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Real-Time Solar Energy Monitoring Using Arduino And ESP8266

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Abstract:

This project demonstrates a single-axis solar tracking system, designed to maximize solar panel efficiency, combined with real-time remote monitoring. An Arduino Uno microcontroller utilizes Light Dependent Resistors (LDRs) to determine the sun's position and controls an MG90S servo motor to adjust the solar panel's angle. Voltage and current sensor modules (ACS712 and a 0-25V DC module) provide accurate measurements of the solar panel's output. The Arduino then transmits this data, via UART serial communication, to an ESP8266 NodeMCU V3. The ESP8266, equipped with Wi-Fi capabilities, sends the data to a remote platform for online visualization and analysis. A local LCD display, connected via I2C, provides immediate feedback of the voltage and current values to the user. The system is powered by a 5V charger and utilizes a 9V 3W solar panel.

Key words: Power Quality, Photovoltaic system, Custom power devices and ANN controller

I. Introduction

In the pursuit of sustainable energy solutions, solar power remains one of the most promising and widely adopted renewable energy sources. However, the efficiency of solar panels is highly dependent on their orientation relative to the sun. To address this limitation, solar tracking systems have been developed to optimize energy capture by dynamically adjusting the panel's angle. This project focuses on the implementation of a single-axis solar tracking system, designed to improve solar energy conversion efficiency while offering real-time remote monitoring capabilities.

The core of the system is based on the Arduino Uno microcontroller, which plays a central role in tracking the sun's position using Light Dependent Resistors (LDRs). By comparing light intensity from multiple directions, the Arduino determines the optimal panel orientation and actuates an MG90S servo motor to align the solar panel accordingly. This active tracking mechanism ensures that the solar panel maintains an optimal angle throughout the day, thus maximizing the absorption of solar radiation and improving overall energy output.

To monitor the system's performance, voltage and current sensor modules (ACS712 and a 0-25V DC module) are integrated to measure the electrical output generated by the solar panel. These real-time measurements are critical for analyzing system efficiency and performance under varying environmental conditions. The collected data is transmitted from the Arduino to an ESP8266 NodeMCU V3 microcontroller via UART serial communication. The ESP8266, equipped with built-in Wi-Fi capabilities, facilitates the wireless transmission of data to a cloud-based platform for remote monitoring and visualization.

In addition to remote access, the system also includes a local feedback mechanism. An I2C-connected LCD display provides instant readouts of voltage and current values, allowing users to observe system performance directly at the installation site. This dual feedback approach—both local and remote—enhances the system's usability, making it suitable for both practical applications and educational purposes. Powered by a 5V charger and supported by a 9V 3W solar panel, the entire setup offers a compact, energy-efficient, and cost-effective solution for solar energy optimization and monitoring.

a) Literature Review

Solar energy has gained significant attention as a clean and renewable energy source, yet one of its primary limitations lies in the static nature of conventional solar panel installations. Numerous studies have shown that solar tracking systems can significantly enhance the efficiency of photovoltaic (PV) panels by maintaining an optimal angle relative to the sun's position throughout the day. A single-axis tracking system, as examined in this project, is a popular approach due to its balance between performance improvement and mechanical simplicity. Research by Mousazadeh et al. (2009) indicates that single-axis systems can increase energy output by 25–35% compared to fixed installations, depending on geographical and environmental factors.

The use of microcontrollers in solar tracking systems has become increasingly common due to their affordability and programmability. Arduino-based systems have been widely adopted in academic and prototyping environments for their ease of use and community support. Light Dependent Resistors (LDRs) are frequently employed in such systems to detect the direction of maximum solar irradiance. A study by Khan and Razzaq (2014) demonstrated the effectiveness of

LDR-based sun-tracking mechanisms in improving energy collection, highlighting their reliability and cost-efficiency in tracking applications.

Motorized tracking, typically using servo motors like the MG90S, provides precise control over the panel's movement. While stepper motors are also used, servo motors are often preferred for their ease of integration in lightweight applications. Additionally, incorporating real-time monitoring and data acquisition systems into solar tracking setups has become a growing area of interest. The use of voltage and current sensors, such as the ACS712 and generic voltage dividers, allows for continuous performance assessment. These sensors have been utilized in various research works to evaluate PV system efficiency and detect potential faults.

With the rise of the Internet of Things (IoT), integrating wireless modules like the ESP8266 NodeMCU has enabled remote monitoring of solar systems. Studies such as those by Sharma et al. (2017) have demonstrated how IoT-based monitoring improves the management and maintenance of solar installations by providing access to real-time performance data. Furthermore, local display units, like I2C-connected LCDs, continue to be a reliable method for on-site data presentation, especially in off-grid or educational setups.

In summary, the design and implementation of a single-axis solar tracking system with real-time monitoring aligns with ongoing trends in solar technology development. The integration of Arduino-based control, LDR sensors, voltage and current measurement, and Wi-Fi-enabled data transmission reflects a multidisciplinary approach that combines energy efficiency with modern IoT solutions. This literature forms the foundation for the current project, which aims to contribute to the growing body of knowledge by presenting a low-cost, efficient, and remotely accessible solar tracking prototype..

II. Solar Panel

The solar system is among the most dependable systems within the renewable energy sector. The solar system produces

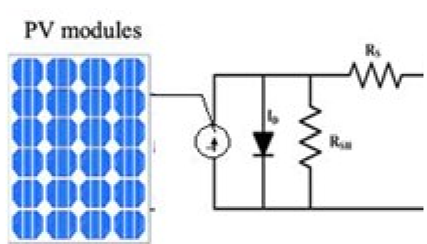

Figure 2 Structure of PV

$$I_{solar} = I_{ph} - I_D - I_{sh}$$

$$I_{solar} = I_{ph} - I_o[e^{(\frac{qV_D}{nKT})}] - (\frac{V_D}{R_s})$$

III. Description of system components

a. Voltage Detection Sensor Module 0-25V DC : The module uses a voltage divider circuit (typically two resistors) to step down the input voltage to a level safe for the microcontroller's analog-to-digital converter (ADC). The output is an analog voltage that is proportional to the input voltage, which you can then read and scale in your code

b. Current Sensor ACS712 Module - 5A: The **ACS712-5A module** is a popular and widely used **hall-effect-based current sensor** that can measure both **AC and DC currents** up to **±5 Amps**. It is ideal for hobby electronics, automation, and energy monitoring projects where current flow needs to be tracked safely and accurately.

The module uses the **Hall effect** to detect magnetic fields generated by the current flowing through a conductor on the chip. The sensor converts this magnetic field into a proportional **analog voltage output**, centered at 2.5V:

- **< 2.5V**: Negative current flow
- **= 2.5V**: No current flow
- **> 2.5V**: Positive current flow

This output can be read by the **analog input pin of a microcontroller** (e.g., Arduino), and using some math, the actual current can be calculated.

c. NodeMcu ESP8266 V3 Lua CH340 Wifi Dev. Board: The NodeMCU ESP8266 V3 is a compact and powerful development board built around the ESP8266 WiFi microcontroller, ideal for IoT (Internet of Things) applications. It features built-in WiFi connectivity, digital I/O pins, and support for the Lua scripting language as well as Arduino IDE, making it beginner-friendly and versatile.

Arduino Uno R3 SMD Development Board: The Arduino Uno R3 SMD works as a microcontroller-based development platform that allows users to read inputs, process data, and control outputs based on pre-programmed logic. It's designed for easy interaction with sensors, actuators, displays, and communication modules.

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1. Microcontroller Core (ATmega328P SMD) : At the heart of the board is the ATmega328P microcontroller in SMD form. It is responsible for executing the user-defined code uploaded via the Arduino IDE. It processes inputs, performs logic operations, and controls outputs accordingly.

Clock Speed: 16 MHz for reliable and stable operation.

Memory: 32KB Flash (for storing code), 2KB SRAM (for variables), 1KB EEPROM (for long-term data).

2. Power Supply System : The board can be powered via USB cable (5V from PC), Barrel jack (7V–12V recommended), Vin pin (direct voltage input) and The onboard voltage regulator ensures the microcontroller and components receive a stable 5V.

3. USB-to-Serial Converter (CH340 or ATmega16U2): Uploading code from a computer, Serial communication between PC and microcontroller and Some clones use the CH340 chip, while originals often use ATmega16U2 for USB communication.

4. Input Section: You can connect various input devices are Push buttons, Sensors (temperature, motion, IR, etc.), Potentiometers and Analog inputs (A0–A5) read varying voltages (0–5V) and convert them into digital values using the built-in ADC (Analog-to-Digital Converter).

5. Output Section: You can control LEDs, Motors, Relays, Displays (LCD, OLED, etc.) and Using digital pins (0–13) and PWM outputs (D3, D5, D6, D9, D10, D11), the board can send control signals to external devices.

6. Programming and Execution Cycle: Write code in the Arduino IDE, Upload code via USB cable to the Uno R3 SMD, Microcontroller runs the code automatically when powered on and It reads inputs, processes logic, and controls outputs continuously.

7. Communication Interfaces: UART (Serial): For communication with PC or other serial devices, I²C (SDA/SCL): For sensors, displays, etc, SPI: For SD cards, RF modules, etc and These allow the Arduino to interact with a wide range of external hardware.

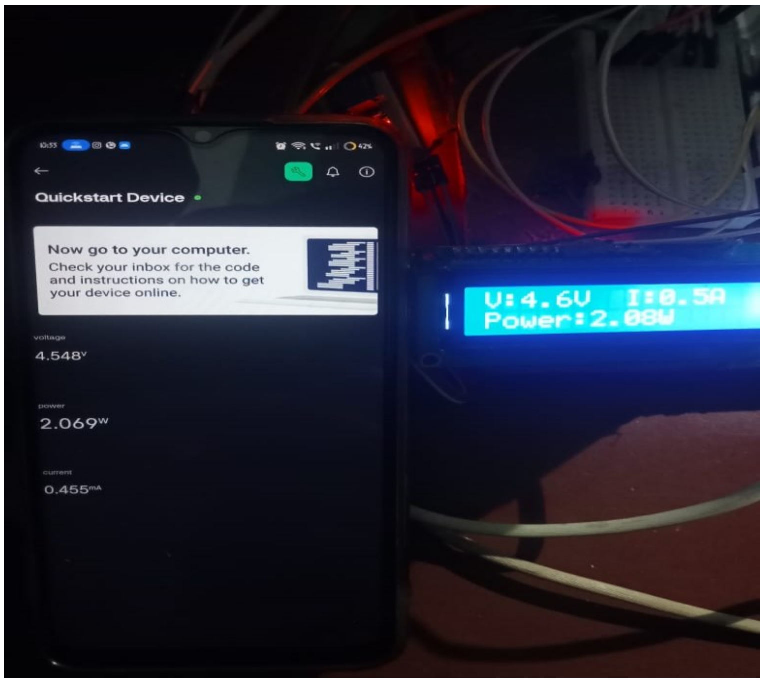
IV. System Working

At the heart of the system is the Arduino Uno R3, which controls the movement of the solar panel by analyzing light data received from four Light Dependent Resistors (LDRs) placed in a specific geometric configuration (typically cross-shaped). These LDRs are used to sense sunlight intensity from multiple directions.

- When sunlight hits the panel unevenly, the LDRs detect variations in brightness.
- The Arduino compares the light levels:
- If one side receives more light, it signals that the panel is not optimally aligned.

- Based on this comparison, the Arduino controls an MG90S servo motor to adjust the angle of the panel toward the direction with greater light intensity.
- This ensures that the solar panel maintains an optimal angle to the sun throughout the day, improving solar radiation capture.

V. Results



VI. Conclusion

This project successfully demonstrates the design and implementation of a single-axis solar tracking system integrated with real-time remote monitoring capabilities. By utilizing an Arduino Uno in combination with Light Dependent Resistors (LDRs), the system efficiently detects the sun's position and adjusts the solar panel's orientation using an MG90S servo motor. This dynamic tracking mechanism enhances solar energy capture compared to fixed-panel systems, improving overall efficiency.

To ensure accurate performance monitoring, voltage and current sensors (ACS712 and a 0–25V DC module) are employed to measure the panel's electrical output. The collected data is transmitted to an ESP8266 NodeMCU V3 module, which leverages its built-in Wi-Fi to send the information to an online platform for remote visualization and analysis. Additionally, a locally connected LCD display via I2C provides users with real-time feedback on voltage and current values directly at the site.

The system demonstrates a cost-effective, compact, and efficient solution for solar tracking and monitoring, making it well-suited for educational projects, small-scale renewable energy applications, and prototype development. The integration of IoT technology with renewable energy systems highlights the potential for smarter, more responsive energy solutions in the future.

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