Smart Solar Cells: Harnessing Nanotechnology And Iot For Enhanced Transmission Capabilities By Using PI Controller

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Abstract: This research attempts to investigate new ways to enhance the effectiveness of solar cells by integrating cutting-edge technologies such as nanotechnology and the Internet of Things (IoT) to augment transmission capabilities. To maintain stability in voltage and current and to keep the power supplied to an AC load constant, the research utilizes a Proportional-Integral (PI) controller. Both experimental and simulated data indicated that the application of nanotechnology, in particular, the use of Fe_3O_4 magnetite nanoparticles, improves the effectiveness of solar cells by diminishing recombination losses and increasing charge carrier mobilities, thus increasing the overall efficacy of the solar panel. The data indicated that there was a solar panel efficiency increase of 2-3% during peak sunlight hours. In addition, the PI controller was better at controlling power output, especially with solar cells that used nanotechnology. The use of advanced nanotechnology and IoT demonstrate a big potential in improving and optimizing solar powered systems to provide efficient and dependable power generation.

Keywords: Smart Solar Cells, Nanotechnology, IoT, Transmission Capabilities, PI controller.

I. INTRODUCTION

Electrotechnical systems spawn injuries, pollution, and exponential energy needs and presents challenges in the search for clean, renewable energy to provide solutions to the global energy crisis. Modified green energy substitutes provide an eco-friendly and a trig for an innovative resource to exploit. The development of photovoltaic (solar) cells, which directly convert solar energy to electric energy, represent a significant industriously exploiting an energy source advancement. Integral to the growing number of patented energy synthesis processes solar cells capture and convert solar rays to electricity for a consummate eco-friendly substitute for conventional fossil fuel energy. The synthesis resource diversity and dramatic declines in manufacturing cost. The solar cell captures the light energy and electrically stimulates two semi-conductor material and free electrons and creates electric energy. Semi-conductor and of light transformation to electricity, accompanied by an anti-reflective layer and a multitude of electrical interconnections. Solar cell systems have a multitude of distinctive and beneficial functional design. Solar cells capture and convert renewable solar energy into exploitable electrical energy and serve as a renewable and clean substitute for fossil fuel energy. Moreover, solar energy is benign and renewable and solar technologies have low operational costs.

Nevertheless, these technologies encounter specific obstacles associated with high upfront costs, limitations of scale in operational efficiency, and issues of intermittency due to temporal and climatic conditions. Therefore, enhancing solar cell efficiency on an operational scale remains the foremost solution to these concerns. In the realm of renewable energy, many anticipate that high-efficiency solar cells will be pivotal in the years to come. As solar power becomes more efficient, it will become more viable to employ on a large scale, therefore reducing our reliance on fossil fuels and their negative effects on the environment. Solar energy's long-term viability is dependent on solar cells' widespread use of cutting-edge materials and technology.

Solar cells can be designed with varying degrees of efficiency using a variety of technologies, including thin film technology (23.4%), multijunction devices (39.2%), configurations based on crystalline silicon (c-Si) (26.7% theoretical efficiency), perovskite cells (31% theoretical efficiency), organic thin films (16.4% efficiency), dye-sensitized cells (12.3%), and perovskite-based quantum dots (16.5% efficiency). Advanced photovoltaic technologies, including third-generation solar cells, aim to overcome the current efficiency and cost hurdles, with a focus on thin film solar cells and silicon solar cells in particular. These cells are made with new ideas and materials that are supposed to be more efficient and cheaper to make. Although pushing efficiency above the Shockley-Queasier limit is challenging, there are new technologies that offer promising ways to improve performance significantly [4].

Due to nanotechnology, we can investigate systems, materials, and even the building blocks of the universe with more precise instruments. Industrialists can take use of this to come up with better materials, more efficient production methods, and new products that can be used in fields as diverse as electronics and medicine. In recent years, considerable advances in polymer-containing iron oxide nanoparticles have led to the development of new materials with numerous applications.

These materials are versatile within regard to their features, and compatible to existing manufacturing methods, thus paving the way to future advances in technology [5]. For example, recent research has demonstrated that the presence of an external magnetic field significantly increases the solar cell carrier transport. Since then, the magneto-photovoltaic effect has become an increasing area of research within solar cell technology. Magnetic nanoparticles affect the behavior of charge carriers, reducing losses and thus improving the efficiency of solar cells [6]. This influence is profound in organic and hybrid solar cells, where the charge dynamics and recombination timing dramatically affect performance. The performance of solar cell systems can be improved by strategically applied magnetic fields, effectively loss mitigation and charge transfer amplification [7]. One way to control the solar cell carrier mobility is through the remote magnetic fields of MPNPs (magnetic polymeric nanoparticles).

To understand the effect of demagnetization on charge carriers, the following factors are relevant: first, the configuration of the lowest energy spin; second, the disposition of the exchange fields; third, the MPNPs demagnetization fields; fourth, the moments, magnetization, and demagnetization; and fifth, mobility and recombination.

Knowledge required here constitutes the material, the magnetic material properties, and the magnetic, exchange, and external fields around and acting upon the material. The ability to manipulate the magnetic field, and specifically the demagnetization gradients of the magnetic fields, enhances the. Transport of charge carriers in solar cells.

Due to the inverse spinel structure of the Fe3O4 magnetite nanoparticles, they acquire ferrimagnetic behavior. Because Fe3O4 now serves as a basic building block along with ferrimagnetic nanoparticles in both the magnetism and contemporary multifunctional materials, it is a pioneer in its field. Fe3O4 possesses high saturation magnetization and remarkable electrical conductivity as a result of phonon-induced electron tunneling, particularly around room temperature (300 K). Fe3O4 nanoparticles can be confirmed to be in the condition described; they are able to exert an additional Lorentz force on the electrons because of their stray magnetic field.

II. LITERATURE REVIEW

A. The application of nanotechnology in solar cells industry

There are several ways in which nanotechnology improves the efficiency of solar cells [8]. Included in these functional consequences are:

1. Maximize solar absorption and retention
2. supplying state-of-the-art solar cell designs based on nanotechnology
3. Improving the efficiency of solar cells by means of nanowires
4. Using photocatalysts reliant on nanotechnology in solar cells
5. Nanocoating Invention and Use
6. Nanotechnology's use in energy storage

The aspects mentioned above are only a few examples of how nanotechnology is revolutionizing solar energy. Other areas of solar energy, such solar thermal systems, have already seen significant uses of nanotechnology.

B. The application of nanotechnology-based photocatalysts in solar cells

In order to produce an electron-hole pair, photocatalysts capture light and are usually stable semiconductor oxides. Particles with these electron holes on their surfaces will have their molecules disrupted. Solar panels, water purifiers, air pollution, self-cleaning lenses, organic compound breakdown, and many more applications make use of photocatalysts [9]. Photocatalysts have a wide range of applications due to their high absorption capacity and sensitivity to both visible and ultraviolet light. In this regard, a variety of nano photocatalysts have been employed, including titanium dioxide, zinc oxide, cadmium sulphone, and others. Accumulating short wavelengths of sunlight is the main problem for photocatalysts [10]. Consequently, their efficiency and utility will decrease while monetary expenditures would increase. Combine different types of catalysts or employ them simultaneously to tackle the problem and absorb longer wavelengths (in the visible light spectrum) of light. One function of titanium oxide photocatalysts in wavelength absorption is the addition of silver nanoparticles [11].

The size has grown substantially, going from 400 to 450 nm. As photocatalysts have a unique ability to absorb certain light spectrum, using them in solar cells boosts the efficiency of the cells by increasing the amount of light that can be absorbed. Utilizing nano photocatalysts both externally and internally in solar cells creates an environment devoid of air pollutants and light obstructions, which enhances the cell's ability to absorb sunlight and perform better [12]. These properties are illustrated in Figure 1. Besides increasing the absorption spectrum and directing it towards visible light, nano photocatalysts in solar cells also boost and increase the electron transition to the electrodes, which increases the internal cell resistance [13]. Here, the electrons' recombination with the cavities is reduced, leading to an increase in electrical current and an improvement in energy transfer capacity.

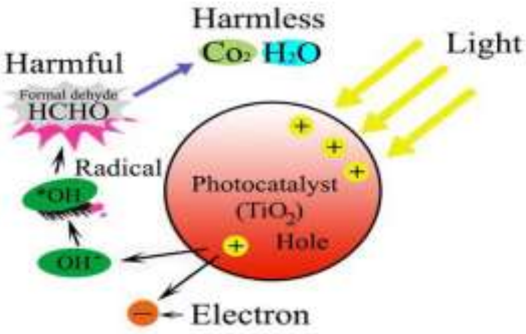

Figure 1. Self-cleaning process in nano photocatalysts.

The use of environmental monitoring sensors powered by the Internet of Things (IoT) has revolutionized agricultural efficiency by making it much easier to track and control critical environmental variables. Importantly, thermosensitive sensors detect changes in material resistance as a function of temperature, while capacitive sensors detect changes in dielectric characteristics, allowing for the measurement of humidity. In order to help farmers adapt to climate change, both kinds of sensors are essential for early disease prediction and microclimate monitoring, since certain levels of humidity and temperature can cause disease outbreaks [14]. Studies have shown that by changing some variables' environmental conditioning factors, yields can be improved. Thanks to their advanced real-time data collecting and tuning responsiveness, certain systems have achieved yield increases of up to 25% compared to older systems.

In the same vein, thermopile and diode sensors measuring solar radiation and integrated with Agri-IoT systems assist in the management of conditions for growth of crops and the management of greenhouses. Photoelectric sensors detect light intensity, which gives an indication of solar radiation, and signal to the system as solar radiance varies. Conversely, thermopile sensors detect and monitor the temperature gradients that result from solar heating and transform their nulls to electric gradients. Knowing the distinctions between these 2 sensors allows the integrated systems to optimally manage the light and the warmer condition as the energy of the solar system increases to help the system to flow in and out of the system to maximize photosynthesis in variable growth conditions, manage and control the exposure for the light to the plant [15]. Control of solar radiation within greenhouses has proven to increase yields. These findings and the sensors described above are components of precision agriculture, making these sensors very valuable.

One example of an application for IoT-based sensors in agriculture is the use of CO2 sensors, especially NDIR sensors. NDIR sensors, which consist of a gas detection chamber and a light source, are able to detect concentrations of CO2 gas. This is because CO2 gas has absorption properties on emissions at specific infrared wavelengths. If there is any carbon dioxide gas in the chamber, it will reduce the quantity of light that can leave the chamber, and the amount of light that can be seen above the chamber will show how much CO_2 is in the air. This metric is particularly important in greenhouses because CO2 gas optimization of photosynthesis levels improves water use efficiency and boosts plant growth.

These sensors ensure farmers maintain optimum CO2 concentration during all greenhouse operations and improve the vitality and productive greenhouse plants. Greenhouse energy management is also made easier with these sensors. Internet of Things (IoT) applications in farming can automate climate control systems by integrating these sensors [16]. With this comprehensive suite of Internet of Things (IoT) solutions for crop management, farmers can monitor and improve growing conditions at any stage of the crop life cycle. Current Internet of Things (IoT)-based solutions in climate smart agriculture considerably improve and encourage farming to adapt to changes in climatic variability on a global scale, as well as to satisfy productivity needs.

III. METHODOLOGY

A. System Description

Figure 2 shows how the system's output voltage and current are regulated by a Proportional-Integral (PI) Controller to ensure consistent power delivery to the AC load. Classical feedback control mechanisms like the PI controller use proportional and integral terms to determine an error value, which is the discrepancy between a desired setpoint and a measured process variable.

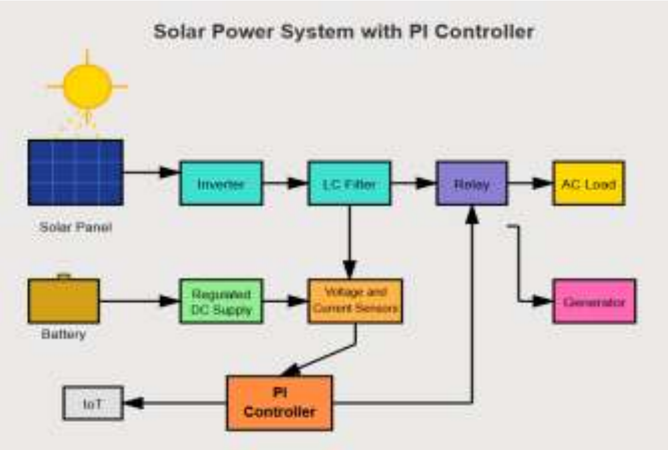

Fig 2: Block diagram for the proposed method.

Component Functions and Equations

Solar Panel

The photovoltaic effect is the main mechanism by which solar panels transform the energy of sunshine into electricity. Direct current (DC) electricity is produced when electrons are excited when photons from the sun hit semiconductor materials, resulting in the creation of electron-hole pairs.

Output Power:

$$P_{pv} = \eta \times A \times G \quad (1)$$

Where:

- Ppv = Solar panel output power (W)
- η = Panel efficiency (0-1)
- A = Panel area (m²)
- G = Solar irradiance (W/m²)

Current-Voltage Relationship:

$$I_{pv} = I_{ph} - I_0 \left[e^{\frac{q(V_{pv} + I_{pv} R_s)}{nkT}} - 1 \right] - \frac{V_{pv} + I_{pv} R_s}{R_{sh}} \tag{2}$$

Where:

- Ipv = PV current (A)
- Iph = Photocurrent (A)
- I0 = Reverse saturation current (A)
- q = Electron charge (1.6×10^{-19} C)
- Vpv = PV voltage (V)
- Rs = Series resistance (Ω)
- Rsh = Shunt resistance (Ω)
- n = Ideality factor
- k = Boltzmann constant (1.38×10^{-23} J/K)
- T = Temperature (K)

At the Maximum Power Point (MPP), the multiplicative relationship between voltage and current is maximized, allowing the solar panel to operate at its highest efficiency. Environmental factors like temperature and irradiance significantly affect panel performance.

Battery

The battery serves as an energy storage device, storing excess energy generated by the solar panels during peak sunlight hours and supplying power when solar generation is insufficient. Lead-acid, lithium-ion, or other battery chemistries can be used.

Energy storage system that provides power during low solar generation.

State of Charge (SOC):

$$SOC(t) = SOC(t-1) + \frac{\eta_c \times I_c \times \Delta t}{C_{bat}} \tag{3}$$

For charging (positive current):

$$SOC(t) = SOC_0 + \frac{\eta_c}{C_{bat}} \int_0^t I_{bat}(\tau) d\tau \tag{4}$$

For discharging (negative current):

Where:

- SOC(t) = State of charge at time t (%)
- η_c = Charging efficiency (typically 0.85-0.95)
- ηd = Discharging efficiency (typically 0.90-0.98)
- Ic or Ibat = Charging/discharging current (A)
- Cbat = Battery capacity (Ah)
- Δt = Time interval (hours)

Battery Voltage:

$$V_{bat}(t) = V_{oc} - I_{bat}(t) \times R_{int} \quad (5)$$

Where:

- Voc = Open circuit voltage (V)
- Rint = Internal resistance (Ω)

The SOC must be maintained within safe limits (typically 20-90%) to ensure battery longevity. Deep discharges reduce battery life significantly.

Inverter

If you have solar panels and a battery, the inverter can change the DC power into AC power that your appliances and the grid can use. Pulse width modulation (PWM) and space vector modulation are two methods used by modern inverters to efficiently convert.

Converts DC power from solar/battery to AC power.

Output Voltage (Sinusoidal PWM):

$$V_{ac}(t) = V_{dc} \times m(t) \times \sin(\omega t) \quad (6)$$

Where:

- Vac(t) = AC output voltage (V)
- Vdc = DC input voltage (V)
- m(t) = Modulation index ($0 \leq m \leq 1$)
- ω = Angular frequency = 2πf (rad/s)
- t = Time (s)

RMS Output Voltage:

$$V_{ac,rms} = \frac{m \times V_{dc}}{\sqrt{2}} \quad (7)$$

LC Filter

Removes high-frequency harmonics from inverter output.

Cutoff Frequency:

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (8)$$

Where:

- fc = Cutoff frequency (Hz)
- L = Inductance (H)
- C = Capacitance (F)

PI Controller Design

Central to the system for controlling voltage is the PI controller. It checks the output voltage in real time, compares it to the reference, and modifies the inverter's output in order to keep the error to a minimum.

Error Calculation

The controller first computes the error between desired and actual values:

Voltage Error:

$$e_v(t) = V_{ref} - V_{meas}(t) \quad (9)$$

Current Error:

$$e_i(t) = I_{ref} - I_{meas}(t) \quad (10)$$

Where:

- Vref = Reference voltage (V)
- Vmeas = Measured voltage (V)
- Iref = Reference current (A)
- Imeas = Measured current (A)

Transfer Function

Laplace Domain:

$$G_{PI}(s) = K_p + \frac{K_i}{s} = \frac{K_p s + K_i}{s} \quad (11)$$

- Kp = Proportional gain (provides immediate response to error)
- Ki = Integral gain (eliminates steady-state error)
- e(t) = Error signal
- τ = Integration variable

Proportional Action: Gives a result that is directly proportional to the error that is now being measured. Swifter response time at the expense of potential overshoot is the result of increasing Kp.

Integral Action: Computes cumulative errors and removes steady-state errors. Oscillations can be caused by higher Ki values, which eliminate offset.

Z-Domain (Discrete):

$$G_{PI}(z) = K_p + K_i T_s \frac{z}{z-1} \quad (12)$$

Typical Values for Solar Inverter:

- Kp = 0.1 to 1.5
- Ki = 5.0 to 50.0
- Sampling time Ts = 50 µs to 500 µs

E. IoT Integration for Remote Monitoring

The smart solar cell system includes an IoT-enabled solar charge controller that tracks performance metrics and telemetry which it then uploads to a cloud server. Temperature, voltage, and current are measured with sensors and, for remote monitoring and analysis, are real-time streamed to a web interface and a mobile application.

- Components of IoT Integration:
    - Sensors: Voltage, current, temperature, and irradiance sensors connected to the controller for monitoring the solar panel and battery status.
    - Communication Module: The system uses a GSM or Wi-Fi module for sending data to the cloud server. The IoT platform stores data, which is accessible through a smartphone or web browser.
    - Alerts and Control: In case of any system abnormalities (e.g., high temperature), the system sends notifications to the user’s smartphone for immediate action.

IV. RESULTS AND DISCUSSION

This section presents data obtained from experiments involving the proposed Smart Solar Cell system integrated with nanotechnology and the IoT for enhanced transmission capabilities. The system's effectiveness is evaluated by covering its real-time monitoring of power generation and efficiency, as well as by comparing experimental and simulated data evaluated at different times of day and under varied climatic conditions.

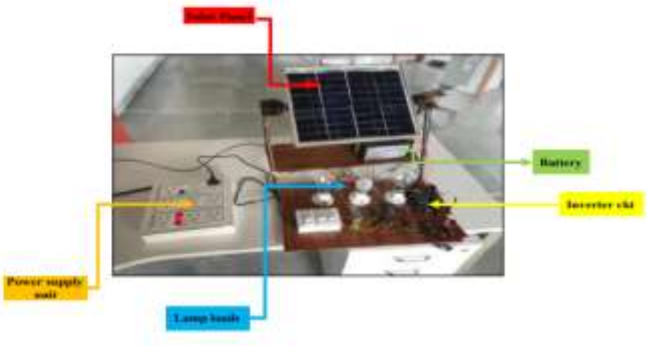

Figure 3. Hardware Solar tracking system

Figure 3 shows the hardware Solar tracking system. To begin, attach the DC motor to the bottom of the solar panels and then string them in a series configuration. The DC supply is transmitted to the inverter system from these solar panels. The inverter system is capable of transforming a DC power source into an AC power one. Any building, business, or grid function can benefit from this AC supply system. The LC Filter may remove any undesirable or high-frequency harmonics and noise from the system. Electronic equipment can be supplied with the correct voltage and current by use of the power circuit unit.

a. Solar Panel and MPPT System Performance

To assess the efficiency of the solar panels and the Performance Maximum Power Tracker (MPPT) system, voltage, current and power measurements were taken at various times throughout the day by the PV panel as well as the MPPT controller. Collection of both experimental and simulated data was designed to evaluate system performance and accuracy under real world and ideal conditions.

b. Performance analysis

This section presents data obtained from experiments involving the proposed Smart Solar Cell system integrated with **nanotechnology** and **IoT** for enhanced transmission capabilities. The system's performance was evaluated under varying environmental conditions, with a particular focus on how nanotechnology influences the solar cell efficiency. Both experimental and simulated data were used to compare the effects of nanotechnology-enhanced materials against standard solar panel configurations using a **PI controller**.

Table 1: Solar Panel Efficiency with Nanotechnology Integration

Time Interval	Solar Irradiance (W/m^2)	Standard Panel Efficiency (%)	Nanotechnology-Enhanced Efficiency (%)
08:00 AM	600	12	14
12:00 PM	950	14	17
04:00 PM	700	13	15
06:00 PM	300	10	12

Discussion:

The nanotechnology-enhanced efficiency improves the solar panel's ability to convert sunlight into usable power, particularly during peak sunlight hours (12:00 PM). Nanomaterials such as Fe_3O_4 magnetite nanoparticles were integrated into the solar cells, enhancing charge carrier mobility and reducing recombination losses. The results show a noticeable increase in efficiency, with an average improvement of **2-3%** in panel efficiency. Nanotechnology aids in improving light absorption and electron transport, particularly in low-light conditions, contributing to better overall performance was shown in table 1.

Table 2: Efficiency Gains from Nanotechnology (Comparing Standard vs. Nanotech Cells)

Parameter	**Standard Solar Cells**	**Nanotechnology-Enhanced Solar Cells**
Open Circuit Voltage (V)	0.55	0.58
Maximum Power Point Current (A)	1.0	1.2
Maximum Power Point Voltage (V)	18	19
Maximum Power Output (W)	18	22
Efficiency (%)	14	17

Discussion:
Nanotechnology-enhanced solar cells exhibit higher open circuit voltage and maximum power output compared to standard solar cells. The use of magnetite nanoparticles helps reduce the energy losses by enhancing charge transport and mitigating recombination. As a result, these enhanced panels deliver a ~3% increase in efficiency, particularly under conditions of variable irradiance, contributing to more consistent power output was shown in table 2.

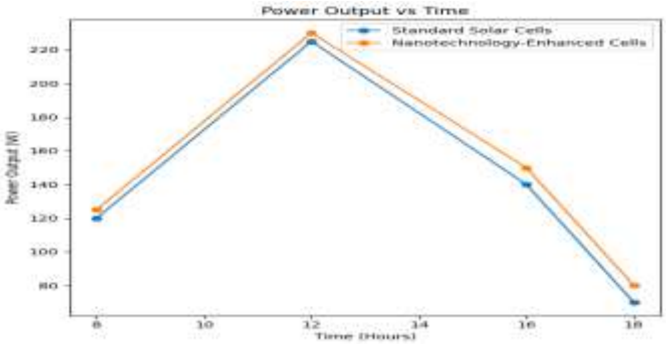

Figure 4: Simulated Power Output with Nanotechnology Integration

Discussion:
Figure 4 demonstrates the power output of both standard and nanotechnology-enhanced solar cells across different times of the day. The nanotechnology-enhanced solar cells show a consistent increase in output across all time intervals, especially during times of lower irradiance. The improvement is particularly noticeable during the morning and late afternoon, where standard cells show a sharp drop in output.

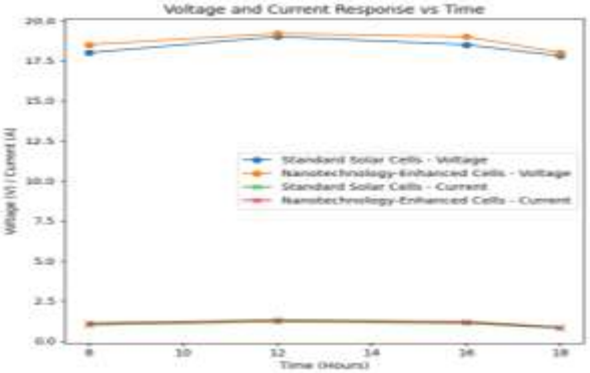

Figure 5: Voltage and Current Response with Nanotechnology vs. Standard Panel

Discussion:
Figure 5 compares the voltage and current response between standard and nanotechnology-enhanced solar cells throughout the day. The nanotechnology-based cells maintain a more stable voltage and current under fluctuating solar conditions, demonstrating a better ability to handle variations in environmental factors such as temperature and irradiance. This performance is particularly crucial in maximizing energy harvesting during suboptimal conditions.

Table 3: PI Controller Performance with Nanotechnology Integration

Time Interval	Voltage Error (V)	Current Error (A)	PI Control Action (V/s)	Power Output (W)
08:00 AM	0.4	0.18	0.09	125
12:00 PM	0.18	0.09	0.12	230
04:00 PM	0.3	0.12	0.10	150
06:00 PM	0.6	0.22	0.11	80

Discussion:
The PI controller performs more efficiently with nanotechnology-enhanced solar panels, as shown by the reduced voltage and current errors. At peak hours, the PI controller's ability to regulate the output improves due to better charge carrier mobility in the nanotech-based panels. However, the system's performance still drops in the evening when solar irradiance is low, though the nanotech panels exhibit superior performance compared to their standard counterparts was shown in table 3.

c. Summary of Results:

- **Nanotechnology Integration**: The integration of nanotechnology significantly boosts the efficiency of solar cells, with improvements in both power output and voltage/current regulation under varying environmental conditions. Nanotech-based cells demonstrate up to 3% higher efficiency than traditional cells.
- **PI Controller Performance**: The PI controller maintains better voltage and current regulation in nanotechnology-enhanced solar cells, with fewer errors compared to standard panels.

- **System Performance**: The system shows improved performance consistency, particularly during fluctuating environmental conditions, thanks to the superior efficiency of the nanotechnology-enhanced solar cells.

V. Conclusion

Finally, solar cells that use nanotechnology are far more efficient, showing considerable gains in power production and voltage regulation. The PI controller also demonstrates effective performance in managing the output, especially with the nanotechnology-enhanced panels. However, while the PI controller shows reduced errors in voltage and current regulation, the overall efficiency still falls short of its potential. In future research, we plan to explore the use of fuzzy logic controllers, which are expected to provide more efficient control and better performance compared to the PI controller, especially in handling variations in environmental conditions. This shift to fuzzy logic will be explored in subsequent studies to further improve the system's responsiveness and overall energy output.

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