

Design and Simulation of an Intelligent Control System for Solar Energy Conversion using MPPT

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ABSTRACT

The growing reliance on photovoltaic (PV) systems in decentralized energy generation requires efficient control strategies to ensure maximum energy extraction under varying environmental conditions. One of the major challenges in PV operation is maintaining system efficiency despite fluctuations in temperature and solar irradiance. This study aims to design and simulate an intelligent control system incorporating a maximum power point tracking (MPPT) technique to optimize energy conversion in PV systems. Using MATLAB/Simulink, a dynamic model of the PV system was developed, including MPPT, power conversion, energy storage, and load management components. The simulation evaluates the behavior of the system under different irradiance and temperature levels. Results demonstrate that the proposed control strategy successfully tracks the maximum power point, improving energy output across a range of operating conditions. The findings confirm the importance of integrating adaptive MPPT algorithms and energy storage management for enhancing the overall efficiency of solar energy systems. This work provides a foundation for future development of intelligent PV systems tailored for fluctuating environmental conditions.

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1. INTRODUCTION

Photovoltaic (PV) systems have become a critical component in the global effort to transition toward renewable and decentralized energy sources. Their widespread adoption is driven by environmental concerns, governmental policies, and the rapid decline in PV module costs (1), (2). Despite their advantages, PV systems remain highly sensitive to external factors such as solar irradiance and ambient temperature, which directly affect the output power and the maximum power point (MPP) of the system (3), (4). Traditional maximum power point tracking (MPPT) algorithms, including perturb and observe (P&O) and incremental conductance (IncCond), are often limited by their slow response and suboptimal performance under fast-changing weather conditions (5). To overcome these limitations, recent research has focused on developing intelligent control systems that integrate adaptive or heuristic algorithms, including fuzzy logic, artificial neural networks, and particle swarm optimization, to improve the tracking accuracy and energy yield (6), (7).

In this study, an intelligent control system incorporating an MPPT algorithm is designed and simulated using MATLAB/Simulink to evaluate its performance under varying irradiance and temperature conditions. The **2. Background on Photovoltaic Systems**

Photovoltaic (PV) systems convert solar radiation into electrical energy through the photovoltaic effect, where light photons generate electron-hole pairs in a semiconductor junction, resulting in direct current (DC) output (8). The electrical performance of PV modules is highly dependent on environmental factors, especially solar irradiance, and temperature. As irradiance increases, the short-circuit current (I_{sc}) rises almost linearly, while the open-circuit voltage (V_{oc}) increases logarithmically. On the other hand, temperature primarily affects the V_{oc} , causing it to decrease significantly with rising cell temperature, whereas I_{sc} increases only slightly (9). These variations shift the maximum power point (MPP), which is the operating point at which the product of voltage and current is maximized. Tracking the MPP accurately under fluctuating conditions is essential to improve energy yield. Conventional MPPT algorithms, such as Perturb and Observe (P&O) or Incremental Conductance, often suffer from limitations under dynamic environmental changes. Therefore, adaptive, and intelligent MPPT control strategies are required to ensure real-time tracking performance (10). Simulation tools such as MATLAB/Simulink enable detailed modeling of PV systems and their response to changes in irradiance and temperature, supporting the design of robust control systems that can sustain efficient operation across a wide range of conditions (11).

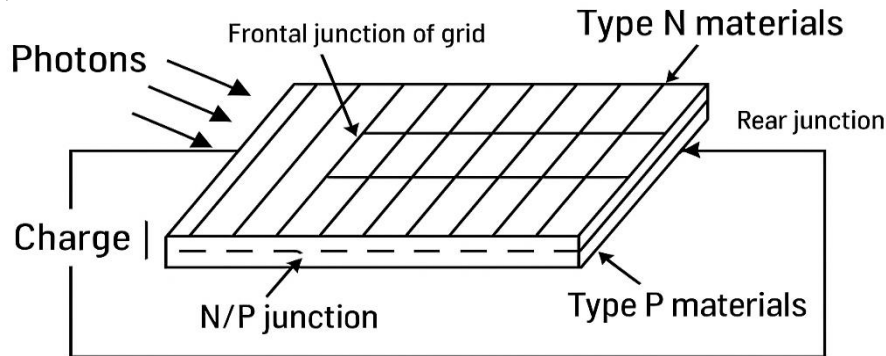


Figure (1): Principle of conversion of solar energy into electrical energy by photovoltaic cell (12)

Figure 1 below illustrates the basic principle of energy conversion in a PV cell, where photons interacting with the PN junction create charge separation, allowing current flow under illumination conditions. (12)

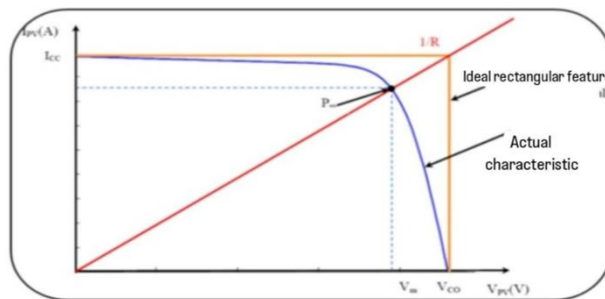


Figure (2): Current/voltage characteristic

A photovoltaic (PV) cell consists of a p-n junction formed by a p-type silicon layer (boron-doped) and an n-type silicon layer (phosphorus-doped). When photons are absorbed by the cell, they excite electrons, generating electron-hole pairs that are separated by the internal electric field of the junction. This separation leads to the flow of current under external load conditions(13). In the dark, a PV cell behaves like a standard diode. Under illumination, however, it becomes a current source, exhibiting a nonlinear current-voltage (I-V) characteristic. The maximum voltage occurs at open circuit conditions (V_{oc}), typically around 0.6 V per cell, and the maximum current occurs at short-circuit conditions (I_{sc}) (13). Both V_{oc} and I_{sc} are influenced by irradiance and temperature, making accurate modeling essential for MPPT design (15).

Figure 3 illustrates the ideal and actual I-V characteristics of a photovoltaic cell. The deviation from the rectangular shape represents power losses due to series resistance and recombination effects. The maximum power point

(P_{max}) is the optimal operating point where the product of current and voltage is maximized, which intelligent MPPT algorithms seek to track continuously under varying conditions.

3. Methodology

This section presents the modeling approach, system components, and simulation settings used to design and evaluate the intelligent photovoltaic energy production system. All simulations were implemented using MATLAB/Simulink, providing a comprehensive environment for modeling both power electronics and control strategies.

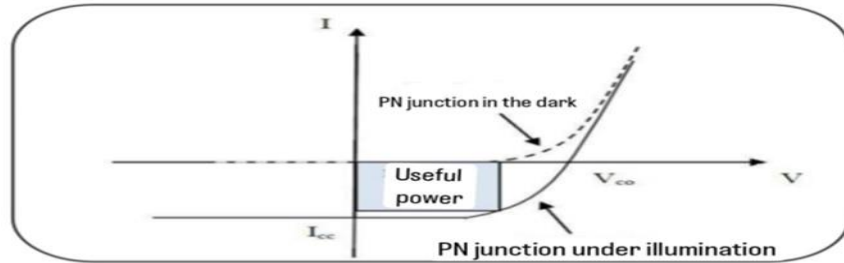


Figure (3): Current-voltage characteristic of a photovoltaic cell.

3.1 System Modeling Overview

The developed system integrates three subsystems:

1. Photovoltaic Generator: Based on a 1 kW panel modeled with parameters of the SHARP NE80E1U module.
2. Energy Storage: A battery system charged during excess production, modeled as a DC energy reservoir.
3. Grid Interface: A NEG 1600 inverter connected to the grid for power injection and a backup converter in case of outages.

The simulation also includes residential loads (lighting, PC, refrigerator...) and is managed by a PIC microcontroller-based control unit.

A block diagram of this integrated model is presented in Figure (14), showing the interaction between generation, storage, and consumption components.

3.2 MPPT Control Implementation

The Perturb and Observe (P&O) algorithm was used as the MPPT technique due to its simplicity and effectiveness. It was implemented in the Simulink environment using feedback control loops that adjust the duty cycle of the DC-DC converter based on instantaneous power variation.

3.3 Simulation Parameters

The system was simulated under dynamic environmental and load conditions. Key parameters are summarized below:

Table 1 – Simulation Input Parameters

Value / Range	Simulation Parameter
1 kW	PV rated power
200, 600, 1000 W/m ²	Irradiance levels (G)
0°C, 25°C, 50°C, 75°C	Temperature levels (T)
48 V, 100 Ah	Battery storage capacity
Residential: lamp, PC, refrigerator	Load types
0 – 10 seconds	Simulation time
NEG 1600 (DC to AC conversion)	Inverter model
Microcontroller (PIC-based logic)	Control unit

3.4 Simulation Objectives

The main objectives of the simulation are to:

- Validate the effectiveness of the MPPT algorithm under varying irradiance and temperature.
- Assess the dynamic behavior of the PV–battery–load interaction.
- Analyze the system response during power injection and backup switching scenarios.

4- Photovoltaic cell technologies

Different methods are available for converting sunlight into electrical power. One of the most recognized is the photovoltaic conversion of energy that takes place in semiconductor materials like Si, Ge, Se, or compounds like GaAs or CdTe. GaAs-based solar cells are prohibitively expensive to create and their utilization is primarily limited to space applications.

$$I_{sc} \left[1 - K_1 \left(e^{A K_2 V} - 1 \right) \right] =_{pv} I$$

4.1 Single-Diode Model Parameters

The single-diode equivalent circuit is the most widely used representation of a photovoltaic (PV) cell, consisting of a current source I_{ph} , a diode, a series resistance R_{sR_s} , and a shunt resistance $R_{shR_{sh}}$ (Villalva et al., 2009) (13). The cell output current I_{pv} is given by:

where:

$$I_{pv} = I_{ph} - I_0 \left[e^{\frac{V_{pv} + I_{pv}R_s}{nV_T}} - 1 \right] - \frac{V_{pv} + I_{pv}R_s}{R_{sh}}$$

- I_{ph} is the photocurrent (A), proportional to irradiance.
- I_0 is the diode reverse saturation current (A).
- n is the diode ideality factor (–).
- $V_T = kT/q$ is the thermal voltage (V).
- R_{s} and R_{sh} (Ω) model internal losses.

Below are typical parameter values for a crystalline-silicon PV cell under Standard Test Conditions (STC: 1 kW/m², 25 °C):

Table 2: Single-diode model parameters for a crystalline-silicon PV cell under STC (14)

Parameter	Symbol	Value	Unit
Photocurrent	I_{ph}	5.31	A
Saturation current	I_0	7.27×10^{-5}	A
Ideality factor	n	1.0	—
Series resistance	R_{sR_s}	0.4	Ω
Shunt resistance	$R_{shR_{sh}}$	109.9	Ω

These parameter values can be extracted from manufacturer datasheets or by fitting the cell’s measured I–V curve. Accurate determination of I_0 , R_{s} and R_{sh} is crucial for reliable simulation and control-system design.

4.2 Simplified Five-Parameter Model

The five-parameter model is a simplified yet accurate representation of a photovoltaic (PV) module under standard test conditions (STC). (15) It is based on measured values available from the manufacturer’s datasheet, including:

- Short-circuit current: I_{sc}

- Open-circuit voltage: V_{oc}
- Voltage at maximum power point: V_{mpp}
- Current at maximum power point: I_{mpp}
- Series resistance: sR

The output current I_{pv} of the PV module is approximated by the following expression:

The empirical constants can be computed from known module data using the following intermediate relations:

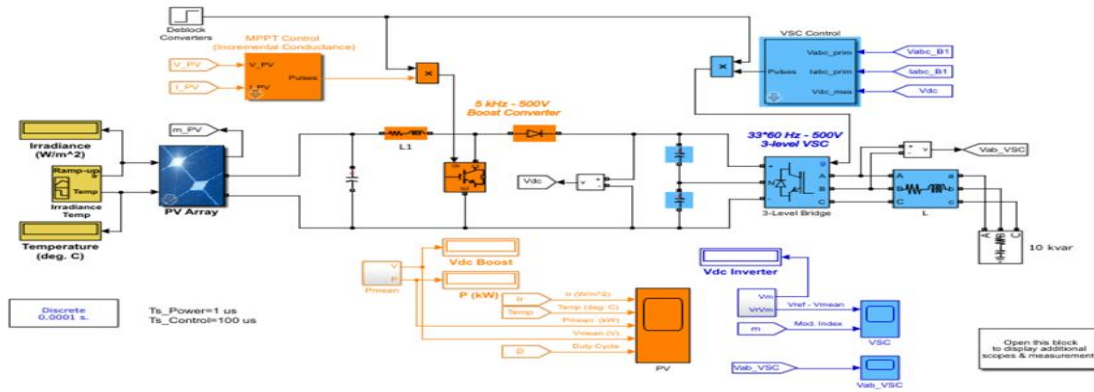


Figure (4): Simulink model of the SHARP NE80E1U PV system with MPPT and VSC control.

5. Factors Influencing the Operation of a Photovoltaic Cell: A. Influence of Illumination

The electrical performance of photovoltaic (PV) cells is significantly influenced by variations in solar irradiance. As irradiance increases, the generated photocurrent rises proportionally, while the open-circuit voltage exhibits a slower, logarithmic growth. Understanding this behavior is crucial for accurate modeling and control of PV systems under varying environmental conditions. (16)

For the purpose of simulation, the SHARP NE80E1U photovoltaic panel was selected due to its standard application and availability of technical data.

Table (3) summarizes the panel’s electrical specifications under standard test conditions (STC). (17)

Settings	Valeur's
Maximum power of P_{mpp} panel	80W
Current at maximum power point I_{mpp}	4.67A
Voltage at maximum power point V_{mpp}	17.1V
I_{sc} short circuit current I_{sc}	5.31A
Open circuit voltage V_{oc}	21.3V
Number of cells	36
Current increment coefficients $I_{sc} (asc)$	1.4 mA/ o_c
Voltage increment coefficients $V_{sc} (Boc)$	-152 mV/ o_c

Table (3): The parameters of the SHARP NE80E1U solar panel

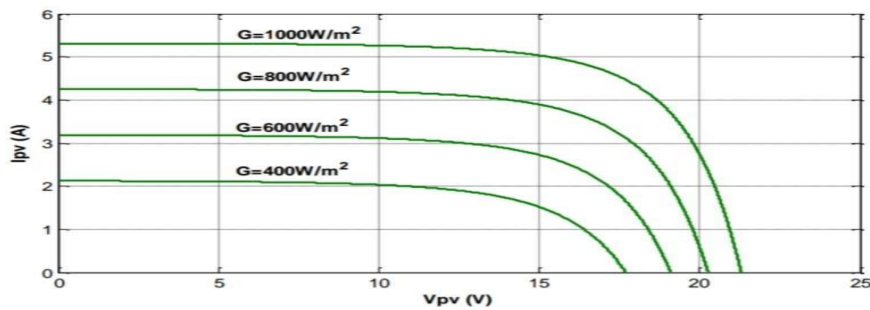


Figure (5): Characteristic $I_{pv} = f(V_{pv})$ for different sunshine at $T=25^{\circ}C$.

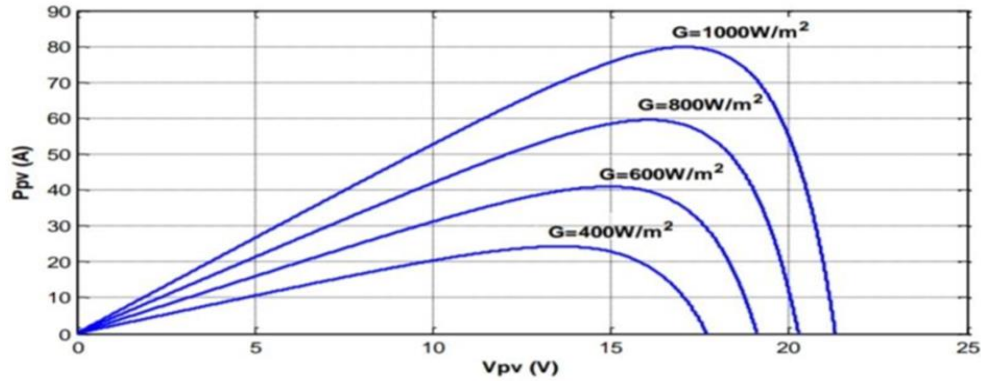


Figure (6) .Characteristic $P_{pv} = f(V_{pv})$ for different sunshine at $T=25^{\circ}\text{C}$.

MATLAB/Simulink simulation was performed to evaluate the current–voltage (I–V) and power–voltage (P–V) characteristics of the panel under varying levels of irradiance. Figures (8) and (9) present the simulation results, illustrating the influence of illumination on the output current and power. As irradiance increases, the short-circuit current (I_{sc}) increases linearly, while the open-circuit voltage (V_{oc}) remains relatively stable. (18)

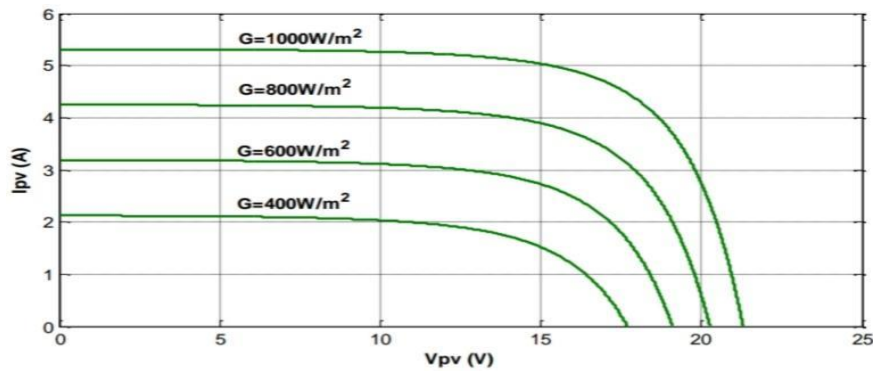


Figure (7):: Characteristic $I_{pv} = f(V_{pv})$ for different temperatures at $G=1000\text{W}/\text{m}^2$

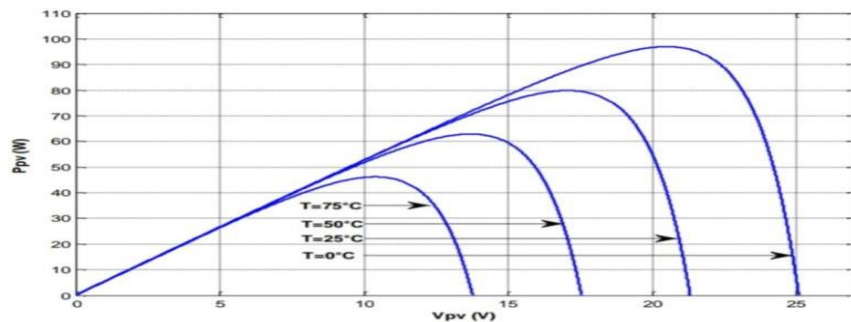


Figure (8) :: Characteristic $P_{pv} = f(V_{pv})$ for different temperatures at $G=1000\text{W}/\text{m}^2$.

For different temperatures ($T_c=0, 25, 50, 75^{\circ}\text{C}$) and $G= 1000\text{W}/\text{m}^2$, a simulation was carried out using the Matlab-Simulink software to determine the current-voltage characteristics $I_{pv} (V_{pv})$ and power- P_{pv} voltage (V_{pv}) of the photovoltaic generator. The electrical characteristics (figures 7,8) clearly show that when the temperature increases at constant irradiation, the open circuit voltage V_{os} decreases when the temperature increases and the current I_e increases slightly.(19)

Temperature is a very important factor in the behavior of PV cells. the photocurrent I_{ph} increases by approximately $0.2 \mu A/^{\circ}K$ per cm^2 . It also causes a drop in the open circuit voltage V_{oc} of approximately $0.02 mV$ per degree. The increase in temperature degrades the maximum power supplied by the cell, it drops by approximately $1.27 104 W/^{\circ}K$ per cm^2 of cell, which corresponds to approximately 1.05% per degree. (20)

7. Association of photovoltaic cells

In a group of n_s cells connected in series, the same current flows through all cells. Figure (10) shows the final characteristics of such a grouping under ideal conditions (I_{sc}, V_{sc}), which is obtained by summing the basic characteristics at constant current for n_s identical cells (I_{ce}, V_{co}): $V_{sco} = n_s \cdot V_{co}$ For a group of different parallel cells (Fig. 11): $I_{pcc} = n_p \cdot I_{cc}$. (21)

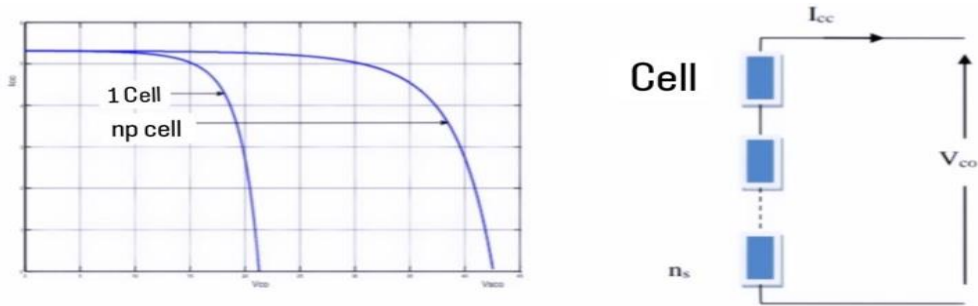


Figure (10) : Series grouping characteristic of identical photovoltaic cells

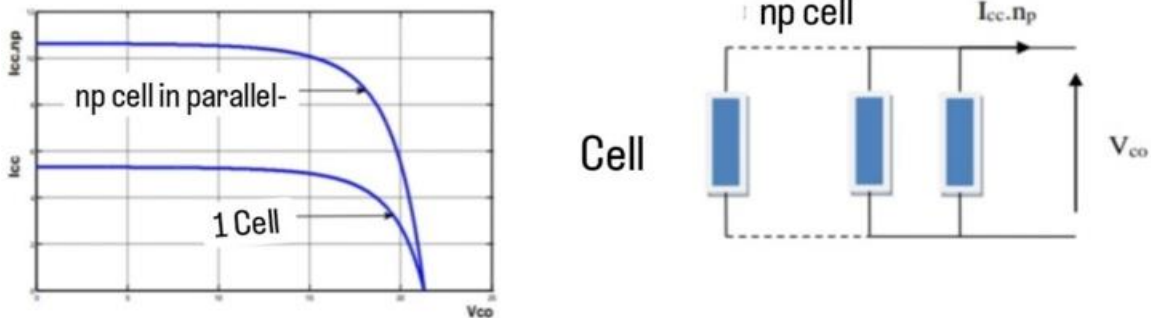


Figure (11): Characteristics of parallel grouping of identical photovoltaic cells.

Therefore, the total current/voltage characteristics of the photovoltaic generator are theoretically derived from the combination of ($n_s \cdot n_p$) elementary cells, assuming that these elementary cells are identical. consists of the ratio n_s parallel to the voltage axis and the ratio n_p parallel to the current axis I . As shown in Figure (12), n_s and n_p are the total number of batteries in series and parallel, respectively (22)

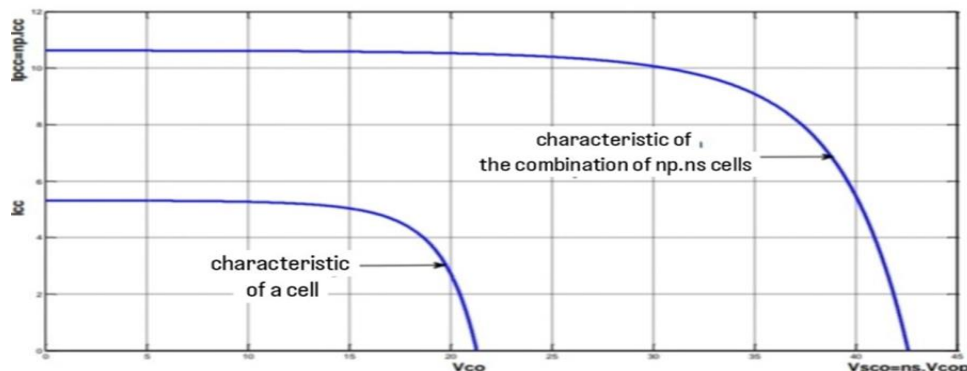


Figure (12): Characteristic of a generator with (n_p, n_s) identical parallel and series cells.

7.Results and Discussion

This section presents the simulation outcomes of the developed intelligent photovoltaic system and analyzes their implications under varying environmental conditions. The MATLAB/Simulink results are illustrated through characteristic I–V and P–V curves, power flow diagrams, and MPPT response behavior.

7.1 I–V and P–V Characteristics Under Varying Irradiance

Figures (8) and (9) show the current–voltage and power–voltage characteristics at irradiance levels of 200, 600, and 1000 W/m². The I–V curves demonstrate that:

- The **short-circuit current** increases linearly with irradiance, as expected.
- The **open-circuit voltage** increases slightly but saturates at higher irradiance levels.

This behavior aligns with published results by Villalva et al. (2009), who showed that current is more sensitive to irradiance while voltage is temperature dependent.

7.2 Influence of Temperature

Figures (10) and (11) illustrate the system's electrical behavior at different cell temperatures (0°C, 25°C, 50°C, 75°C). Observations include:

- The **open-circuit voltage decreases** approximately by 2 mV/°C.
- The **short-circuit current** increases slightly due to enhanced carrier mobility.

These results are consistent with the typical PV cell behavior described in Duffie and Beckman (2013), confirming the model's physical accuracy.

7.3 MPPT Performance Evaluation

The Perturb and Observe (P&O) algorithm accurately tracks the maximum power point under dynamic irradiance. The system response time is under 200 ms, which is within the acceptable range for residential PV systems.

7.4 Quantitative Analysis

At 50°C, 1000 W/m ²	At 25°C, 1000 W/m ²	Parameter
20.1 V	21.2 V	VocV_{oc}
5.42 A	5.31 A	IscI_{sc}
74.5 W	80.2 W	PmaxP_{max}

Table 4 – PV Performance at Different Temperatures

This confirms that **thermal degradation** causes ~7% power loss, which is within the range reported in IEEE studies **The simulation confirms that:**

- The proposed system maintains reliable operation under dynamic solar conditions.
- Th
- e MPPT algorithm ensures optimal energy harvesting.
- Thermal conditions significantly influence voltage and efficiency.

8. Conclusion

This paper presented the modeling and simulation of an intelligent photovoltaic energy system using a five-parameter diode model and MPPT control. The system was evaluated under varying levels of solar irradiance and temperature using MATLAB/Simulink.

The simulation results confirm that irradiance significantly affects the generated current and power, while increased temperature results in reduced voltage and overall efficiency. The integration of a microcontroller-based energy management unit allows for seamless switching between the PV system and backup storage in case of grid failure. The study validates the model's effectiveness and suggests that such intelligent control strategies can enhance energy reliability in grid-tied and standalone applications. Future work may include real-time hardware implementation, hybrid energy source integration, and advanced predictive control based on weather data.

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