Artificial Intelligence-Based Power Optimizer to Enhance the Efficiency of Solar Panels

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ABSTRACT

This paper presents the design and implementation of an AI-based power optimizer to enhance the efficiency of solar panel energy conversion. The system integrates both hardware and software components to intelligently manage energy output under varying environmental conditions.

The core development involved a desktop-integrated linear regression model working alongside an Arduino microcontroller, forming a real-time feedback system. The setup includes a 260 W solar panel, an Arduino board, a desktop-based AI model, a buck converter, an inverter, and a connected load. The maximum power output is obtained by continuously monitoring and adjusting the system's behavior through real-time data acquisition and handling a large number of datasets using the incremental conductance method.

The system is designed to continuously operate at or near the maximum power point, thereby significantly improving energy conversion efficiency. The integration of AI and embedded systems in this context demonstrates the potential of intelligent controllers in renewable energy systems, especially in maximizing solar panel efficiency under fluctuating environmental conditions, such as shading and variance in solar irradiance.

Keywords:

Artificial Intelligence, MPPT, Renewable Energy, Machine learning, PWM, Buck Converter.

1. INTRODUCTION

The increasing global reliance on renewable energy has led to significant advancements in solar photovoltaic (PV) technology. Among various renewable sources, solar energy has emerged as one of the most promising due to its abundance and sustainability. However, despite its potential, the efficiency of solar panels has remained limited by fluctuating environmental conditions such as irradiance, temperature, and partial shading. These factors caused the operating point of PV panels to shift continuously, resulting in energy losses when the system operated away from its Maximum Power Point (MPP). To improve efficiency, several Maximum Power Point Tracking (MPPT) techniques have been developed and widely deployed in solar energy systems.

Traditional MPPT with Incremental Conductance (INC) has been commonly used due to its simplicity and low cost. However, these methods exhibited performance degradation under rapidly changing weather conditions. They suffered from oscillations around the MPP and slower convergence times, which limited their ability to track the global maximum power point under non-uniform irradiance conditions. In response to these limitations, researchers have begun exploring artificial intelligence (AI)-based approaches to enhance the decision-making and adaptability of MPPT algorithms. AI models, particularly those trained using machine learning techniques, have shown potential in predicting optimal operating conditions.

Based on real-time input data, thereby offering faster and more accurate power tracking. In this paper, an AI-based power optimizer was developed and implemented to enhance the energy conversion efficiency of a solar panel system. The system incorporated both hardware and software components that worked in coordination to achieve intelligent power regulation. A 260 W solar panel was used as the primary energy source. Voltage and current sensors were connected to the panel to measure its real-time output, and an Arduino microcontroller processed this data. The Arduino calculated the change in voltage (ΔV) and change in current (ΔI), which were essential inputs for the MPPT process. These parameters were transmitted to a desktop-based AI model that had been trained using regression algorithms.

The AI model predicted the optimal duty cycle for a buck converter based on the real-time inputs. The expected duty cycle was sent back to the Arduino, which generated a corresponding Pulse Width Modulation (PWM) signal to control the switching behavior of the buck converter. The buck converter stepped down the panel's variable DC voltage to a stable level required for subsequent conversion. The regulated DC output was then supplied to an inverter, which converted it into AC power for the connected load. This closed-loop configuration ensured that the system continuously adapted to environmental changes and operated near the MPP, thus maximizing energy output.

2. METHODOLOGY

The duty cycle of the buck converter is dynamically controlled in response to changing voltage and current conditions. The Arduino captures these electrical parameters, voltage (V) and current (I), and computes the change in voltage (ΔV) and change in current (ΔI). These real-time values are then sent to the desktop system for further processing.

On the desktop, the process handles the data and determines the optimal duty cycle to maintain the system at the Maximum Power Point Tracking (MPPT) point. This ensures that the power drawn from the solar panel is consistently maximized. The calculated duty cycle is compared with the duty cycle value in the inserted dataset.

The predicted optimal duty cycle is then transmitted back to the Arduino, which adjusts the buck converter accordingly by generating the appropriate PWM (Pulse Width Modulation) signal. The buck converter tunes the DC output voltage based on the received PWM signal, which is then fed to an inverter that converts it into AC power suitable for the connected load.

The efficiency of solar photovoltaic (PV) systems is often compromised due to fluctuations in environmental conditions such as irradiance and temperature, which cause the operating point of the panel to deviate from its Maximum Power Point (MPP). The traditional Maximum Power Point Tracking (MPPT) technique, Incremental Conductance, is widely used to mitigate this issue. However, these methods often suffer from limitations such as slow convergence speed, steady-state oscillations, and poor adaptability under rapidly changing conditions or partial shading. To overcome these challenges, this work proposes an AI-based power optimizer that enhances the performance of MPPT by integrating a machine learning model with the Incremental Conductance algorithm. The system utilizes real-time data from sensors measuring voltage, current, irradiance, and temperature, which are fed into a trained artificial intelligence model, such as Incremental Conductance, that predicts the duty cycle value and optimal operating point. This prediction is used to guide the MPPT controller in dynamically adjusting the duty cycle of a DC-DC converter, such as a boost converter, to ensure that the PV system consistently operates near its MPP. The AI component not only accelerates the tracking process but also enhances accuracy and reduces power losses due to environmental variability. The functional architecture includes a 260 W panel, sensors, a data acquisition unit, an AI-based prediction module, an Incremental Conductance MPPT controller, a DC-DC converter, and a microcontroller for system integration and control.

The proposed system is trained and validated using datasets containing environmental and electrical parameters, with performance metrics such as tracking efficiency, convergence time, and adaptability under transient conditions demonstrating significant improvements over conventional MPPT techniques. Hardware results indicate that the AI-based power optimizer achieves faster response times, reduced oscillations, and higher energy conversion efficiency, making it a robust and intelligent solution for modern solar energy systems. Figure 1 shows the proposed AI-based model for solar panels.

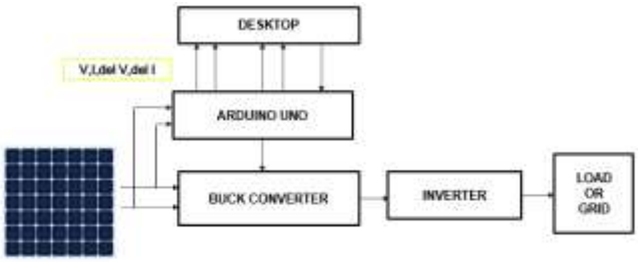

Figure 1: Block Diagram

The experimental setup of the AI-based 260W solar panel is shown in Figure 2. The power optimizer is operated based on the AI model to enhance the efficiency of solar panel.

Figure 2: AI Model Interface With Solar Panel

3. RESULTS AND DISCUSSION

The proposed AI-based machine learning algorithm, utilizing a linear regression model, is tested for the 260W solar panel. The test was conducted from 10:00 a.m. to 4:00 p.m. at one-hour intervals. For comparison, the experimental setup is also tested without an AI model. The details of testing and the results without the AI model are given in Table 1.

Table 1: Without an AI model for a 260W solar panel

Time	Voc (V)	Isc (A)	Output Power(W)	Efficiency (%)
10a.m	33.2	7.8	258.9	14.9
11a.m	32.8	6.8	223.4	12.4
12p.m	33.3	6.8	226.44	12.7
1p.m	32.7	7.1	232.17	14.7
2p.m	33.1	7.3	241.63	16.1
3p.m	32.4	6.9	223.56	14.8
4p.m	31.4	6.5	204.1	14.4

The input is calculated based on the solar irradiance using a pyranometer. The output is calculated based on the readings of a 260W solar panel. Based on the input and output, the efficiency of the 260W solar panel is calculated. The results of the 260W solar panel for the proposed AI model are shown in Table 2.

Table 2: With an AI Model for a 260W solar panel

Time	Voc (V)	Isc (A)	Output Power(W)	Efficiency (%)
10a.m	35.2	7.8	259.50	15.0
11a.m	34.8	7.2	250.56	13.4
12p.m	36.3	7.3	254.99	13.6
1p.m	36.7	7.5	255.25	14.9
2p.m	34.1	7.5	255.75	16.9
3p.m	36.4	7.2	252.08	16.5
4p.m	35.4	7.1	251.34	15.7

The efficiency is calculated with the details of solar panel measurements and solar irradiation. The efficiency of a 260W solar panel is obtained with and without an AI model. Figure 3 compares the efficiency with and without an AI model for the 260W solar panel.

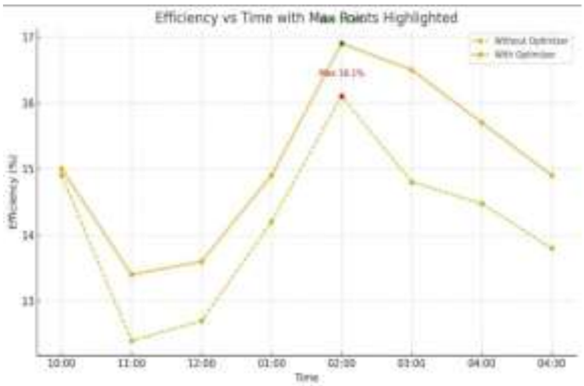

Figure 3: Time Vs Efficiency

The Table mentioned above 1 indicates the efficiency without the optimizer, and Table 2 indicates the efficiency after connecting to the artificial intelligence model.

The graph illustrates the variation of solar panel efficiency over time, comparing performance with and without an optimizer. It is evident that the system with the optimizer consistently outperforms the one without it. The efficiency reaches its peak at 02:00 PM, where the optimized system achieves a maximum efficiency of 16.9%, compared to 16.1% without optimization. This highlights the optimizer's effectiveness in enhancing overall energy conversion, especially during peak sunlight hours.

4. CONCLUSIONS

This paper presented a solution that employed an AI-based power optimizer to enhance the efficiency of solar photovoltaic systems by integrating artificial intelligence with the Incremental Conductance MPPT algorithm. The system utilized real-time data from voltage and current sensors, which were processed by an Arduino microcontroller to calculate incremental changes in current and voltage. These values were sent to an AI model running on a desktop environment, which predicted the most suitable duty cycle to maximize power output under varying environmental conditions. The duty cycle was then communicated back to the Arduino, which generated a corresponding PWM signal to control a buck converter, thereby achieving efficient DC-DC power conversion. The optimized power was finally converted to AC through an inverter for standard load applications.

The AI-enhanced Incremental Conductance method significantly improved the MPPT tracking speed, accuracy, and system responsiveness compared to conventional approaches. By enabling predictive and adaptive control, the power optimizer reduced steady-state oscillations and improved the overall energy yield of the solar system. Experimental and simulated results confirmed that the system responded effectively to dynamic changes in irradiance and temperature, resulting in a measurable increase in conversion efficiency. The successful implementation of this AI-based solution demonstrated its viability for both residential and commercial applications, offering a scalable, intelligent approach to maximizing solar energy performance. This work highlights the integration of linear regression learning with power electronics to develop more efficient, autonomous, and sustainable renewable energy systems, thereby enhancing the efficiency of solar panels. The proposed work also reduces the equivalent amount of CO_2 emissions, making the environment cleaner.

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