A Study on the Design and Analysis of Solar Photovoltaic Systems Using MATLAB

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Abstract

This study focuses on the design and modelling of a photovoltaic (PV) system using MATLAB/Simulink, with the primary goal of optimizing system performance through the implementation of the Maximum Power Point Tracking (MPPT) technique. The project investigates the impact of solar irradiance and temperature variations on system performance under two simulation scenarios. Scenario one involves testing the PV system at three irradiance levels (200 W/m^2, 500 W/m^2, and 800 W/m^2) with a fixed temperature. Scenario two fixes irradiance and varies the temperature (25°C, 30°C, 35°C). The simulations incorporate a Perturb and Observe (P&O) MPPT algorithm to maximize power extraction. The results demonstrate a strong correlation between irradiance levels and PV output, while temperature effects were comparatively minimal. This work contributes to developing more efficient PV systems for residential and small-scale industrial applications.

1. Introduction

The growing energy demand, coupled with environmental concerns such as climate change and fossil fuel depletion, has amplified the need for renewable energy solutions. Among various renewable resources, solar energy stands out due to its abundance, sustainability, and low environmental impact. Photovoltaic (PV) systems convert sunlight into electricity, offering a clean and renewable energy alternative. However, many PV systems suffer from inefficiencies resulting from environmental factors such as shading, temperature fluctuations, and variable solar irradiance.

This paper aims to design and simulate a PV system using MATLAB/Simulink, with a focus on optimizing its performance through Maximum Power Point Tracking (MPPT) algorithms. By assessing system behaviour under varying irradiance and temperature conditions, the study provides practical recommendations for improving PV efficiency in residential and small-scale industrial settings.

2. Literature Review

2.1 Overview of PV System Performance Factors

Photovoltaic systems are influenced by various factors, including solar irradiance, temperature, shading, and orientation. These factors contribute to fluctuations in energy output, making the use of optimization methods necessary to enhance efficiency.

2.2 Maximum Power Point Tracking (MPPT) Techniques

MPPT techniques are essential for adjusting the operating point of a PV system to its maximum power output. Common methods include Perturb and Observe (P&O) and Incremental Conductance (IC). P&O is simple but can produce oscillations near the optimal point, whereas IC offers better performance under rapidly changing conditions. Advanced methods such as fuzzy logic, neural networks, and the Arithmetic Optimization Algorithm (AOA) offer improved convergence and stability [1].

2.3 Impact of Environmental Conditions

Environmental parameters significantly affect PV performance. Increased irradiance generally results in higher power output, while elevated temperatures tend to reduce open-circuit voltage, lowering overall efficiency [2]. Shading effects can lead to a reduction in output of up to 22%, requiring mitigation strategies such as bypass diodes and improved system layout [3].

2.4 Role of MATLAB/SIMULINK In PV Simulation

MATLAB/Simulink is widely used to model and simulate PV systems due to its flexibility and accuracy. It allows the implementation and testing of MPPT algorithms under various operating conditions, making it a powerful tool for design and optimization [4].

3. Methodology

3.1 System Input Parameters

The design process began by identifying the environmental and operational parameters influencing PV system performance. Solar irradiance data were sourced from NASA and Solargis databases to reflect realistic Malaysian conditions. The system was designed for a target daily energy consumption of 1200 Wh, with a panel generation factor (PGF) of 3.43 specific to Malaysia. A 1.3 safety factor was applied to account for energy losses due to weather and conversion efficiency.

The following technical parameters were used:

Reference Yield (Yr) = Total Solar Radiation / Rated Panel Power

$$Y_r = \frac{H_t}{G_o}$$

Final Yield (Yf) = Actual PV Output / Rated Power

$$Y_f = \frac{E_{grid}}{P_o}$$

These parameters are the foundation for effectively evaluating system performance and recognizing areas for optimization.

3.2 Simulink System Architecture

The system model includes a user-defined PV module, boost converter, and resistive load, all configured in MATLAB/Simulink. The boost converter is controlled using the output of the MPPT algorithm, which dynamically adjusts duty cycles. The PV model was built using simplified assumptions rather than based on actual commercial panel parameters, which may limit the realism of the simulation results. However, it still serves the purpose of analysing the effects of irradiance and temperature on MPPT performance within a controlled simulation environment.

3.3 MPPT and Optimization Techniques

This study employed the Perturb and Observe (P&O) method for real-time MPPT, as detailed earlier. Additionally, a genetic algorithm (GA) was briefly explored during the design phase for offline optimization of system parameters such as load resistance and duty ratio under fixed conditions. However, for real-time implementation, the simpler and faster P&O algorithm was preferred due to its responsiveness and lower computational overhead.

The simulation and analysis in this study were carried out using a single-diode equivalent model of a photovoltaic (PV) module. This model accurately represents the current-voltage (I-V) behaviour of a solar cell and is commonly used in MATLAB/Simulink for realistic performance evaluation.

$$I = I_{ph} - I_0 * [exp(\frac{q(V + IR_s)}{nkT}) - 1] - \frac{(V + IR_s)}{R_p}$$

Where:
- I_{ph}: Photocurrent (proportional to irradiance)
- I_0: Reverse saturation current
- V: Voltage across the PV cell
- I: Output current
- R_s, R_p: Series and parallel resistances
- n: Ideality factor
- V_t: Thermal voltage = kT/q

This equation forms the basis of the PV module's behaviour under different irradiance and temperature inputs.
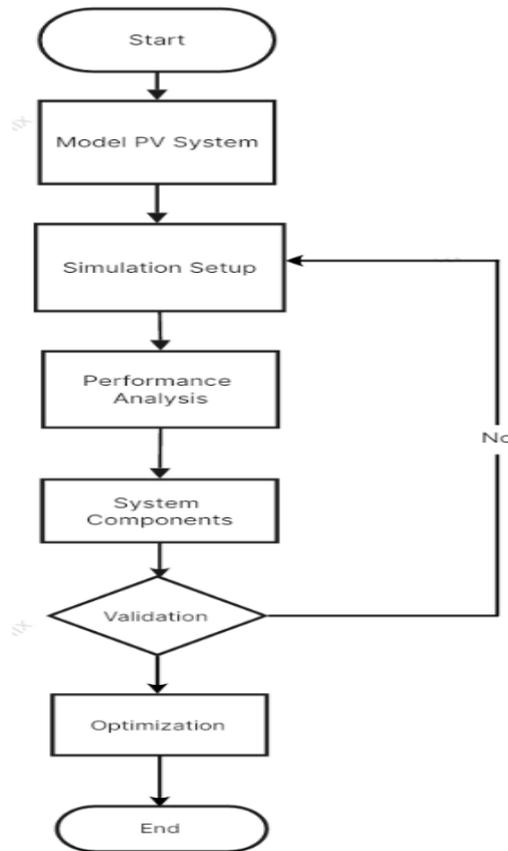
3.4 Flowchart

Fig 1 Project Flowchart

4. Results and Discussion

4.1 Impact of Solar Irradiance

In the first simulation scenario, the PV system was tested at three levels of solar irradiance (200 W/m², 500 W/m², and 800 W/m²) while maintaining a constant ambient temperature of 25°C. The output power (P), voltage (V), and current (I) all showed direct proportionality to the irradiance levels. As the irradiance increased, the number of photons striking the PV module rose, thereby increasing the photocurrent and the overall power output.

This trend validates the critical role of irradiance in influencing PV performance. The simulation revealed that lower irradiance resulted in significantly reduced output power and efficiency, emphasizing the importance of optimal solar exposure in real-world installations.
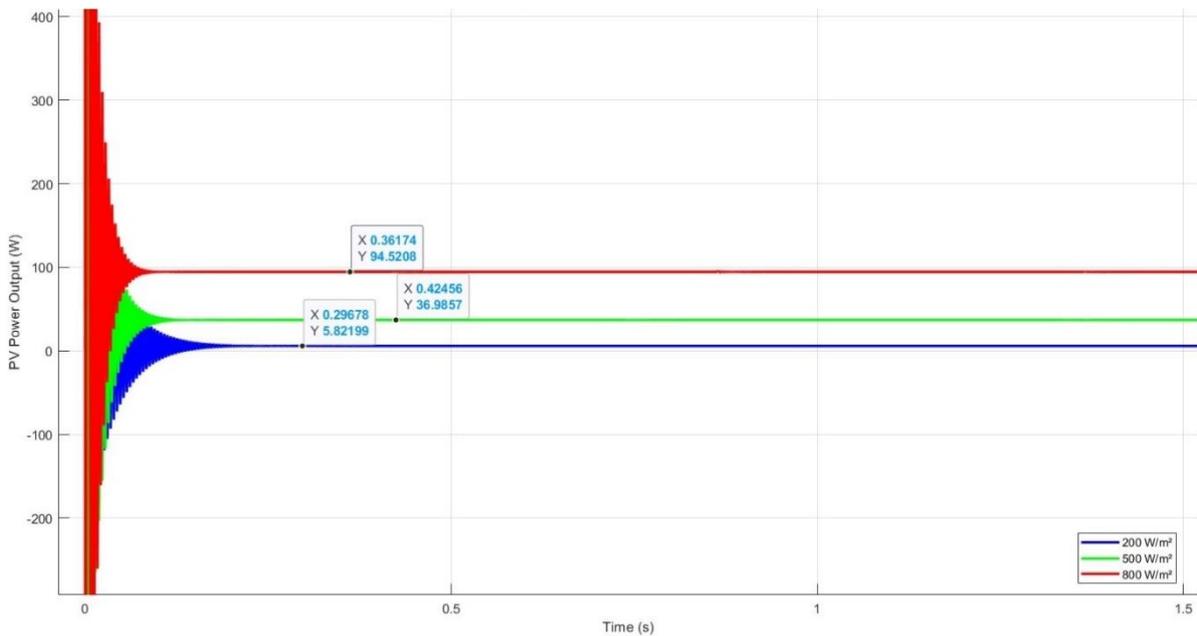

Fig 2 PV Output Power for Different Solar Irradiance Levels

4.2 Impact of Temperature

In the second scenario, the ambient temperature was varied across three values (25°C, 30°C, and 35°C) while the irradiance was fixed at 800 W/m². The simulations indicated only minor increases in current and power output with rising temperature, but these results contrast with typical experimental observations where voltage tends to drop and power decreases due to increased thermal energy [5].

This anomaly is attributed to the simplified user-defined PV model used in the simulation, which may not fully capture the negative thermal effects on open-circuit voltage. The output trend highlights the need for improved modeling accuracy, particularly when analyzing temperature-sensitive behaviors in PV modules.
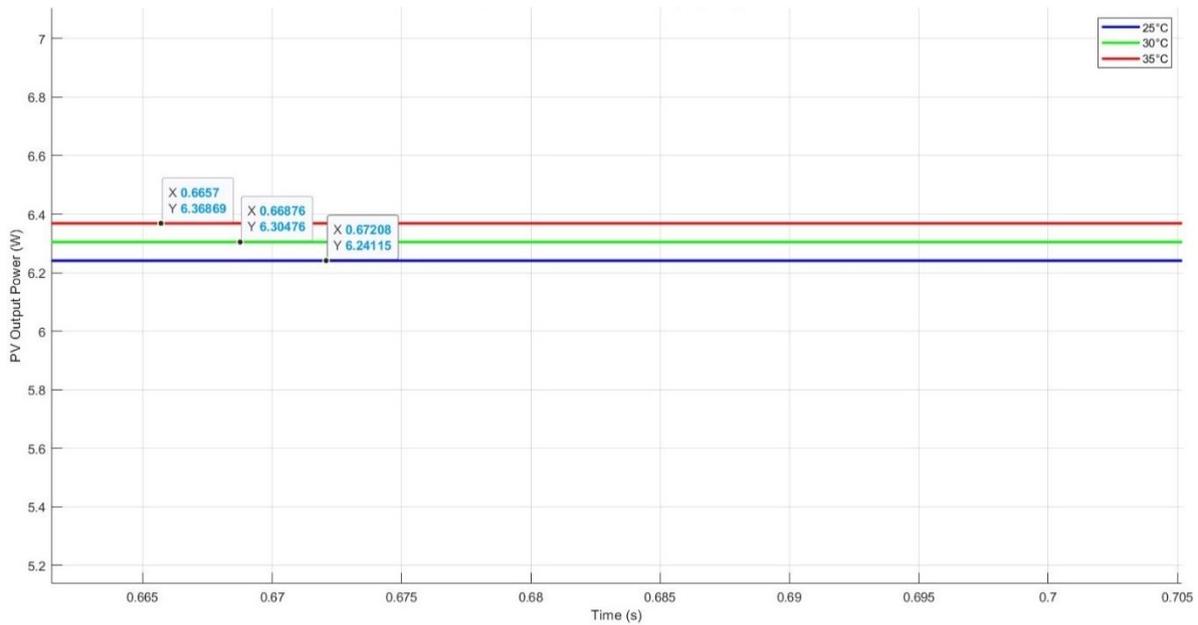
Fig 3 PV Output Power for Different Temperature Levels

4.3 Summary of Findings

Irradiance has a significant and direct impact on PV output characteristics, as demonstrated in the simulations, where power output increased substantially with higher irradiance levels. Temperature effects, on the other hand, were minimal in this simulation—likely due to simplifications in the PV model that did not account for the typical voltage drop observed with rising temperatures in real-world PV modules. Nevertheless, the MPPT (P&O) algorithm performed effectively in tracking the maximum power point across all tested conditions, dynamically adjusting the duty cycle to optimize output. Overall, it is recommended that future work incorporate more realistic PV modeling to better capture temperature-related performance losses.

5. Conclusion and Recommendations

5.1 Conclusion

This study successfully demonstrated the modelling and simulation of a solar photovoltaic (PV) system using MATLAB/Simulink, with a focus on performance analysis under varying environmental conditions. Two simulation scenarios were evaluated: one with changing irradiance and fixed temperature, and another with varying temperature and constant irradiance. The results confirmed that irradiance significantly affects power output, voltage, and current, while temperature had a minimal impact in the context of this simplified PV model.
The Perturb and Observe (P&O) algorithm proved to be effective for MPPT implementation, adapting quickly to environmental changes and consistently achieving near-optimal power output. The system managed to reach and maintain the maximum power point across different scenarios without major fluctuations, indicating its reliability under steady and moderate environmental changes.
Although a simplified, user-defined PV module was used, which may not perfectly reflect real-world behaviour, the study was still successful in providing a clear understanding of how solar irradiance and temperature influence PV system output. Additionally, the research validates that MPPT techniques, even those as basic as P&O, can significantly enhance system efficiency. This suggests that with proper algorithm tuning and system configuration, PV systems can be effectively optimized for practical applications.
Overall, this work contributes valuable insight into PV modelling and serves as a stepping stone for future efforts to implement more advanced optimization strategies, increase system fidelity, and align simulation outcomes with field-based performance expectations.

5.2 Recommendations

Future simulations should incorporate manufacturer-provided PV panel data or standardized, validated PV libraries to significantly improve the realism and accuracy of simulation outputs. Accurate modelling is particularly crucial when analysing the impact of temperature and partial shading effects, which were underrepresented due to the simplified approach in this study. Utilizing more advanced solar irradiance and temperature datasets from localized sources will also increase the relevance of findings for site-specific installations.

Furthermore, it is recommended to experiment with alternative MPPT strategies such as Incremental Conductance, fuzzy logic controllers, or metaheuristic algorithms like Genetic Algorithms or Particle Swarm Optimization. These methods have shown improved convergence speeds and greater resilience in unpredictable weather conditions. Future implementations could compare their performances against traditional methods in terms of efficiency, tracking speed, and computational demand.

To enhance the system's practical relevance, future models should integrate energy storage systems such as batteries, along with grid-connected configurations. This will allow assessment of energy management strategies, peak load handling, and overall energy autonomy. Finally, transitioning from simulation to hardware-in-the-loop (HIL) testing would validate the model's real-world performance, bridging the gap between theoretical analysis and practical deployment. These recommendations can guide future research and development efforts to design more robust and efficient PV systems tailored to real-world environmental variations.

Acknowledgment

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