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IoT-Based Solar Power Monitoring and Optimization System for Industrial Applications

[1]Prof. Ashwini Anjikar, [2]Miss.Vaishnavi Thakre, [3]Mr. Aditya Khadaskar,
[4]Miss. Janvi Awari, [5]Miss. Megha Thakare
[1]Assistant Professor, [2,3,4,5]Students
Department of Electronics and Communication,
Priyadarshini College of Engineering, Nagpur, India

Abstract : This research proposes an IoT-based solar monitoring and optimization system for industrial applications, designed to enhance the efficiency and reliability of solar PV systems under dynamic environmental conditions. Utilizing an ATmega328 microcontroller, ESP32 Wi-Fi module, and super-capacitors, the system performs real-time monitoring of voltage, current, and light intensity, with data displayed locally and transmitted to the cloud via Thing Speak. Super-capacitors provide short-term energy storage to stabilize output during power drops, while a relay-based mechanism ensures seamless power switching. The system offers a cost-effective, scalable solution for improving solar energy self-consumption and reducing grid dependence.

Index Terms - IoT-based Solar PV Systems with Super-Capacitors enable Real-Time Monitoring, Light Intensity Tracking, and Relay-Controlled Load Management using Thing Speak API, MPPT (P&O) Algorithm, and Smart Energy Storage, Data Logging, Renewable Energy, Hybrid Energy Storage, Industrial Solar Monitoring.

I.INTRODUCTION

In the pursuit of sustainable development and energy efficiency, solar photovoltaic (PV) systems have emerged as a vital component of the renewable energy landscape. As industries shift to green technologies, smart monitoring systems are essential for improving solar power system performance and reliability. The system leverages IoT technologies for its operation creates a real-time solar monitoring and optimization framework, specifically designed for industrial environments. The concept of self-sustainability lies at the heart of this system, where power generation and monitoring are managed autonomously without reliance on fossil fuels or complex wiring. Leveraging ambient energy through solar panels, the system utilizes super-capacitors for short-term energy storage, enabling it to buffer sudden power drops and maintain stable output. This is especially important in fluctuating environmental conditions where irradiance levels vary due to shading or weather changes, affecting the overall efficiency of solar PV output. A key challenge with energy storage technologies, such as batteries, is the non-linear voltage behavior, which makes it difficult to directly estimate stored energy. The paper also addresses the issue of solar panel alignment and positioning, which significantly impacts energy harvesting. In tropical regions, fixed panel installations often fail to maintain optimal angles with respect to the sun's movement, leading to energy losses. A tracking system or energy buffer like a super-capacitor helps in maintaining consistent energy supply by compensating for the variations in sunlight exposure. The use of microcontrollers (ATmega328) and ESP32 Wi-Fi modules in the system architecture enables real-time data acquisition, decision making, and remote communication. Voltage and current sensors monitor safely, while relays automate energy flow between the solar panel, super-capacitor, and load. All operational data are logged to a cloud platform (Thing Speak), offering complete transparency, analysis, and control from remote locations.

1.OBJECTIVE

The main goal of this project is to enhance the efficiency and reliability of solar photovoltaic (PV) systems by integrating super-capacitors for short-term energy storage and implementing real-time monitoring using IoT-based technologies. By addressing issues such as temporal load resolution errors and fluctuations in solar output, the system aims to enhance energy self-consumption, reduce grid dependency, and ensure stable power delivery. The use of optimized super-capacitor sizing and intelligent switching further contributes to smoothing energy flow and minimizing energy loss in dynamic environmental conditions.

2. HARDWARE COMPONENTS

2.1 Solar Panel (12V, 20W)

Converts sunlight into electrical energy. It provides DC voltage, which is used to charge a super-capacitor and supply power to the load. When sunlight is adequate, it directly powers the system; during low light, backup power is used.

2.2 ATmega328 Microcontroller

Acts as the brain of the system. It reads voltage and current values from the solar panel and the super-capacitor using sensors. Based on real-time data, it controls relays to manage energy flow and ensures that the system operates within the specified voltage thresholds.

2.3 ESP32 Wi-Fi Module

Provides IoT functionality. It transmits the collected voltage, current, and light intensity data to the cloud (Thing Speak). This allows remote monitoring and logging of system performance in real-time.

2.4 Super-Capacitor

Serves as an energy buffer. It stores charge from the solar panel when surplus power is available and supplies power to the load during low solar output.

2.5 ULN2003 Driver IC

Drives the 12V relays using control signals from the 5V microcontroller. It contains Darlington pairs that amplify current, allowing the microcontroller to control high-power components.

2.6 7805 Voltage Regulator IC

Steps down 12V DC from the solar panel output is regulated to 5V to safely power the ATmega328 and other low-voltage components.

2.7 Current Transducer Sensor

The CT sensor measures current from the solar panel and super-capacitor to the load for accurate performance monitoring.

Since the microcontroller can only read voltages up to 5V, a voltage divider scales down the solar and capacitor voltages for safe Analog input readings.

2.8 LCD Display (16x2)

Displays real-time information including battery voltage, solar voltage, light intensity, and other relevant system parameters for quick visual monitoring.

3.SOFTWARE COMPONENTS

3.1 Arduino IDE

Used for writing, compiling, and uploading code to both the ATmega328 and ESP32 modules. It manages sensor data collection, relay control logic, and Wi-Fi communication.

3.2 Thing Speak Cloud Platform

An IoT analytics platform where real-time data (solar voltage, battery voltage, light intensity) is uploaded. This platform allows remote monitoring and data analysis via a web interface.

3.3 ESP32 Libraries (WiFi.h & HTTPClient.h)

*** WiFi.h:** Connects the ESP32 to a Wi-Fi network using provided SSID and password**.**

*** HTTPClient.h**: Used to send HTTP GET requests to Thing Speak, pushing sensor data at defined intervals.

3.4 Liquid Crystal Library

Controls the 16x2 LCD screen to display data such as voltage readings and sunlight levels directly from the microcontroller.

II. METHODOLOGY

The methodology for this project is based on designing and implementing a smart, self-sustaining energy monitoring and optimization system using solar energy as the primary source, coupled with IoT technologies for real-time monitoring. The system is aimed at addressing inconsistencies in solar power generation due to environmental factors like shading and changing sunlight intensity.

1. System Overview

The system integrates a solar panel, super-capacitor, ATmega328 microcontroller, ESP32 Wi-Fi module, and multiple relays to enable intelligent energy switching and data monitoring. It is designed to:

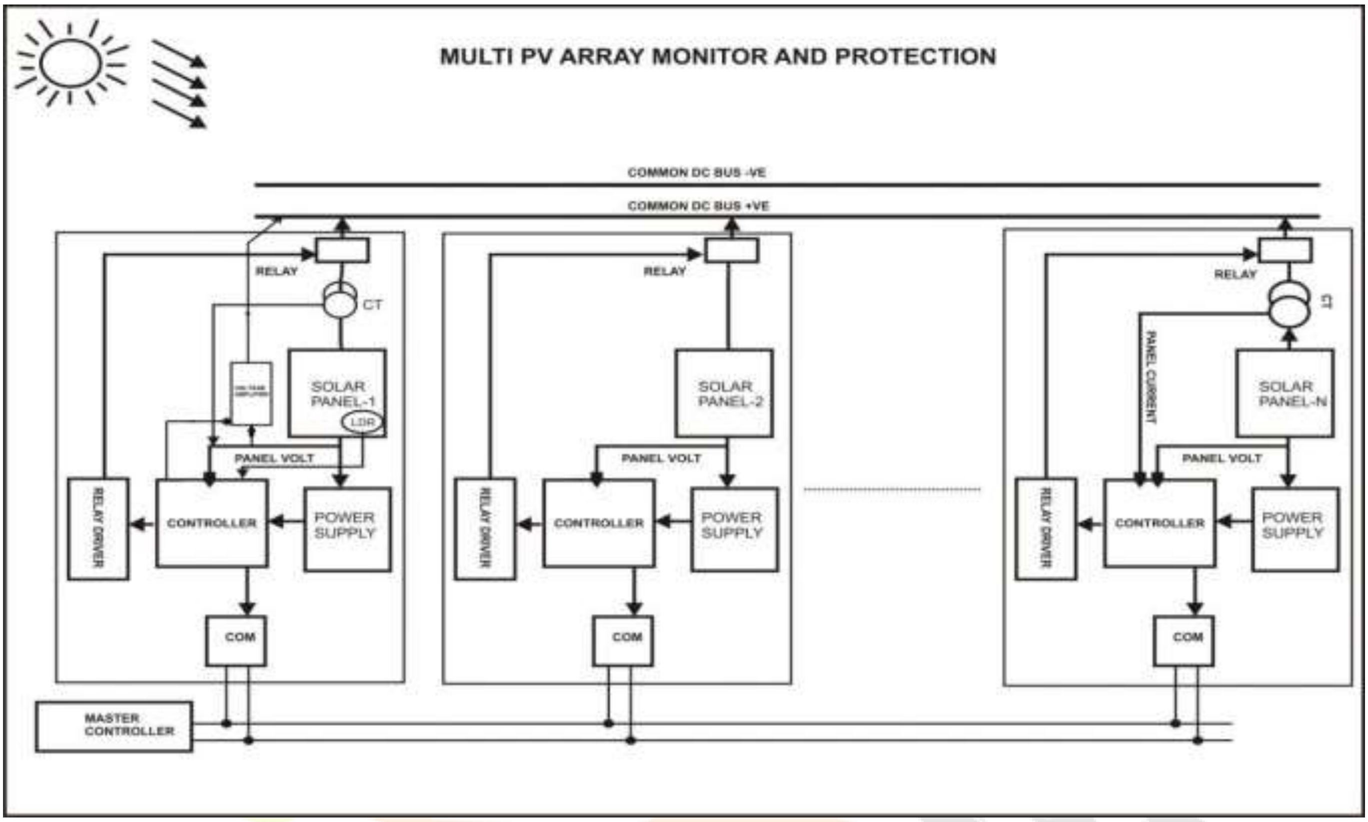
- Monitor solar panel voltage and current in real-time.
- Store excess energy in super-capacitors.
- Switch power supply to load from the super-capacitor when solar output is low.
- Log data on a cloud platform (Thing Speak) for remote analysis.

2. Working Principle

The solar panel generates electricity when exposed to sunlight. This energy is primarily used to power the load and charge the super-capacitor. The system is designed to detect the drop in solar panel voltage using analog sensors. When the voltage falls below a pre-defined reference, the system switches the power supply to the super-capacitor using relay control logic. The ATmega328 reads analog values from sensors via voltage dividers and current transducers. Based on the readings, it activates or deactivates relays using a ULN2003 driver IC (since the microcontroller outputs 5V while relays require 12V). The switching logic is programmed to:

- Supply load from the solar panel when solar output is sufficient.
- Charge the super-capacitor with surplus solar energy.
- Supply load from the super-capacitor when solar output drops.

Block diagram:



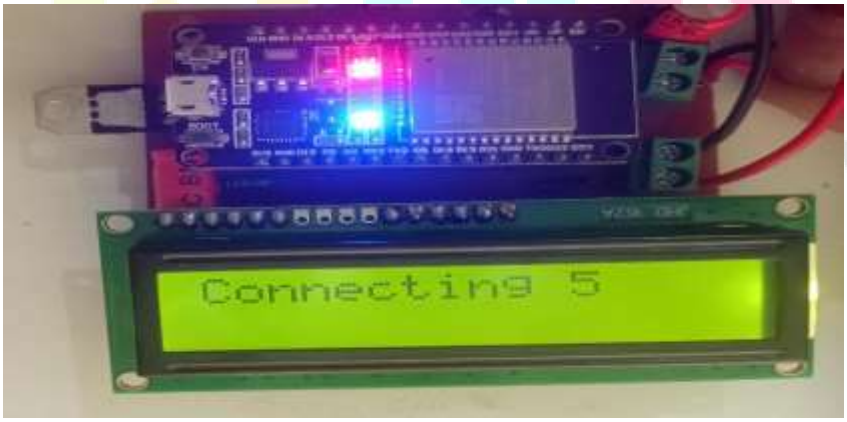
3. IoT Integration and Monitoring

The ESP32 module is used for wireless data transmission. It connects to a Wi-Fi network and sends the following parameters to the Thing Speak API:

- Solar Panel Voltage
- Super-Capacitor Voltage
- Light Intensity (via LDR sensor)

The software running on ESP32 uses the WiFi.h and HTTPClient.h libraries to connect to the internet and send HTTP GET requests. These requests carry sensor data and update it on the cloud at regular intervals (e.g., every 20 seconds). An LCD display module is also integrated for on-site monitoring. It shows live data like:

- Battery and solar voltages
- Light intensity in percentage
- System status counters (for operation cycles)



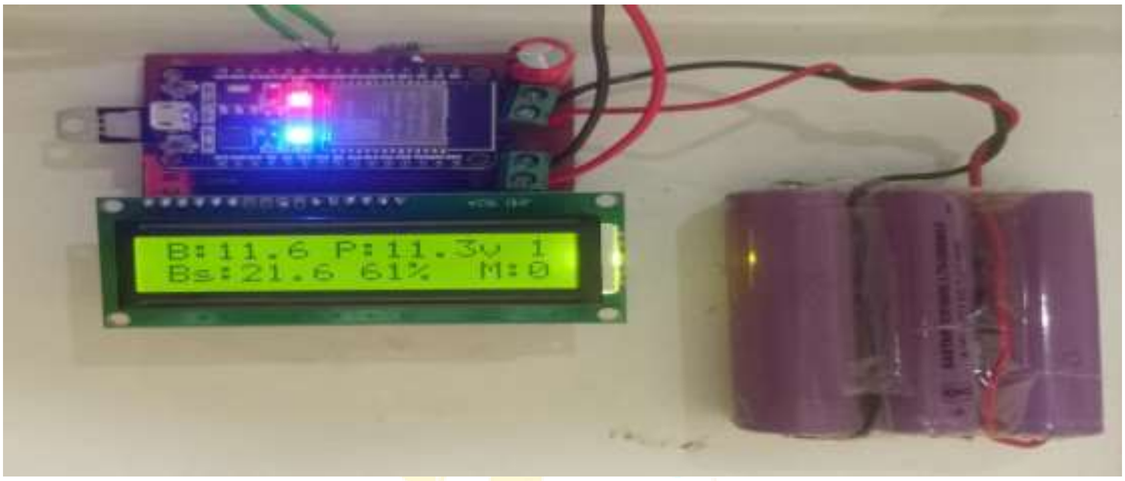
4. Power Management and Protection

The system uses a 7805 voltage regulator to convert 12V DC bus supply to 5V suitable for the microcontroller. Voltage divider circuits scale down input voltages to safe analog reading levels. A current transducer measures the output current of the panel and capacitor. Relay switching is protected using flyback diodes to suppress voltage spikes during coil de-energization.

5. Circuit Logic Summary

Relay 1 ON: Solar panel directly powers the load.
Relay 2 ON: Solar panel charges the super- capacitor.

Relay 3 ON: Super-capacitor powers the load when solar panel voltage drops below the threshold.
All relays OFF: If both solar and capacitor voltages are low, the system stops functioning until input conditions improve.



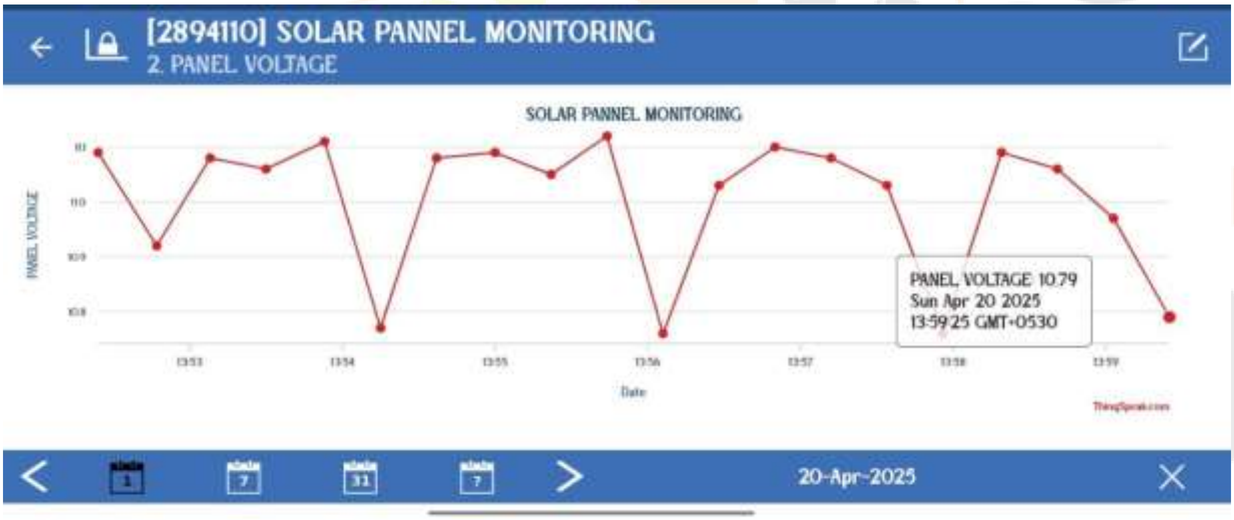
6. Simulation and PCB Implementation

The circuit was designed and tested in simulation before hardware fabrication. PCB layout was created using Express PCB software. Post-etching, components were mounted, and soldered in their designated positions based on the layout to ensure optimal circuit performance and ease of debugging.

7. Final Output and Monitoring

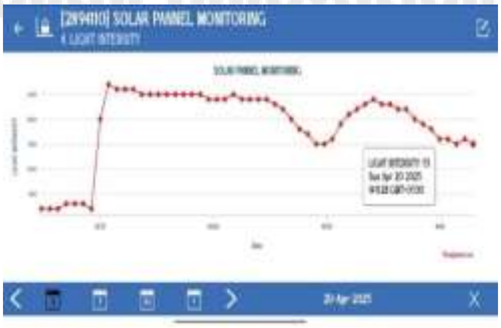
The setup enables:

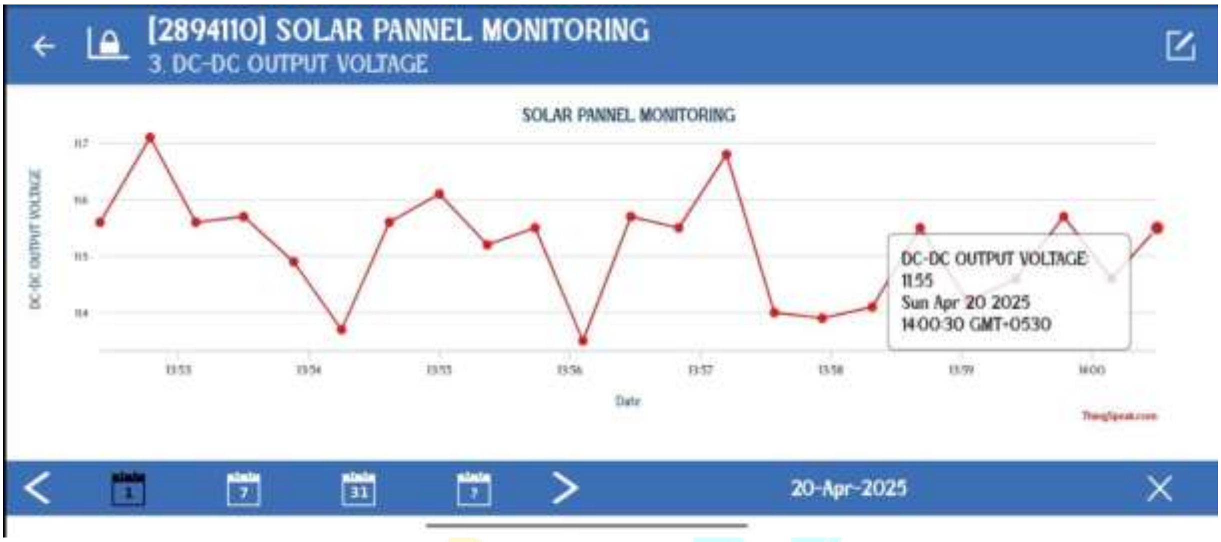
- Real-time monitoring on LCD
- Remote visualization via Thing Speak
- Intelligent relay switching for energy optimization.
- Enhanced reliability through super-capacitor buffering.


[2894110] SOLAR PANNEL MONITORING
2. PANEL VOLTAGE

PANEL VOLTAGE 10.79
Sun Apr 20 2025
13:59:25 GMT+0530


[2894110] SOLAR PANNEL MONITORING
1. BATTERY VOLTAGE


[2894110] SOLAR PANNEL MONITORING
4. LIGHT INTENSITY



III. APPLICATIONS

Applications of the IoT-Based Solar Power Monitoring and Optimization System

Based on the provided document, the IoT-based system optimizes solar energy use by enabling real-time monitoring and smart energy management under varying conditions. Below are the key applications along with their use cases:

1. Industrial Solar Power Monitoring

Real-time tracking of solar energy generation in factories or plants. It Ensures efficient energy management, minimizes grid dependency, and optimizes energy usage during peak loads by switching to super-capacitor backup.

2. Smart Industrial Automation Systems

Integration with automated industrial control systems to power sensors, microcontrollers, or embedded units.The system automatically regulates power sources depending on solar conditions, maintaining uninterrupted operation of automation equipment.

3. Residential Solar Systems with Grid Feedback

For homes equipped with solar panels, where power generated can be fed back to the grid or stored temporarily. By using super-capacitors and smart switching, the system improves power reliability and enables optimized grid interaction.

4. IoT-Based Energy Analytics Platforms

Monitoring and logging energy generation and load data to platforms like Thing Speak for remote access. Enables engineers, technicians, or facility managers to Analyz trends, detect faults, and optimize performance via dashboards and cloud data.

5. Smart Solar Tracking and Control

Systems that adjust panel orientation or manage electrical switching based on sunlight availability.

IV. FUTURE SCOPE

Future scope includes improving system intelligence, scalability, and efficiency using advanced technologies. One of the most promising directions includes the incorporation of automatic solar tracking mechanisms, It can dynamically adjust the solar panel's orientation to track the sun throughout the day. This will ensure maximum sunlight exposure and improve energy generation efficiency. Integrating hybrid storage (super-capacitors and batteries) can enhance short- and long-term backup, improving energy reliability in industrial settings.

V. CONCLUSION

The study focused on a photovoltaic (PV) system integrated with a monitoring setup to enhance the utilization of renewable energy through increased self-consumption and reduced energy fluctuations. Researchers examined how different temporal resolutions of electrical load data impact the energy flow within the PV system. The goal was to determine the optimal temporal resolution that minimizes calculation errors while accurately representing energy usage patterns. Findings from the paper demonstrate that even in a single-household PV system, the granularity of load data has a significant influence on energy flow analysis and self-consumption accuracy.

VI. REFERENCES

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