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Original Article

Analysis of Single Diode Model of Solar Cell Simulated with MATLAB for Maximum Electric Power Extraction

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Abstract *- The quest for efficient utilization of solar energy has led to significant advancements in photovoltaic technology. Understanding the behavior of solar cells under varying conditions is crucial for optimizing their performance. The single-diode model serves as a fundamental tool for simulating solar cell characteristics and extracting maximum electric power. In this study, the paper presents a comprehensive analysis of the single diode model implemented in MATLAB for electric power extraction. The study begins with an overview of the theoretical foundations of the single diode model, elucidating the key parameters that govern solar cell behavior. Subsequently, the MATLAB simulation framework is described, detailing the implementation of the model equations and the numerical techniques employed for accurate computation. The analysis encompasses a range of operating conditions, including variations in irradiance and temperature, which profoundly influence solar cell performance. Through systematic simulation experiments, the impact of these factors on key metrics such as the Current-Voltage (I-V) curve, Power-Voltage (P-V) curve, and efficiency are examined. Furthermore, the study explores optimization strategies aimed at maximizing electric power extraction from the solar cell. Techniques such as Maximum Power Point Tracking (MPPT) algorithms are investigated to enhance energy harvesting efficiency under dynamic environmental conditions.*

Keywords *- SDM - Single Diode Model, SC - Solar Cell, EPE - Electric Power Extraction, MS - MATLAB Simulation, MPPT - Maximum Power Point Tracking, PS - Photovoltaic Systems, TE - Temperature Effects, I-V curves - Current-Voltage curve.*

1. Introduction

The utilization of solar energy as a sustainable and renewable power source has gained significant momentum in recent years, driven by the increasing global focus on mitigating climate change and reducing dependence on fossil fuels. Photovoltaic (PV) technology, which converts sunlight directly into electricity, lies at the forefront of this renewable energy revolution. Maximizing the efficiency and output of solar cells is paramount to harnessing the full potential of solar energy. Central to the analysis and optimization of solar cell performance is the Single Diode Model, a widely employed mathematical representation that describes the behavior of solar cells under various operating conditions. This model provides valuable insights into the complex interplay of factors influencing solar cell output, such as irradiance, temperature, and electrical characteristics.

In this context, this study presents a comprehensive analysis of the Single Diode Model of solar cells, focusing specifically on the extraction of maximum electric power. Leveraging the computational power and versatility of MATLAB, a powerful numerical computing environment, conducting a thorough simulation study to investigate the intricacies of solar cell behavior and optimize its performance. The objectives of this study are multifaceted. Firstly, this paper aims to elucidate the theoretical underpinnings of the Single Diode Model, offering a clear understanding of its parameters and equations. Subsequently, delving into the implementation of this model within the MATLAB framework, detailing the simulation techniques employed to capture solar cell characteristics accurately.

Furthermore, this study explores the effects of environmental variables such as irradiance and temperature on solar cell performance, examining their impact on key metrics such as the Current-Voltage (I-V) curve and the Power-Voltage (P-V) curve. Understanding these effects is crucial for designing robust and efficient photovoltaic systems capable of operating optimally under diverse conditions.

1.1. Objectives

Provide a clear and comprehensive explanation of the Single Diode Model of solar cells, elucidating the significance of its parameters and equations in describing solar cell behavior. Develop and implement the Single Diode Model within the MATLAB environment, ensuring accuracy and efficiency in simulating solar cell characteristics under varying conditions.

1.2. Overview of Existing Research

Research on the single diode model in MATLAB for solar cells has covered various aspects, including:

- Model Parameter Extraction: Techniques to determine the parameters of the SDM, such as ideal factor, series resistance, shunt resistance, photo-generated current, and diode saturation current.
- Performance Optimization: Methods to optimize the performance of PV systems using Maximum Power Point Tracking (MPPT) algorithms.
- Temperature and Irradiance Effects: Studies on how varying environmental conditions like temperature and irradiance affect the performance of the SDM.
- Advanced Simulation Techniques: Enhancements in the simulation models using MATLAB/ Simulink. The following things incorporate dynamic behaviour and interactions with other system components.

1.3. Identified Research Gaps

1.3.1. Advanced MPPT Algorithms Integration

Gap: While traditional MPPT techniques such as Perturb and Observe (P&O) and Incremental Conductance are well-studied, there is a lack of integration and analysis of advanced algorithms like Artificial Neural Networks (ANN), Fuzzy Logic, and machine learning-based approaches in the context of the SDM.

Opportunity: Investigate and implement advanced MPPT algorithms in MATLAB for the SDM and compare their efficiency and effectiveness in real-time simulations.

1.3.2. Model Accuracy under Dynamic Conditions

Gap: Existing models often assume steady-state conditions. There is a limited exploration of model performance under rapidly changing environmental conditions and load variations.

Opportunity: Develop and validate dynamic models that can accurately predict the performance of PV cells under transient conditions. This includes incorporating thermal effects and partial shading scenarios.

1.3.3. Enhanced Parameter Extraction Techniques

Gap: Parameter extraction techniques for the SDM often rely on simplifications or approximations that may not capture the full complexity of real PV cells.

Opportunity: Develop more robust and precise parameter extraction methodologies that can handle non-ideal behaviour and discrepancies observed in real PV cells. This could involve optimization techniques, genetic algorithms, or machine-learning approaches.

1.3.4. Incorporation of Aging and Degradation Effects

Gap: The impact of aging and degradation on the SDM parameters and overall PV performance is underexplored.

Opportunity: Extend the SDM to account for the long-term aging and degradation of solar cells. Develop models that can simulate performance degradation over time and propose maintenance or operational strategies to mitigate these effects.

1.3.5. Integration with Smart Grid and IoT

Gap: Limited research exists on integrating the SDM with smart grid technologies and the Internet of Things (IoT) for real-time monitoring and control.

Opportunity: Explore the integration of the SDM in MATLAB with IoT platforms and smart grid technologies to enable real-time data acquisition, monitoring, and adaptive control of PV systems for optimized performance.

1.3.6. Multi-Objective Optimization

Gap: Most studies focus on maximizing power output without considering other critical factors such as cost, reliability, and environmental impact.

Opportunity: Implement multi-objective optimization frameworks in MATLAB that consider various objectives, including economic and environmental factors, alongside power maximization to provide more holistic optimization solutions for PV systems.

1.3.7. Comparative Analysis with Other Models

Gap: There is a need for comprehensive comparative studies between the SDM and other more complex models like the double diode model or numerical models under various conditions.

Opportunity: Conduct detailed comparative analyses to evaluate the trade-offs between model complexity and simulation accuracy. This can help in identifying the conditions under which the SDM is most effective and when more complex models might be necessary.

1.3.8. Hybrid Systems and Energy Storage Integration

Gap: Integration of the SDM with hybrid systems involving other renewable energy sources and energy storage solutions is limited.

Opportunity: Investigate the performance of the SDM in hybrid renewable energy systems, including wind and battery storage, to develop comprehensive models that optimize energy management and power extraction in diverse renewable setups.

1.3.9. Educational and Training Tools

Gap: There is a lack of user-friendly educational tools and resources for training engineers and researchers in the use of SDM simulations in MATLAB.

Opportunity: Develop interactive and user-friendly simulation tools and educational modules within MATLAB that can be used for training purposes, helping bridge the gap between theoretical knowledge and practical application.

2. Ideal and Practical Single Diode Model of Solar Cell

The single diode model is a widely used representation of a Photovoltaic (PV) cell, capturing its essential electrical characteristics. This model helps in understanding and predicting the performance of PV cells under various operating conditions [1]. It represents the PV cell using a current source, a diode, and sometimes resistive elements to account for losses. The model can be divided into two versions: the ideal single-diode model and the practical single-diode model [2].

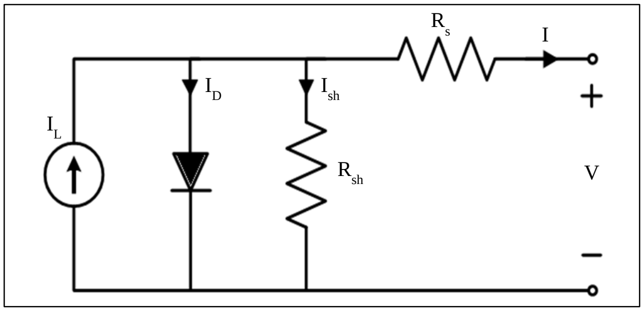

Fig. 1 Single diode model of solar cell

2.1. Ideal Single Diode Model

The ideal single-diode model of a PV cell consists of a current source in parallel with a diode. This model assumes no losses other than those due to the diode [3].

Mathematical Representation: The output current (I) can be described by the following equation:

$$I=I_{ph}-I_D \quad (1)$$

Where:
I_{ph} is the photo-generated current.
I_D is the current through the diode.

2.2. Practical Single Diode Model

The practical single-diode model adds more components to account for real-world inefficiencies and losses, such as series and shunt resistances [4].

Mathematical Representation: The output current (I) in the practical model is given by:

$$I=I_{ph}-I_D-I_{sh} \quad (2)$$

Where:
I_{ph} is the photo-generated current.
I_D is the current through the diode.
I_{sh} is the current through the shunt resistance.

3. PV Module of a Solar Cell

A Photovoltaic (PV) module, commonly known as a solar panel, is an assembly of multiple PV cells encapsulated within a protective frame. PV modules are designed to convert sunlight into electrical energy efficiently. Understanding the structure, function, and key parameters of a PV module is essential for optimizing solar power systems [5].

3.1. Structure of a PV Module

A typical PV module consists of the following components:

PV Cells: The basic building blocks, usually made of silicon, which convert sunlight into electricity. These cells are connected in series and/or parallel to achieve the desired voltage and current output.

Encapsulation: PV cells are encapsulated within layers of protective material, typically Ethylene-Vinyl Acetate (EVA), to protect against environmental factors like moisture and physical damage.

Front Cover: A transparent layer, usually made of tempered glass that protects the PV cells from mechanical impacts and weather conditions while allowing maximum light transmission.

Back sheet: A protective layer on the rear side, often made of a polymer material, providing electrical insulation and protection against environmental damage.

Frame: Typically made of aluminium, the frame provides structural support and facilitates mounting of the module.

Junction Box: Houses the electrical connections and bypass diodes to prevent hot spots and ensure safe operation [6, 7].

3.2. Applications and Considerations

PV modules are used in various applications, from residential rooftop installations to large-scale solar farms. When designing a PV system, consider factors like:

- Location: Solar irradiance and climatic conditions.
- Orientation and Tilt: Angle to maximize sunlight exposure.
- Shading: Avoiding shadows that can significantly reduce efficiency.

- Temperature Coefficient: Performance variation with temperature changes.
- Degradation: Long-term performance loss due to environmental exposure [8].

4. Maximum Power Point Extraction Technique

Maximum Power Point Tracking (MPPT) is a critical technique employed in solar power systems to optimize energy conversion from solar panels by ensuring they operate at their maximum power output under varying environmental conditions [9]. Here is how the MPPT technique works in a solar system:

4.1. Voltage and Current Tracking

Solar panels generate DC electricity and are so adjusted to maintain their output voltage and current [10].

4.2. MPP Voltage Determination

The MPP is the operating point where the product of the solar panel's voltage and current is maximized, resulting in the highest power output [11, 12]. The MPP voltage of SC varies with factors like solar irradiance and temperature, and it is crucial to track these variations to extract the maximum available power.

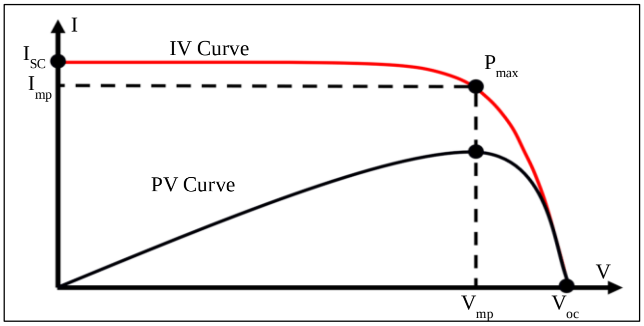

Fig. 2 MPPT voltage determination by IV and PV curves

These are two characteristics, I-V and P-V, in solar array systems by which MPP voltage is determined. For the global MPP and local MPP, there is another curve that is given over here [13, 14].

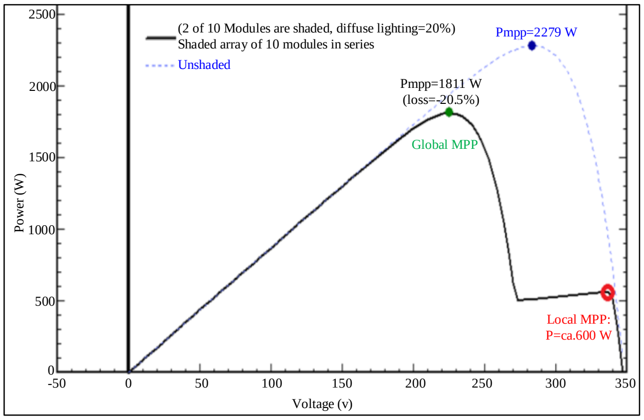

Fig. 3 Global MPP and local MPP voltage curves

4.3. MPPT Algorithms

In Figure 3, various MPPT algorithms are employed to track and maintain the solar panel's operation at the MPP. These algorithms include Perturb and Observe (P&O) and various AI-based techniques [15, 16]. Each algorithm has its advantages and is suited to different system configurations and environmental conditions.

4.4. Sensing and Control

MPPT controllers continuously monitor the voltage and current output of the solar panels and compare them with reference values to determine whether the panels are operating at the MPP [17]. Based on this comparison, the controller adjusts the operating parameters of the solar panels to track the MPP.

4.5. Efficiency Optimization

By ensuring that the solar panels operate at their MPP, MPPT maximizes the efficiency and energy yield of the solar system. This optimization is particularly crucial in grid-tied systems where maximizing energy production directly impacts the system's financial returns [18, 19].

4.6. Real-Time Adaptation

MPPT controllers dynamically adapt to changes in environmental conditions, like variations in solar irradiance and temperature, to maintain optimal operation [20]. This real-time adaptation ensures that the solar system consistently operates at its peak performance.

Overall, MPPT is an essential technology in solar power systems, allowing them to efficiently harness solar energy and maximize power output under varying environmental conditions [21, 22]. It plays a crucial role in optimizing the performance and economic viability of solar installations across residential, commercial, and utility-scale applications [23].

5. Investigations on Maximum Power Extraction Technique

Maximizing power extraction in a solar system involves optimizing various components and parameters to ensure efficient energy generation [24]. Here are some investigation techniques commonly used:

5.1. System Modeling and Simulation

Utilize software tools to model the solar system and simulate its performance under different conditions. This helps in understanding the system's behavior and identifying potential areas for improvement [25, 26].

5.2. Performance Monitoring

Install sensors to continuously monitor the performance of the solar panels, inverters, and other components. Analyze the data collected to detect inefficiencies or abnormalities and take corrective actions [27, 28].

5.3. Weather Analysis

Investigate the local weather patterns and their impact on solar irradiance levels. Understanding the weather conditions helps in predicting energy generation and adjusting system parameters accordingly [29, 30].

5.4. Optimal Tilt and Orientation

Study the optimal tilt angle and orientation of solar panels based on the location to maximize sunlight exposure throughout the day and across seasons [31].

5.5. Shading Analysis

Conduct shading analysis to identify potential obstructions such as buildings, trees, or nearby structures that may cast shadows on the solar panels. Minimizing shading helps in maximizing power output. Inverter efficiency analysis: Evaluate the efficiency of inverters in converting DC power from solar panels to AC power for use in the grid [32, 33]. Investigate the performance of different inverter types and configurations to optimize energy conversion [34].

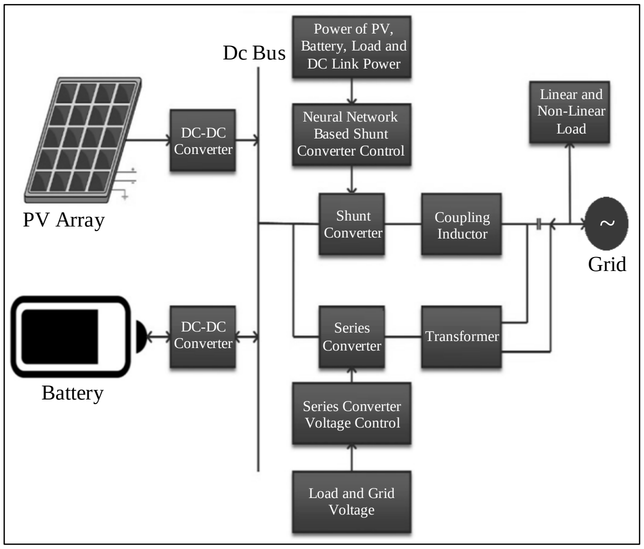

Fig. 4 Block diagram of solar power plant

5.6. Panel Cleaning and Maintenance

Investigate the impact of dust, dirt, and debris on solar panel performance. Develop cleaning and maintenance protocols to ensure Optimal Efficiency (OE) over time [35].

5.7. Battery Storage Optimization

If the solar system includes battery storage, investigate charging and discharging patterns to optimize battery usage and increase overall system efficiency [36].

5.8. Advanced Control Algorithms

Develop and implement advanced control algorithms to optimize the operation of the solar system in real time, considering factors such as solar irradiance, temperature, and load demand [37].

5.9. Financial Analysis

In this analysis, several factors such as upfront costs, potential energy savings, and return on investment. By employing these investigation techniques, solar system operators can optimize power extraction, improve energy efficiency [38], and maximize the return on their investment in solar energy.

6. MPPT Control

MPPT (Maximum Power Point Tracking) control in SC is a vital aspect of optimizing energy conversion from solar panels [39]. Here are five key points about MPPT control:

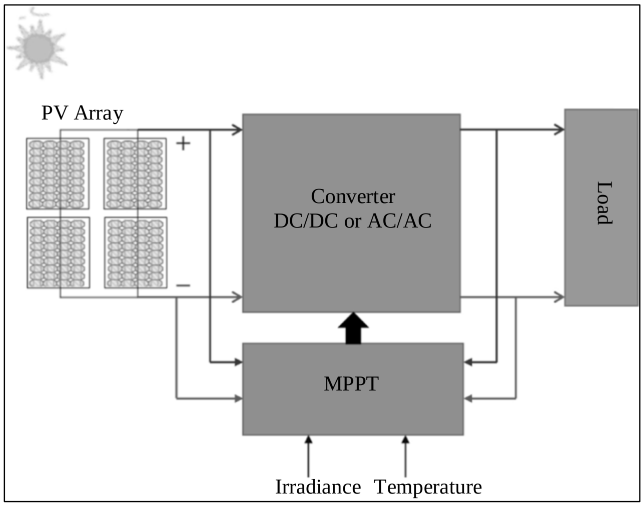

Fig. 5 Block diagram of MPPT-based solar power plant

6.1. Continuous Optimization

MPPT control continuously adjusts the operating conditions of solar panels to ensure they are operating at their Maximum Power Point (MPP) [40, 41]. This involves dynamically tracking changes in environmental factors such as sunlight intensity and temperature to maintain optimal performance.

6.2. Algorithmic Approach

MPPT control relies on sophisticated algorithms to determine the optimal operating voltage and current of the solar panels. Controller Implementation: MPPT control is typically implemented using dedicated MPPT controllers or embedded within the power electronics of solar inverters [42, 43].

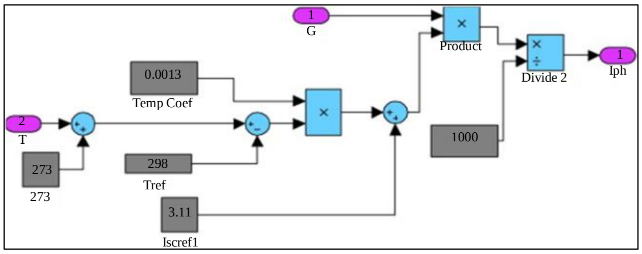

Fig. 6 MATLAB simulation model of PV system

6.3. Adaptive Performance

MPPT control systems exhibit adaptive behavior, meaning they can quickly respond to changes in environmental conditions to optimize energy production. This adaptability is essential for maximizing energy yield, especially in environments with variable sunlight conditions or partial shading [44].

6.4. Efficiency Enhancement

By ensuring that solar panels operate at their MPP, MPPT control systems enhance the overall efficiency of solar power systems. This optimization maximizes energy production and improves the system's ability to harvest solar energy, leading to higher energy yields and improved economic returns.

In summary, MPPT control is a crucial aspect of solar power systems, enabling efficient energy conversion and maximizing the utilization of solar resources [45]. Through continuous optimization and adaptive performance, MPPT control systems enhance the efficiency and effectiveness of solar installations, contributing to the growth and adoption of renewable energy technologies [46].

Variation of the I-V curve according to sunlight is shown over here [47, 48]. The MPPT control for the PV system is divided into four sections, as shown in the figure.

7. Literature Review

The Single Diode Model (SDM) is extensively utilized in Photovoltaic (PV) research due to its simplicity and ability to provide accurate representations of solar cell behavior. MATLAB, with its robust computational and graphical tools, is commonly used to simulate and analyze SDM for optimizing maximum electric power extraction. This literature review covers the key aspects of research conducted on SDM using MATLAB, focusing on parameter extraction, MPPT algorithms, environmental impacts, and model enhancements.

Sajid Sarwar et al. - A novel hybrid MPPT Technique to maximize power harvesting from PV systems under partial and complex partial shading [26].

- Efficiency: The InC-DFO technique demonstrated high efficiency across different shading scenarios. Specifically, it achieved efficiencies of 99.93%, 99.88%, 99.92%, and 99.98% under Uniform Irradiance (UI), Partial Shading (PS1), Partial Shading (PS2), and Complex Partial Shading (CPS) conditions, respectively. This performance is superior to many existing MPPT techniques.
- Settling Time: The hybrid technique significantly reduced the settling time to 0.75 seconds, even in the case of complex partial shading. This is a notable improvement, indicating faster response times in dynamic weather conditions.
- Oscillation Reduction: The InC-DFO method effectively minimized undesired oscillations around the maximum power point, which is particularly challenging under partial and complex shading conditions. This stability is crucial for maintaining optimal power output.
- Comparative Performance: When compared with six other MPPT techniques, the proposed hybrid approach showed superior performance in terms of tracking speed and efficiency. The methods it outperformed included classical and other bio-inspired algorithms.
- Real-time Verification: The performance of the proposed MPPT algorithm was validated using real-time data from the Beijing database, ensuring its practical applicability and robustness.

2022: Gong, L.; Hou, G.; Huang, C. A two-stage MPPT controller for PV system based on the improved artificial bee colony and simultaneous heat transfer search algorithm [39].

- Hybrid Algorithm Performance: The combination of the improved ABC and SHTS algorithms allows for efficient exploration and exploitation of the power-voltage characteristic curve. This hybrid approach ensures rapid convergence to the Global Maximum PowerPoint (GMPP), even under partial shading conditions, which are notoriously challenging for MPPT algorithms.
- Efficiency and Speed: The two-stage controller demonstrates a significant improvement in both efficiency and tracking speed. The initial stage, utilizing the ABC algorithm, quickly narrows down the search area for the GMPP, while the SHTS algorithm in the second stage fine-tunes the search to achieve precise tracking. These results in faster settling times and higher overall efficiency compared to traditional methods.
- Robustness under Variable Conditions: The study highlights the robustness of the proposed method under different shading patterns and irradiance levels. It effectively mitigates the effects of local maxima that can trap conventional MPPT algorithms, ensuring consistent power extraction across various environmental conditions.
- Comparative Analysis: Compared to other existing MPPT techniques, the two-stage controller showed superior performance in terms of maximum power extraction and dynamic response. The research demonstrated that the proposed method outperforms several well-known algorithms, such as Perturb and Observe (P&O) and Incremental Conductance (InC), particularly under complex partial shading scenarios.
- Practical Implications: The implementation of this two-stage MPPT controller in real-world PV systems can lead to substantial improvements in energy yield and system reliability. The study provides a comprehensive analysis and simulation results, validating the practical benefits of the proposed approach.

2022: Saibal Manna et al. A novel MRAC-MPPT scheme to enhance speed and accuracy in PV systems [40].

- Improved Tracking Accuracy: The MRAC-MPPT scheme demonstrates superior accuracy in tracking the maximum power point, even under rapidly changing irradiance and temperature conditions. This results in more efficient energy harvesting from the PV system.
- Faster Response Time: The adaptive nature of the MRAC technique allows the system to respond to changes in environmental conditions quickly. This rapid response helps in maintaining optimal performance and reduces the time the PV system operates below its maximum power point.
- Enhanced Stability: The MRAC-based approach improves the stability of the MPPT process. The controller adapts to the system's dynamics, reducing oscillations and ensuring smooth operation around the maximum power point.
- Simulation and Validation: The effectiveness of the MRAC-MPPT scheme is validated through both simulation and experimental results. The study highlights that the proposed method outperforms traditional MPPT techniques like Perturb and Observe (P&O) and Incremental Conductance (InC) in terms of tracking efficiency and speed.

2022: Saibal Manna et al. A novel robust model reference adaptive MPPT controller for Photovoltaic systems [41].

- Adaptive Control Approach: The MRAC algorithm introduced in this study is designed to adapt dynamically to changes in the PV system's operating conditions. This adaptability helps in achieving more precise and quicker convergence to the Maximum PowerPoint (MPP).
- Performance under Partial Shading: One significant advantage of the proposed MRAC technique is its effectiveness under partial shading conditions. Traditional MPPT methods, such as Perturb and Observe (P&O) and Incremental Conductance (INC), often struggle with local maxima caused by shading. The MRAC method, however, demonstrates superior capability in navigating these local maxima to find the Global Maximum Power Point (GMPP) effectively.
- Simulation and Real-Time Verification: The study includes both simulation and real-time experiments to validate the performance of the proposed MRAC-MPPT scheme. The results indicate that the controller can achieve MPP and GMPP in less than 3.8 milliseconds and 10 milliseconds, respectively, under various scenarios of radiation, temperature, and load changes.
- Comparative Advantage: When compared to other state-of-the-art MPPT techniques such as ANFIS, INC, VSPO, and P&O, the MRAC method shows significant improvements in tracking speed and power efficiency. This is particularly evident in rapidly changing environmental conditions, where traditional methods may fail to maintain optimal performance.
- Lyapunov Stability: The MRAC controller is based on Lyapunov's stability theory, ensuring that the system remains stable while converging rapidly to the MPP. This stability is crucial for the reliable operation of PV systems, especially under dynamic environmental conditions.
- Ripple-Free Performance: One of the notable achievements of the MRAC method is its ability to provide ripple-free power output. This characteristic is essential for maintaining the quality of power supplied by the PV system, reducing the wear and tear on the components, and improving overall system efficiency.

8. Result

Using MATLAB, after solving the single diode equation and plotting the I-V and P-V curves. The key points on these curves are:

8.1. I-V and P-V Characteristics

8.1.1. I-V Curve

This shows the relationship between current and voltage for the PV cell. This curve helps identify the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}).

Short-Circuit Current (I_{sc}): The current when the voltage is zero.

$$I_{sc} \approx I_{ph} = 3.1\text{A}$$

Open-Circuit Voltage (V_{oc}): The voltage when the current is zero.

$$V_{oc} \approx 22\text{V}$$

8.1.2. P-V Curve

Illustrates the power output as a function of voltage. The peak of this curve represents the Maximum Power Point (MPP), which is crucial for maximum power extraction.

Maximum Power Point (MPP)

The maximum power point is identified from the P-V curve: Maximum Power (P_{mpp}): The peak power point on the P-V curve.

$$P_{mpp} \approx 54\text{W}$$

The Voltage at MPP (): The voltage at which the maximum power occurs.

$$V_{mpp} \approx 20\text{V}$$

Current at MPP (): The current at which the maximum power occurs.

$$I_{mpp} \approx 2.7\text{A}$$

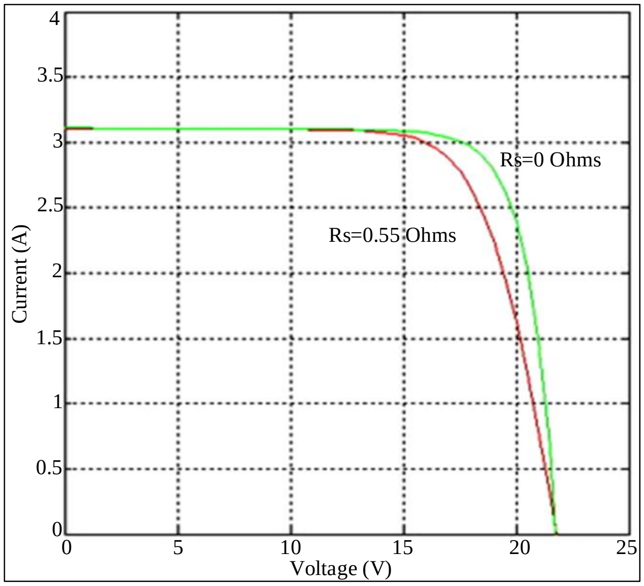

Fig. 7 I-V curve at different parameters

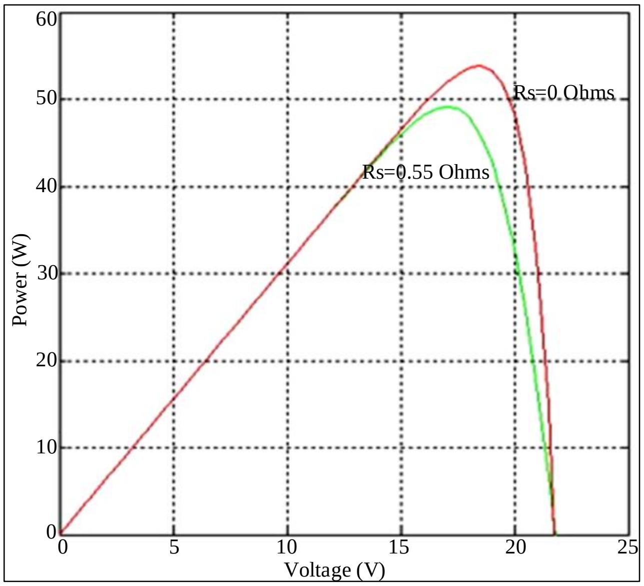

Fig. 8 P-V curve at different parameters

Table 1. Result in comparison with existing data

Parameter	Existing Result	Result
Maximum Power (P_{MAX})	$50W_p$	**$54W_P$**
Voltage at MPP (V_{MPP})	19.3V	**20.2V**
Current at MPP (I_{MPP})	2.61A	**2.7A**
Open Circuit Voltage (V_{OC})	22V	
Short Circuit Current (I_{SC})	3.1A	
Temperature Coefficient of I_{sc} (α)	$3.18x10^{-3}$A/°C	

9. Conclusion

The analysis of the single-diode model of a solar cell using MATLAB simulation provides detailed insights into the PV cell's performance. The key outcomes include the accurate determination of the I-V and P-V characteristics, the identification and optimization of the MPP, and the assessment of various MPPT algorithms. These results are crucial for designing efficient PV systems and improving their energy yield.

9.1. Future Scope

The future scope of investigations on Maximum Power Extraction Techniques (MPPT) in solar power systems is promising and multifaceted. Here are some potential directions for future research:

- Advanced MPPT Algorithms
- Hybrid MPPT Systems
- Distributed MPPT Systems
- Integration with Energy Storage
- Smart Grid Integration
- Hardware Development
- Field Validation and Standardization

Overall, the future of investigations on MPPT in solar power systems is characterized by a multidisciplinary approach, combining advances in control theory, power electronics, data analytics, and system integration to unlock the full potential of solar energy as a clean and sustainable power source.

References

[1] A. Elmitwally, S. Abdelkader, and M. Elkateb, “Performance Evaluation of Fuzzy Controlled Three and Four Wireshunt Active Power Conditioners,” *2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings*, Singapore, pp. 1650-1655, 2000. [CrossRef] [Google Scholar] [Publisher Link]

[2] Dalila Beriber, and Abdelaziz Talha, “MPPT Techniques for PV Systems,” *4th International Conference on Power Engineering, Energy and Electrical Drives*, Istanbul, Turkey, pp. 1437-1442, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[3] Azmi Saleh et al., “Comparison of MPPT Fuzzy Logic Controller Based on Perturb and Observe (P&O) and Incremental Conductance (InC) Algorithm on Buck-Boost Converter,” *2018 2nd International Conference on Electrical Engineering and Informatics (ICon EEI)*, Batam, Indonesia, pp. 154-158, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[4] Nasir Hussein Selman, and Jawad Radhi Mahmood, "Comparison between Perturb & Observe, Incremental Conductance and Fuzzy Logic MPPT Techniques at Different Weather Conditions," *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 5, no. 7, pp. 12556-12569, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[5] R.Sridhar et al., "Modeling of PV Array and Performance Enhancement by MPPT Algorithm," *International Journal of Computer Applications*, vol. 7, no. 5, pp. 35-39, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[6] Hairul Nissah Zainudin, and Saad Mekhilef, "Comparison Study of Maximum Power Point Tracker Techniques for PV Systems," *Proceedings of the 14th International Middle East Power Systems Conference (MEPCON'10)*, Cairo, Egypt, pp. 750-755, 2010. [Google Scholar] [Publisher Link]

[7] Mostafa Barzegar Kalashani, and Murtaza Farsadi, "New Structure for Photovoltaic Systems with Maximum Power Point Tracking Ability," *International Journal of Power Electronics and Drive System*, vol. 4, no. 4, pp. 489-498, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[8] M. Berrera et al., "Experimental Test of Seven Widely-Adopted MPPT Algorithms," *2009 IEEE Bucharest PowerTech*, Bucharest, Romania, pp. 1-8, 2009. [CrossRef] [Google Scholar] [Publisher Link]

[9] Lakshmi P.N. Jyothy, and M.R. Sindhu, "An Artificial Neural Network Based MPPT Algorithm for Solar PV System," *2018 4th International Conference on Electrical Energy Systems (ICEES)*, Chennai, India, pp. 375-380, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[10] Ali Reza Reisi, Mohammad Hassan Moradi, and Shahriar Jamasb, "Classification and Comparison of Maximum Power Point Tracking Techniques for the Photovoltaic System: A Review," *Renewable and Sustainable Energy Reviews*, vol. 19, pp. 433-443, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[11] Bidyadhar Subudhi, and Raseswari Pradhan, "A Comparative Study on Maximum Power Point Tracking Techniques for Photovoltaic Power Systems," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 1, pp. 89-98, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[12] Hyeon-Seok Lee, and Jae-Jung Yun, "Advanced MPPT Algorithm for Distributed Photovoltaic Systems," *Energies*, vol. 12, no. 18, pp. 1-17, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[13] Farhad Khosrojerdi, Shamsodin Taheri, and Ana-Maria Cretu, "An Adaptive Neuro-Fuzzy Inference System-Based MPPT Controller for Photovoltaic Arrays," *2016 IEEE Electrical Power and Energy Conference (EPEC)*, Ottawa, Canada, pp. 1-6, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[14] Rayane Hijazi, and Nabil Karami, "Neural Network Assisted Variable-Step-Size P&O for Fast Maximum Power Point Tracking," *2020 32nd International Conference on Microelectronics (ICM)*, Aqaba, Jordan, pp. 1-6, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[15] S. Narendiran et al., "Fuzzy Logic Controller Based Maximum Power Point Tracking for PV System," *2016 3rd International Conference on Electrical Energy Systems (ICEES)*, Chennai, India, pp. 29-34, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[16] Ahmed G. Abdullah, Mothanna Sh. Aziz, and Bashar Abdullah Hamad, "Comparison between Neural Network and P&O Method in Optimizing MPPT Control for Photovoltaic Cell," *International Journal of Electrical and Computer Engineering*, vol. 10, no. 5, pp. 5083-5092, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[17] Mohammad Sarvi, and Ahmad Azadian, "A Comprehensive Review and Classified Comparison of MPPT Algorithms in PV Systems," *Energy Systems*, vol. 13, pp. 281-320, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[18] Parag K. Atri, P.S. Modi, and Nikhil Shashikant Gujar, "Comparison of Different MPPT Control Strategies for Solar Charge Controller," *2020 International Conference on Power Electronics & IoT Applications in Renewable Energy and its Control (PARC)*, Mathura, India, pp. 65-69, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[19] Ihssane Chtouki, Patrice Wira, and Malika Zazi, "Comparison of Several Neural Network Perturb and Observe MPPT Methods for Photovoltaic Applications," *2018 IEEE International Conference on Industrial Technology (ICIT)*, Lyon, France, pp. 909-914, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[20] Mahyar Khosravi et al., "A Novel Hybrid Model-Based MPPT Algorithm Based on Artificial Neural Networks for Photovoltaic Applications," *2017 IEEE Southern Power Electronics Conference (SPEC)*, Puerto Varas, Chile, pp. 1-6, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[21] Naveen, and Anil Kumar Dahiya, "Implementation and Comparison of Perturb & Observe ANN and ANFIS Based MPPT Techniques," *2018 International Conference on Inventive Research in Computing Applications (ICIRCA)*, Coimbatore, India, pp. 1-5, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[22] Nora Kacimi et al., "New Improved Hybrid MPPT Based on Neural Network-Model Predictive Control-Kalman Filter for Photovoltaic System," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 20, no. 3, pp. 1230-1241, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[23] Kannabiran Kanimozhi, and Bagarudeen Raja Mohamed Rabi, "Development of Hybrid MPPT Algorithm for Maximum Power Harvesting under Partial Shading Conditions," *Circuits and Systems*, vol. 7, no. 8, pp. 1611-1622, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[24] Khaled Bataineh, "Improved Hybrid Algorithms-Based MPPT Algorithm for PV System Operating under Severe Weather Conditions," *IET Power Electronics*, vol. 12, no. 4, pp. 703-711, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[25] Gianluca Aurilio et al., "Fast Hybrid MPPT Technique for Photovoltaic Applications: Numerical and Experimental Validation," *Advances Power Electronics*, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[26] Sajid Sarwar et al., "A Novel Hybrid MPPT Technique to Maximize Power Harvesting from PV System under Partial and Complex Partial Shading," *Applied Sciences*, vol. 12, no. 2, pp. 1-26, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[27] Ratnakar Babu Bollipo, Suresh Mikkili, and Praveen Kumar Bonthagorla, "Hybrid, Optimization, Intelligent and Classical PV MPPT Techniques: A Review," *CSEE Journal of Power and Energy Systems*, vol. 7, no. 1, pp. 9-33, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[28] Said Azzouz, Sabir Messalti, and Abdelghani Harrag, "A Novel Hybrid MPPT Controller Using (P&O)-Neural Networks for Variable Speed Wind Turbine Based on DFIG," *Modelling, Measurement and Control A*, vol. 92, no. 1, pp. 23-29, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[29] M. Arjun, and J.B. Zubin, "Artificial Neural Network Based Hybrid MPPT for Photovoltaic Modules," *2018 International CET Conference on Control, Communication, and Computing (IC4)*, Thiruvananthapuram, India, pp. 140-145, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[30] Hadeed Ahmed Sher et al., "A New Sensorless Hybrid MPPT Algorithm Based on Fractional Short-Circuit Current Measurement and P&O MPPT," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 4, pp. 1426-1434, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[31] B. Pakkiraiah, and G. Durga Sukumar, "Research Survey on Various MPPT Performance Issues to Improve the Solar PV System Efficiency," *Journal of Solar Energy*, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[32] Laxman Bhukya, Narender Reddy Kedika, and Surender Reddy Salkuti, "Enhanced Maximum Power Point Techniques for Solar Photovoltaic System under Uniform Insolation and Partial Shading Conditions: A Review," *Algorithms*, vol. 15, no. 10, pp. 1-29, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[33] Muhammad Rameez Javed et al., "Comparison of the Adaptive Neural-Fuzzy Interface System (ANFIS) Based Solar Maximum Power Point Tracking (MPPT) with other Solar MPPT Methods," *2020 IEEE 23rd International Multitopic Conference (INMIC)*, Bahawalpur, Pakistan, pp. 1-5, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[34] Moirangthem Dennis Singh, V.J. Shine, and Varaprasad Janamala, "Application of Artificial Neural Networks in Optimizing MPPT Control for Standalone Solar PV System," *2014 International Conference on Contemporary Computing and Informatics (IC3I)*, Mysore, India, pp. 162-166, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[35] Jobeda Khanam, and Simon Y. Foo, "Neural Networks Technique for Maximum Power Point Tracking of Photovoltaic Array," *SoutheastCon 2018*, St. Petersburg, USA, pp. 1-4, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[36] Wafa Hayder et al., "On Improved PSO and Neural Network P&O Methods for PV System under Shading and Various Atmospheric Conditions," *Energies*, vol. 15, no. 20, pp. 1-15, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[37] Idriss Dagal, Burak Akın, and Erdem Akboy, "MPPT Mechanism Based on Novel Hybrid Particle Swarm Optimization and Salp Swarm Optimization Algorithm for Battery Charging through Simulink," *Scientific Reports*, vol. 12, pp. 1-17, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[38] Ziad M. Ali et al., "Novel Hybrid Improved Bat Algorithm and Fuzzy System Based MPPT for Photovoltaic under Variable Atmospheric Conditions," *Sustainable Energy Technologies and Assessments*, vol. 52, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[39] Linjuan Gong, Guolian Hou, and Congzhi Huang, "A Two-Stage MPPT Controller for PV System Based on the Improved Artificial Bee Colony and Simultaneous Heat Transfer Search Algorithm," *ISA Transactions*, vol. 132, pp. 428-443, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[40] Saibal Manna et al., "A Novel MRAC-MPPT Scheme to Enhance Speed and Accuracy in PV Systems," *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, vol. 47, pp. 233-254, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[41] Saibal Manna et al., "A Novel Robust Model Reference Adaptive MPPT Controller for Photovoltaic Systems," *Scientia Iranica*, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[42] Abd Essalam Badoud, Saad Mekhilef, and Belkacem Ould Bouamama, "A Novel Hybrid MPPT Controller Based on Bond Graph and Fuzzy Logic in Proton Exchange Membrane Fuel Cell System: Experimental Validation," *Arabian Journal for Science and Engineering*, vol. 47, pp. 3201-3220, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[43] V. Vinothkumar, and R. Kanimozhi, "Power Quality Improvement by PV Integrated UPQC Using a Multi-Level Inverter with Resilient Back Propagation Neural Network Approach," *Journal of Intelligent & Fuzzy Systems*, vol. 43, no. 5, pp. 6277-6294, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[44] Farzad Rastegar, and Zohreh Paydar, "Improving the Performance of Unified Power Quality Conditioner Using Interval Type 2 Fuzzy Control," *2022 30th International Conference on Electrical Engineering (ICEE)*, Tehran, Iran, pp. 437-441, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[45] S. Rechka et al., “A Comparative Study of Harmonic Detection Algorithms for Active Filters and Hybrid Active Filters,” *2002 IEEE 33rd Annual Power Electronics Specialists Conference*, Cairns, Australia, vol. 1, pp. 357-363, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[46] Yujia Shang, and Aiguo Wu, “TS-Fuzzy-Controlled Shunt Active-Power Filter for Power Quality Improvement,” *2011 International Conference on Electrical and Control Engineering*, Yichang, China, pp 1869-1872, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[47] A. Hamadi et al., “Comparison of Fuzzy Logic and Proportional Integral Controller of Voltage Source Active Filter Compensating Current Harmonics and Power Factor,” *2004 IEEE International Conference on Industrial Technology*, Hammamet, Tunisia, vol. 2, pp. 645-650, 2004. [CrossRef] [Google Scholar] [Publisher Link]

[48] H.L. Jou, J.C. Wu, and H.Y. Chu, “New Single-Phase Active Power Filter,” *IEE Proceedings - Electric Power Applications*, vol. 141, no. 3, pp. 129-134, 1994. [CrossRef] [Google Scholar] [Publisher Link]