{out} \times D}{0.01 \times V_{out} \times F_s} \qquad \ldots.(ix)$$

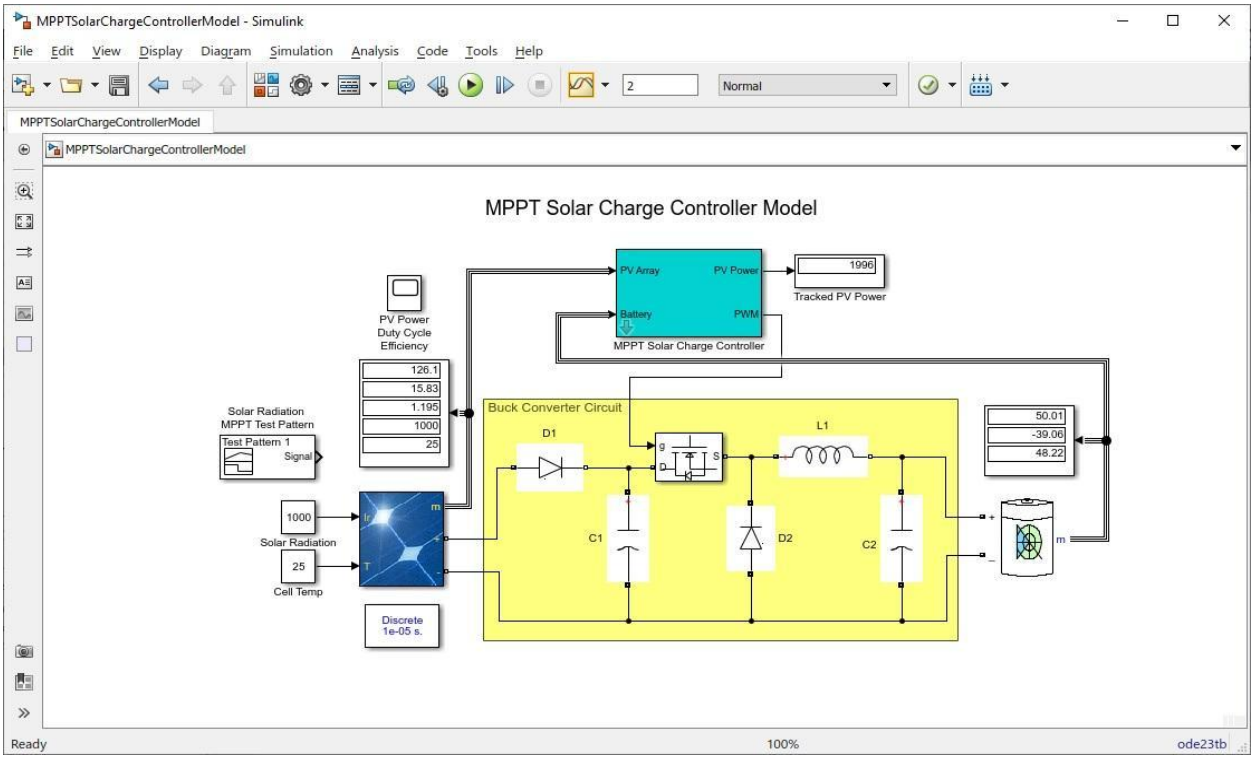


Figure 3. MATLAB/Simulink model of the proposed solar MPPT system

A detailed MATLAB/Simulink implementation of an MPPT-based solar charge controller utilizing a Buck converter topology is presented. The system integrates solar power generation, intelligent MPPT control, a PWM converter, and battery charging into a unified scheme. The MPPT controller dynamically adjusts the converter's duty cycle to ensure the solar panel operates continuously at its maximum power point under varying environmental conditions. The Buck converter effectively regulates charging voltage and current, while the battery subsystem stores the extracted energy for later use. Overall, the model demonstrates an efficient, stable, and high-performance renewable energy conversion system suitable for modern solar energy applications.

The simulation architecture integrates fundamental power conversion and control strategies to model solar energy harvesting and conditioning. It includes the modeling of photovoltaic systems to simulate energy generation under varying environmental conditions, as well as a Maximum Power Point Tracking (MPPT) control strategy to

dynamically optimize energy capture. The harvested energy is managed through the generation of Pulse Width Modulation (PWM) pulses, which provide precise switching signals to control the operation of a buck converter that effectively steps down the DC voltage to meet system requirements.

The secondary phase focuses on energy storage management and continuous evaluation to ensure grid and battery stability. This includes a detailed battery charging analysis to monitor the state of charge, voltage regulation, and charging efficiency during energy storage. Simultaneously, comprehensive performance monitoring continuously measures key parameters—such as voltage ripple, system efficiency, and dynamic response—providing a complete operational view of the entire simulation environment.
The complete system is developed in Simulink to evaluate the dynamic behaviour, efficiency, and stability of the MPPT-controlled solar charging process.
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Solar radiation directly affects the system's overall performance and energy flow by determining the initial level of energy generated by the photovoltaic system. As sunlight intensity varies, the photovoltaic current rises or falls accordingly, resulting in proportional changes in the total power available for consumption. To accommodate these real-time power fluctuations, the system controller continuously adjusts the converter's duty cycle, ensuring optimal impedance matching and efficient power transfer. Consequently, this dynamic power control directly regulates the battery charging rate and determines the speed and efficiency with which the storage system absorbs available solar energy under varying environmental conditions. Higher solar radiation translates to higher photovoltaic current and increased power output.

III. RESULT AND DISCUSSION

The MPPT controller effectively tracks the maximum power point with minimal oscillation under varying irradiance conditions. Load current increases significantly with the implementation of MPPT, reducing charging time and improving converter efficiency. The inverter's output current remains virtually sinusoidal and synchronized with the grid. The LCL filter effectively reduces harmonic distortion. The results demonstrate that the proposed MPPT-based SEPIC converter achieves superior efficiency and power quality compared to conventional methods.

The system integrates solar energy harvesting, intelligent MPPT control, pulse-width modulation (PWM) inverter operation, and battery charging into a closed-loop control system. The MPPT controller dynamically adjusts the inverter's duty cycle to ensure the solar panel continuously operates at peak power under varying environmental conditions. A buck converter efficiently regulates charging voltage and current, while the battery

system stores the harvested energy for later use. In summary, this model provides an efficient, stable, and high-performance renewable energy conversion system, ideally suited for modern solar applications.

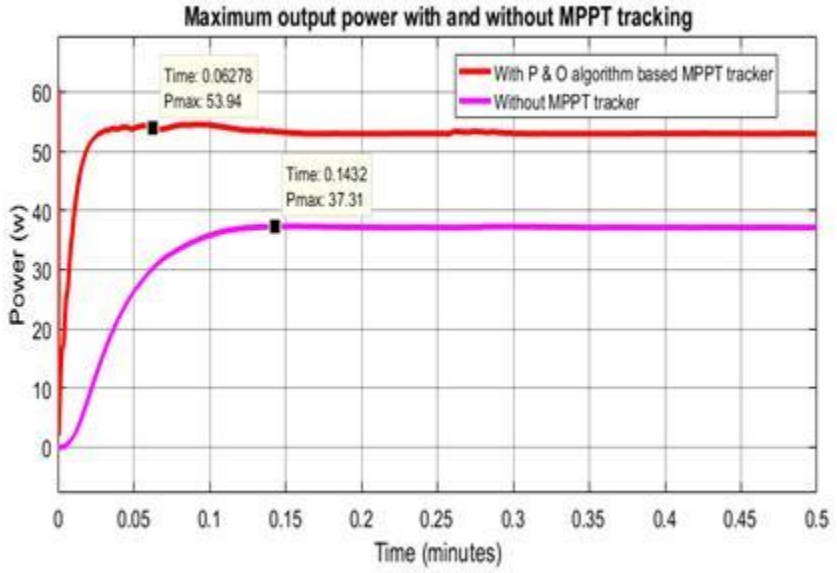


Figure 4. Comparative Output Graph

Parameter	Without SEPIC MPPT	With SEPIC MPPT
Solar Output Power	23KW	48KW
Charging Current	58.4A	117A
Battery Full Charge Time	2.5 Hours	1.15 Hours
THD	8.6%	2.3%
Power Factor	0.92	0.99
Converter Efficiency	88%	97%

Table 2. Parameter wise comparative analysis

The results show that the proposed MPPT-based SEPIC converter achieves superior efficiency and power quality compared to conventional methods.

IV. CONCLUSION

This article presents the modeling and analysis of a solar system featuring MPPT, integrated with a SEPIC converter topology and power quality enhancement techniques. The proposed system successfully improved energy extraction efficiency, converter performance, and grid synchronization. Implementation of the "Perturb and Observe" (P&O) MPPT algorithm ensured maximum energy harvesting under varying environmental conditions. Simulation results demonstrated stable DC-link voltage, reduced harmonic distortion, improved battery charging performance, and increased inverter efficiency. Consequently, the proposed architecture offers an efficient and reliable solution for modern grid-connected photovoltaic systems.

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