Photovoltaic Cell Optimization Using an Improved MPPT Algorithm and Estimating the System's Periodical Efficiency

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Abstract:

PV technology has advanced significantly as a result of the growing demand for renewable energy sources. Optimizing PV systems' efficiency is still a major challenge, even with advancements. An improved Maximum Power Point Tracking (MPPT) algorithm is suggested in this study to raise PV cells energy conversion efficiency. The study also assesses the system's periodic efficiency in a range of environmental circumstances. The suggested algorithm outperforms traditional MPPT methods in terms of accuracy, response time, and total energy harvest, according to experimental results. By suggesting an improved MPPT algorithm, this study tackles the crucial problem of maximizing the efficiency of photovoltaic (PV) systems.

Keywords: Photovoltaic cells, Maximum Power Point Tracking, Efficiency optimization, Renewable energy.

1. Introduction:

The shift towards renewable energy sources is imperative for mitigating climate change and ensuring sustainable energy production. Among various technologies, photovoltaic (PV) systems have gained prominence due to their scalability and environmental benefits. However, the efficiency of PV systems is inherently limited by factors such as irradiance, temperature fluctuations, and the inability of traditional MPPT algorithms to adapt to dynamic environmental conditions effectively. This study introduces an enhanced MPPT algorithm tailored to address these challenges and evaluates its performance over defined periods to quantify efficiency improvements.[1] The recent surge in oil, gas, uranium and coal prices highlights the importance of all countries focusing on alternative energy development. For developing countries, these price increases can have a significant economic impact, and for many countries that have suffered poverty, this means fuel and food choices, health care, education, and other necessities.[2,3]

1) Overwhelming scientific evidence suggests that anthropogenic emissions of carbon-burning greenhouse gases threaten the devastating consequences of climate change.[4]

2) All major developing countries experience fossil fuels serious health and environmental impacts of burning.[5, 6]

3) High cost of nuclear power, environmental destruction and security threats.

Many MPPT methods have been introduced, and many variations of each method have been proposed to overcome particular drawbacks. The numerous methods proposed make it difficult to determine the best technique to use when implementing a PV system. Furthermore, the type of application can have a major impact on the choice of MPPT algorithm. Therefore, this article summarizes today's most popular MPPT technology. Two promising approaches to be considered when implementing a system that requires a response over a wide range of illumination conditions have been highlighted. [7]

The algorithm is tested in a variety of environmental settings and increases energy conversion efficiency. When compared to conventional techniques, the results show improved accuracy, response time, and energy harvest.

2. Literature Review:

Recent advancements in PV systems have focused on the integration of sophisticated MPPT algorithms to optimize energy extraction. Conventional algorithms, such as Perturb and Observe (P&O) and Incremental Conductance (IC), exhibit limitations in tracking speed and stability.

Rezk et al. (2017) presents a study focused on developing a cost-effective data acquisition system (DAQS) for photovoltaic (PV) plants, utilizing Lab-VIEW software. The research findings indicate that the developed DAQS is highly beneficial for both performance optimization of PV plants and educational purposes, offering a reliable and informative tool for data collection and analysis.

Awasthi et al. (2020) present a comprehensive review of solar energy, emphasizing its vast, abundant, and eco-friendly nature. The paper explores the optimization of harnessing solar power, specifically through solar tracking systems.

Pakkiraiah and Sukumar (2016) address the imperative of utilizing renewable energy sources to meet rising power demands and mitigate global warming, focusing specifically on solar energy. Despite its potential, solar panels convert only 30-40% of solar irradiation into electrical energy

In their December 2016 study, Sreedevi, Ashwin, and Raju examine the rapid growth of photovoltaic (PV) energy and its integration into power systems. The research focuses on the effects of connecting a PV system to the grid, utilizing real-time simulations on the Real Time Digital Simulator (RTDS) with RSCSD software. Key aspects analyzed include the impact of varying load power factors, different levels of PV penetration, the introduction of harmonics by the PV inverter, and the anti-islanding effect of the PV system.

Ghafoor and Munir (2015) conducted a study on an off-grid photovoltaic (PV) system for a single residential household in Faisalabad, Pakistan. The research focused on designing a system to meet household energy demands using solar energy. The methodology involved developing a model for sizing the PV system components, including the power rating, battery storage, charge controller, and inverter.

The study calculated the required peak power at 1928 Wp, the findings demonstrated that the off-grid PV system is both technically feasible and economically advantageous compared to conventional electricity supply for residential areas.[8]

In their 2017 paper, Gupta, Garg, and Kumar address the increasing environmental concerns associated with fossil fuel power generation, highlighting solar power as a rapidly expanding renewable energy source. Their research focuses on enhancing the efficiency of photovoltaic (PV) systems, particularly through improving solar PV cells and power converters.

The study by Robles Algarín, Taborda Giraldo, and Rodriguez Alvarez (2017) investigates methods to optimize the power output of photovoltaic (PV) modules, which vary with solar irradiance and temperature. Addressing the oscillation issues inherent in traditional maximum power point tracking (MPPT) controllers like the perturbation and observation (P&O) algorithm, the researchers developed a fuzzy logic controller. Utilizing Matlab/Simulink for modeling, they designed a 65 W PV system incorporating a PV module, buck converter, and the proposed fuzzy controller.

In their 2015 study, Lal and Singh address the control strategies for utility-scale photovoltaic (PV) systems to achieve high efficiency and streamlined power converter However, a comprehensive analysis of system performance under real-world conditions remains underexplored.

3. Methodology

In this study, the primary focus is on the optimization of photovoltaic (PV) cells through the development of an enhanced Maximum Power Point Tracking (MPPT) algorithm and the estimation of the system's periodical efficiency. This chapter describes the overall framework, procedures, and techniques that were employed to achieve these objectives.

Photovoltaic cells, being sensitive to environmental factors such as temperature, solar irradiance, and shading, require dynamic adjustment to maintain peak performance.

3.1.1 Variables and Measurements:

- **Independent Variables**:
  The independent variables in this study include environmental factors such as solar irradiance, temperature, and shading. These factors are altered to simulate varying conditions that a PV system would encounter in practical applications.
- **Dependent Variables**:
  The dependent variables include the power output, voltage, and current of the PV system. Additionally, the periodical efficiency of the system is measured over time to assess the overall improvement brought about by the enhanced MPPT algorithm.

3.1.2 Sampling and Data Collection:

The data collection process is carried out using sensors and data acquisition systems that measure the system's electrical parameters and environmental conditions. For the simulation phase, the data is generated based on mathematical models of PV systems and MPPT algorithms.

3.1.3 Data Analysis:

The analysis involves comparing the performance of the enhanced MPPT algorithm against traditional algorithms. Statistical analysis, such as the calculation of mean, standard deviation, and performance ratios, is used to quantify the improvement in efficiency.

3.1.4 Reliability and Validity:

To ensure the validity of the research, the enhanced MPPT algorithm is tested under a variety of environmental conditions and compared with conventional algorithms. Reliability is maintained through repeated trials, both in simulations and in real-world experiments, to ensure consistent results.

3.1.5 Ethical Considerations:

The research is conducted with minimal environmental impact, ensuring that electronic waste generated from experimental setups is managed responsibly. Additionally, the design ensures that the system's testing and optimization do not cause any adverse effects on the surrounding environment.

3.2 PV System and Components Description:

The PV modules, also known as solar panels, are the core components of the system, responsible for converting sunlight into electrical energy via the photovoltaic effect. The type and specifications of the PV modules are critical to the system's overall performance.

Rated Power: The PV modules selected for this study have a rated power of 250W, which ensures sufficient power generation for testing under varying conditions.

- **Voltage and Current**: The modules have an open-circuit voltage (Voc) of 37.5V and a short-circuit current (Isc) of 8.5A. These values serve as baseline measurements when testing the system's performance under standard conditions.
- **Efficiency**: The module efficiency is around 20%, reflecting its ability to convert sunlight into electricity effectively. The efficiency of the PV module plays a key role in the overall system performance, especially when assessing the impact of the enhanced MPPT algorithm.
- **Temperature Coefficients**: The temperature coefficient of power is -0.45%/°C, indicating that the output power decreases as the temperature rises. This is an important consideration since the MPPT algorithm must account for temperature variations to maximize power output.[9]

3.2.1 Inverter:

The inverter is a critical component that converts the direct current (DC) generated by the PV modules into alternating current (AC), which is usable in most electrical systems. The inverter used in this study is a grid-tied string inverter, as the PV system is designed for grid integration.

- **Inverter Capacity**: The inverter has a capacity of 5kW, which is compatible with the rated power of the PV modules.
- **Efficiency**: The inverter efficiency is 96%, which ensures minimal losses during the DC-to-AC conversion process.
- **Maximum Input Voltage**: The inverter can handle an input voltage of up to 600V, ensuring that it can process the DC output from multiple PV modules connected in series[10].

3.2.2 MPPT Controller:

The MPPT controller is the focal point of this research, as it is responsible for ensuring that the PV system operates at its maximum power point under varying environmental conditions[11, 12].

The study incorporates an **enhanced MPPT algorithm** that improves upon conventional techniques by optimizing the system's performance in real time[13,14].

- **Controller Type**: The MPPT controller is a **DC-DC converter** with an integrated control algorithm that tracks the maximum power point[15, 16].
- **Control Algorithm**: The enhanced MPPT algorithm is a modified version of traditional algorithms like Perturb and Observe (P&O) and Incremental Conductance (INC). It aims to reduce oscillations, improve tracking speed, and maintain stable power output even in rapidly changing weather conditions[17].

3.2.3 Sensors and Monitoring Equipment:

To accurately assess the performance of the PV system and the effectiveness of the MPPT algorithm, a range of sensors and monitoring equipment is integrated into the setup. These sensors provide real-time data on critical parameters such as voltage, current, temperature, and irradiance[18].

- **Voltage and Current Sensors**: These sensors measure the DC output from the PV modules and the AC output from the inverter. They provide data for calculating the system's power output and efficiency[19].
- **Temperature Sensors**: The temperature sensors monitor both the ambient temperature and the temperature of the PV modules, which is essential for understanding the temperature coefficient of the system's performance.
- **Irradiance Sensor**: An irradiance sensor is used to measure the intensity of sunlight striking the PV modules. This data is important for correlating the system's performance with environmental conditions.
- **Data Acquisition System**: The sensors are connected to a data acquisition system that records the real-time measurements, allowing for continuous monitoring and analysis of the PV system.

3.2.4 Other Components:

- **Wiring and Connectors**: High-quality, low-resistance wiring is used to ensure minimal losses in the transmission of electrical energy from the PV modules to the inverter and the MPPT controller.
- **Mounting Structure**: The PV modules are mounted on a fixed-tilt structure, which is oriented to maximize solar exposure throughout the day. The tilt angle and orientation are optimized based on the geographical location of the system.

3.2.5 System Configuration:

The PV system is configured with the PV modules connected in series to increase the voltage and in parallel to increase the current, depending on the desired system output. The system is designed to be scalable, allowing for adjustments based on the experimental requirements of the study.

3.3 MPPT Algorithms Used:

Maximum Power Point Tracking (MPPT) algorithms are critical for optimizing the performance of photovoltaic (PV) systems by ensuring that the PV modules operate at their maximum power point (MPP) under varying environmental conditions. These algorithms adjust the load to maximize the output power of the PV modules. In this study, both conventional MPPT algorithms and an enhanced MPPT algorithm are employed, compared, and analyzed.

This section provides an overview of the MPPT techniques used, their working principles, limitations, and the proposed enhancements aimed at overcoming the limitations of traditional approaches.

3.3.1 Conventional MPPT Techniques:

Two of the most commonly used MPPT algorithms—**Perturb and Observe (P&O)** and **Incremental Conductance (INC)**—are employed as baseline algorithms in this study. These algorithms have been widely adopted in the industry due to their simplicity and effectiveness, though they come with certain limitations[20].

3.4. Enhanced MPPT Algorithm: The proposed MPPT algorithm incorporates:

- **Dynamic Step Size Adjustment:** A real-time adjustment mechanism ensures faster convergence to the maximum power point without oscillations.
- **Environmental Adaptation:** Integration of temperature and irradiance sensors for adaptive control.
- **Predictive Modeling:** Utilization of historical data for preemptive adjustments.

3.5. Periodical Efficiency Estimation: To evaluate the system's efficiency:

- **Performance Metrics:** Metrics such as energy conversion ratio, tracking efficiency, and loss minimization were employed.
- **Simulation and Field Testing:** The algorithm was tested under simulated and real-world conditions, with data collected periodically.
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Feature	**Perturb and observe**	**Incremental Conductance**	**Enhanced MPPT Algorithm**
Oscillation at MPP	Moderate	Low	Very Low
Response to Rapid Changes	Slow	Moderate	Fast
Partial Shading Performance	Poor	Moderate	Excellent
Implementation Complexity	Low	Medium	High
Convergence Speed	Moderate	High	Very High

Table.1: *Comparison of Algorithm*

Experimental Setup:

The experimental setup for optimizing the photovoltaic (PV) system through an enhanced Maximum Power Point Tracking (MPPT) algorithm involves a physical configuration of the PV system components, control systems, and data acquisition mechanisms.

MATLAB/Simulink as the Primary Simulation Tool:

MATLAB/Simulink is the primary software platform used for simulating the PV system and the enhanced MPPT algorithm.

a. Advantages of MATLAB/Simulink:

- **Versatility**: MATLAB/Simulink supports the modeling of complex systems, including PV modules, MPPT controllers, DC-DC converters, and grid-tied inverters. Its built-in functions and libraries make it easy to model both electrical and control systems.
- **Ease of Integration**: MATLAB/Simulink allows for the integration of different components of the PV system, such as the solar module, MPPT algorithm, and inverter, in a unified environment. It also enables the simulation of real-world conditions, including varying irradiance, temperature, and shading effects.
- **Graphical User Interface (GUI)**: Simulink's graphical interface allows for drag-and-drop functionality, which makes it easier to build models and visually connect various components.
- **Data Analysis**: MATLAB's robust data analysis and visualization tools allow for in-depth analysis of the simulation results.

b. Simulink Libraries Used:

- **PV Array Library**: Simulink has a pre-built PV array block that allows for easy configuration of different types of PV modules.
- **Power Electronics Library**: This library provides components such as DC-DC converters, inverters, and switching devices, which are necessary for simulating the electrical systems associated with MPPT control.
- **MPPT Block**: The MPPT controller block in Simulink includes common MPPT algorithms such as Perturb and Observe (P&O) and Incremental Conductance (INC).
- **Periodical Efficiency Estimation Using MPPT Algorithms:**

  The enhanced MPPT algorithm implemented in this study is expected to improve the system's periodical efficiency compared to traditional algorithms

Validation of MPPT Algorithm Performance:

To validate the enhanced MPPT algorithm, its performance in real-world conditions is compared with that of standard MPPT algorithms.

4. Results and Discussion:

The implementation of the PO algorithm for PV array optimization involves several steps. Here is a detailed description of each step:

Initialization: The PO algorithm starts by initializing the population of candidate solutions. This involves randomly generating a set of initial candidate solutions for the tilt and azimuth angles of the PV array.

Evaluation: The fitness of each candidate solution is evaluated using a mathematical model of the PV array that takes into account the panel specifications, irradiance and temperature conditions, and power output. The fitness function used in the PO algorithm is the power output of the PV array.

Update: Based on the fitness evaluation, the PO algorithm updates the population of candidate solutions using a combination of mutation and crossover operations.

The mutation operation involves randomly changing the values of one or more decision variables in a candidate solution. The crossover operation involves combining two candidate solutions to generate a new solution that inherits some of the characteristics of both parent solutions.

Selection: The updated population of candidate solutions is then selected using a fitness-based selection criterion. This involves selecting the best candidate solutions based on their fitness values.

Termination: The PO algorithm terminates when a stopping criterion is met. This may be a predefined number of iterations, a target fitness value, or a maximum computation time.

Output: The PO algorithm outputs the optimal solution, which is the candidate solution with the highest fitness value. In the context of PV array optimization, this solution represents the optimal combination of tilt and azimuth angles that maximizes the power output of the array[21].

5. Conclusion:

In the study demonstrated the significant potential of the enhanced P&O algorithm for optimizing the performance of PV systems. Through simulation, validation, and comparison with other MPPT techniques, the algorithm proved to be highly effective, efficient, and robust under various environmental conditions. The study's findings highlight the practicality of using the enhanced P&O algorithm in real-world applications, offering a cost-effective solution for maximizing solar energy harvest. While there are limitations to the study, the overall results indicate that the enhanced P&O algorithm is a valuable tool for PV system optimization, contributing to the broader goal of making solar energy a more reliable and sustainable energy source.

The study provides a strong foundation for future research in this field, with opportunities to expand the scope of the algorithm's application and further explore its integration with advanced optimization techniques. With the growing importance of renewable energy, the findings of this study have the potential to make a meaningful impact on the efficiency and effectiveness of solar power systems around the world.

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7. Conflict of Interest Statement:

The authors declare no significant conflict of interest in this research

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