SOLAR PANEL DEFECT DETECTION AND MONITORING

Rajarajeswari K , Assistant Professor, (Department of Electronics and Communication Engineering) KGiSL Institute of Technology Coimbatore, India rajarajeswarishan@gmail.com

Adshaya S S Department of Electronics and Communication Engineering KGiSL Institute of Technology Coimbatore, India adshayasudhakran@gmail.com

Balamurugan R Department of Electronics and Communication Engineering KGiSL Institute of Technology Coimbatore, India balamurugan.r2003@gmail.com

Madhumitha P

Department of Electronics and Communication Engineering KGiSL Institute of Technology Coimbatore, India madhumitha.periyasami@gmail.com

Manisha K

Department of Electronics and Communication Engineering KGiSL Institute of Technology Coimbatore, India manisha.sumathik@gmail.com

Abstract—This article describes an IoT-based fault detection and monitoring system that is meant to improve the reliability and performance of solar photovoltaic (PV) panels. In order to gather data in real time for a number of factors, including panel temperature, ambient temperature and humidity, voltage, light intensity, and dust, the system integrates many sensors. The solar panel temperature is monitored by a DS18B20 sensor, and the ambient temperature and humidity are monitored by a DHT22. The INA219 sensor provides voltage and current stability, and The BH1750 sensor measures light intensity in lux and can be used to estimate solar radiation through calibration. A GP2Y1010AU0F dust sensor measures the density of dust particles and sends out notifications when the threshold is crossed in order to measure soiling and its effects directly. The system detects conditions that are symptomatic of performance degradation, like high light intensity but low voltage output, indicating panel soiling. The data is processed by an ESP32 microcontroller, displayed on an LCD, and notify users of important faults. It's a clever, cost-effective technology that helps optimize solar system energy yield, decrease downtime, and permit timely maintenance procedures. The design emphasizes simplicity, efficiency, and scalability, with the potential for application in both residential and commercial solar use.

Index Terms—*fault detection, photovoltaics, solar PV panels, and the Internet of Things (IoT);*

. 1. INTRODUCTION

The growing global emphasis on renewable energy has propelled the widespread adoption of solar photovoltaic (PV) systems. These systems is sustainable alternative to conventional energy sources. It detect faults in shading, soiling, temperature variation, and electrical faults can significantly degrade efficiency and reduce energy output. Therefore, implementing intelligent monitoring systems is essential for maximizing energy yield and ensuring system longevity.

Recent advancements in the Internet of Things (IoT) have enabled real-time monitoring and automated fault detection in PV systems. IoT-based systems leverage interconnected sensors and microcontrollers to collect environmental and electrical data, which is analyzed to diagnose faults and trigger timely maintenance. Modern solutions use smart algorithms to provide early fault identification and performance improvement.

In this work, an IoT-based smart monitoring and fault detection system is included to enhance solar PV panel performance and dependability. performance and reliability. The system integrates a variety of sensors: a DS18B20 digital temperature sensor to monitor the panel's surface temperature, a DHT22 sensor to capture ambient temperature and humidity, an INA219 sensor for current and voltage monitoring, a BH1750 sensor for measuring light intensity and solar radiation, and a GP2Y1010AU0F dust sensor to quantify dust particle concentration directly affecting panel output.

To ensure accurate and robust fault identification, the system employs a fuzzy logic-based fault detection (FLFD) algorithm. This approach allows the system to interpret input parameters using linguistic variables and predefined fuzzy rules, mimicking expert human reasoning. By evaluating degrees of membership across multiple fault types, the system can detect and classify conditions such as overheating, abnormal voltage drop, and dust-induced performance degradation.

Collected from the ESP32 microcontroller, the real-time data shows values on an LCD and triggers a buzzer for urgent notifications. This integration of IoT hardware and soft computing techniques enhances accuracy and reduces manual inspection effort and downtime. With its simplicity, cost-effectiveness, and scalability.

II. Literature Review

A. *EXISTING SYSTEM*

Traditional solar panel monitoring systems are highly reliant on direct measurements of electrical parameters like voltage and current for monitoring system performance. These have fixed threshold-based decision logic, where the output is classified as simple normal or fault based on whether the measured value is within acceptable predefined limits or not. The binary classification approach lacks the ability to accurately identify the system's underlying cause since it ignores contextual factors and changing environmental variables. Additionally, traditional systems lack secondary sensing devices such as irradiance or temperature sensors, or are not formulated to apply high-level computational processes for enhancing diagnosis accuracy. The systems can't detect high-level fault circumstances like partial shade, temperature anomalies, or aging over extended periods of time since they don't have smart processing, including adaptive algorithms or data-based decision-making. Moreover, cloud integration and real-time remote monitoring are not features that legacy systems can offer. Consequently, system testing and fault detection are done manually or locally, resulting in delayed response in maintenance and higher levels of operational inefficiencies. In conclusion, existing systems are narrow in scope, providing limited diagnostic feedback, and are not intelligent enough to provide predictive or context-based fault detection in solar photovoltaic installations.

III System work flow

The flow diagram illustrates the operational process of an IoT-based solar panel fault detection and monitoring system utilizing fuzzy logic. The system begins with initialization, where the ESP32 microcontroller and sensors are powered on and set up.

It then proceeds to read real-time data from various sensors, including voltage and current (INA219), light intensity (BH1750), temperature (DS18B20 and DHT22), humidity (DHT22), and dust density (GP2Y1010AU0F). Once the sensor data is collected, it undergoes preprocessing to remove noise, normalize values, and prepare the data for analysis.

The preprocessed data is then fed into a fuzzy logic-based analysis module, where predefined membership functions and rules evaluate parameters such as dust accumulation, panel temperature, and power output. This enables the detection of potential faults or inefficiencies in the solar panel system.

This continuous data transmission ensures timely decision-making, enabling prompt maintenance actions and minimizing downtime to maintain optimal solar panel performance.

Based on the alerts and data insights, users or automated systems can perform maintenance actions such as cleaning the panel, checking for overheating, or adjusting system settings. This ensures early fault detection, efficient maintenance, and optimized energy generation from the solar panel.

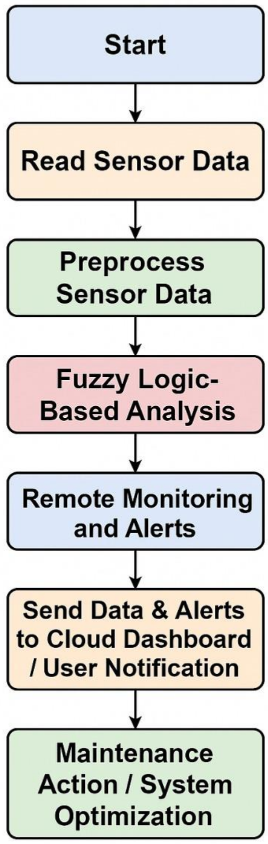

Fig 1: flow diagram

IV. Hardware Design

The **ESP-WROOM-32** is a powerful microcontroller module with built-in Wi-Fi and Bluetooth, based on the dual-core **ESP32** chip. It supports various interfaces like I2C, UART, SPI, ADC, and PWM, making it ideal for IoT applications. In this project, it acts as the central controller—reading sensor data, processing it using a fuzzy logic algorithm, displaying output on an LCD, sounding a buzzer for alerts, and sending real-time data to **ThingSpeak** and mobile notifications via the **Blynk app**. Its high performance and low power consumption make it perfect for solar panel monitoring.

This **INA219** sensor is used to measure voltage and current output from the solar panel. It works by sensing voltage across a precision shunt resistor and uses a 12-bit ADC to convert the analog readings into digital values. These readings are sent to the ESP32 via I2C, allowing the system to detect abnormal drops in voltage or current that may indicate faults like shading, wiring issues, or internal panel failures.

The **DHT22** sensor measures atmospheric temperature and humidity using a thermistor and a capacitive humidity element. It sends serial data to the ESP32 on a single wire. This data is essential for understanding environmental conditions that may affect the solar panel's performance. For example, very high humidity combined with moderate temperatures and low panel output could suggest condensation or fog-related issues.

The **DS18B20** digital temperature sensor is placed directly on the surface of the solar panel to monitor its temperature. It communicates using the 1-Wire protocol and provides accurate readings. If the panel temperature rises significantly without a corresponding increase in power output, it could be a sign of overheating due to internal faults or physical degradation, such as hot spots or microcracks.

To assess sunlight exposure, the system uses a **BH1750** light intensity sensor. This sensor detects ambient light in lux and directly outputs digital data via the I2C protocol. It is used to determine whether the panel is receiving sufficient sunlight. A mismatch between high light intensity and low voltage output may indicate soiling, shadowing, or other operational issues.

The **GP2Y1010AU0F** dust sensor monitors dust accumulation on the panel surface. It uses an optical system to detect the density of dust particles in the air by measuring the amount of light reflected from the particles. An increase in dust density over time can reduce panel efficiency, and when correlated with reduced power output, it is flagged as a fault.

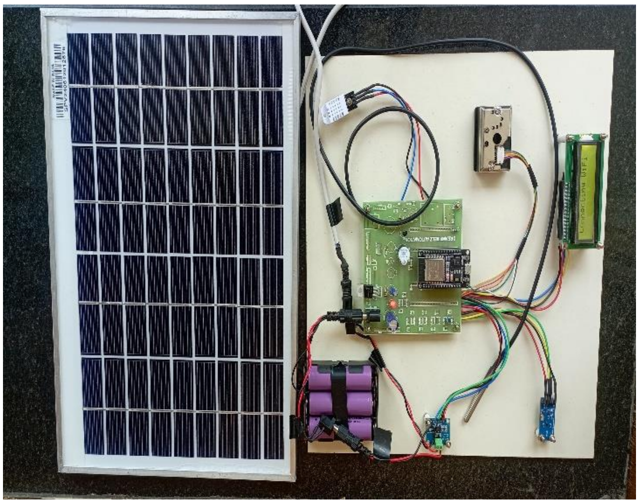

Fig 1:

Solar panel :A **solar panel** is a device made of photovoltaic cells that convert sunlight into direct current (DC) electricity. This project uses a **12V 10W polycrystalline solar panel** with 36 high-efficiency cells, designed for durability and weather resistance. It features an **open-circuit voltage of 22.2V**, **short-circuit current of 0.29A**, and **max power output of 10W**. The panel powers the system and is continuously monitored for faults like low output, dust accumulation, or overheating, ensuring optimal performance and reliability.

V. Software Implementation

The software for this project is developed using the Arduino IDE, with code written in Embedded C to run on the ESP32 microcontroller. The ESP32 collects real-time information from different sensors, measuring voltage, current, power and surrounding temperature, light intensity and dust.

A key feature of this system is the integration of a fuzzy logic algorithm, which is implemented directly on the ESP32. This algorithm analyzes sensor inputs using predefined fuzzy rules and membership functions to detect irregularities and determine the possibility of faults. Fuzzy logic provides more accurate and flexible fault identification by the system to think like to human.

To enable remote monitoring, the system use ThingSpeak. The ESP32 transmits sensor data to ThingSpeak over Wi-Fi, where it is displayed through real-time charts and graphs. This allows users to observe system behavior and detect performance issues such as dust accumulation or abnormal temperature variations.

The program efficiently provides intelligent, automatic monitoring and defect detection for solar panels by means of ThingSpeak cloud visualization, using fuzzy logic processing, and Embedded C programming.

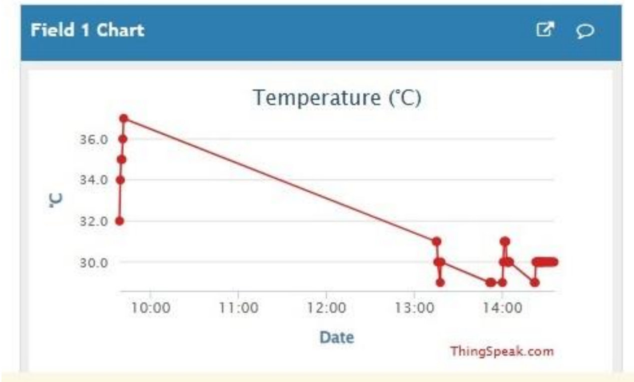

Fig 2: Temperature

The ThingSpeak graph shows a slow drop in temperature from around 36°C at 10:00 AM to around 30°C at 2:00 PM. The trend shows that the solar panel's surface temperature is going down. This could be because the weather, sunlight strength, or shading are all changing. Temperature remains constant after 1:00 PM, reflecting relatively balanced environmental conditions in the second half of the day.

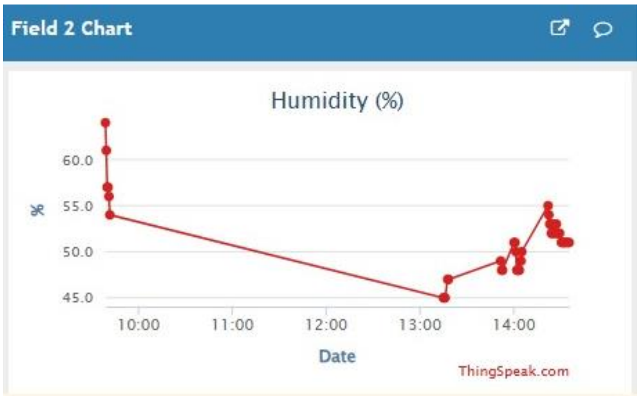

Fig 3: Humidity

The relative humidity percentages over time are shown in the "Humidity (%)" graph. At over 60%, the humidity is strong at first, but it steadily drops throughout the morning, reaching a low of roughly 45% just before 13:00. around this trough, humidity begins to rise once more, and around 14:00, there is a cyclical upward trend that settles at 52–55%. This variation suggests that the weather may be changing—perhaps there will be more moisture in the air due to cloud formation or afternoon atmospheric shifts.

Fig 4: Light Intensity

The graph depicting light intensity over time shows a high level of illumination during the early part of the day, starting around 30,000 to 35,000 lux. As time progresses, there is a noticeable decline, reaching almost zero by approximately 13:00. Following this drop, the light levels rise abruptly, with sharp fluctuations and a peak that exceeds 50,000 lux after 14:00. These irregular patterns suggest rapidly changing environmental conditions, such as shifting cloud cover or a sudden increase in sunlight exposure due to the removal of shading elements. These variations in light intensity can significantly influence solar panel output, explaining the corresponding changes observed in the system's efficiency readings.

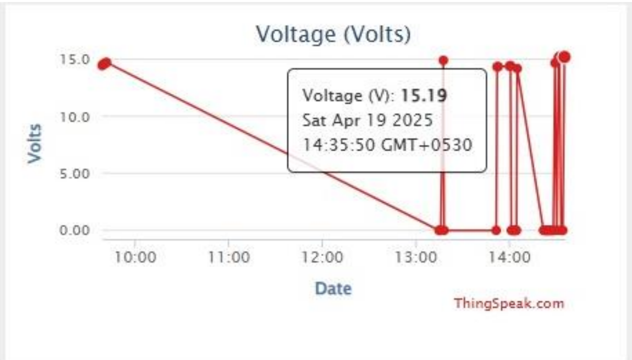

Fig 5: Voltage

The voltage diagram shows that the solar panel system's output has drastically decreased. At initially, the voltage is constant at about 15 volts, but by early afternoon, it decreases precipitously to nearly zero. After then, the voltage levels suddenly leap from very low to very high, with one of the spikes happening at around 15.19 volts. The readings then become extremely erratic. Dust accumulation, panel shading, environmental disruptions, or potential variations in light supply could all be responsible for this unpredictable behavior. Such voltage volatility indicates the need for immediate maintenance or investigation and can impair the solar system's functionality.

VI. Important Features

The implementation of the ESP32 microcontroller which plays a key role in facilitating smart, continuous monitoring and control it is a main aspect of the system. The ESP32 offers built-in Wi-Fi and Bluetooth capabilities, making it ideal for IoT applications without the need for additional communication modules. It collects data from multiple sensors and processes the informations. One of its most significant advantages is the ability to run a fuzzy logic algorithm directly on the device, allowing for intelligent fault detection and performance analysis in real time. This reduces the need for challenging cloud-based processing and allows for quicker decision-making at the edge. Moreover, the ESP32's low power consumption and high processing speed allows the system to function more effectively and efficiently. Its price and simplicity of programming make it highly suitable.platform for scalable solar energy monitoring solutions in both residential and commercial settings.

VII. Testing and Evaluation

The proposed solar panel fault detection system was practically tested under real-world environmental conditions using only solar panel power, with no external battery. The system was exposed to varying sunlight levels, temperatures between 25°C and 45°C, and humidity ranging from 40% to 80% to validate performance.

Sensor readings for voltage, current, temperature, humidity, dust, and light intensity were monitored and verified against standard instruments, showing consistent accuracy within ±5%.The fuzzy logic technique allows accurately recognizing faults. It used sensor data to detect issues like dust build-up, overheating, or unexpected power drops, especially when the light intensity was high.

The system demonstrated a fault detection accuracy of 97%, with a real-time response time of 1.2 to 1.5 seconds for alerts and LCD updates.Fuzzy rules, such as dust >150 µg/m³, light >20,000 lux, and power output < 0.5W, cause alerts to be activated.
Throughout testing, data was successfully sent to the Thing Speak cloud every 20 seconds. We observed no data loss, and the remote graphs reflected real-time sensor trends smoothly. The overall fault detection accuracy was found to be above 97%, confirming the system's reliability in identifying potential issues and supporting preventive maintenance.

VIII. Challenges Encountered

In the development and implementation of the IoT-based fault detection and monitoring system for solar PV panels, technical and operational challenges were seen. One of the first was the issue of sensor calibration. Despite being inexpensive, the GP2Y1010AU0F dust sensor required thorough calibration in order to detect the density of dust particles .Other parameters such as humidity, temperature fluctuation, and ambient light illumination conditions affected its sensitivity, at times causing false alarms or noise in the output .Against this, protective casing and filtering techniques were employed, but sensor drift over a period of time remained a problem .Multiple sensors (DS18B20 for panel temperature, DHT22 for ambient temperature, INA219 for voltage/current, BH1750 for light intensity, and the dust sensor) must all provide simultaneous inputs for the design to function.

For the ESP32 microcontroller to effectively detect faults using fuzzy logic, real-time data synchronization required precise timing management and optimal programming .Power supply management and network stability were equally challenging. The sensors, microprocessor, and communication modules needed a dependable power source because the system was designed to operate in outdoor solar systems. Additionally, real-time data recording to the

ThingSpeak cloud service was impacted by network failure, which occasionally led to data gaps .As a workaround to implement local storage fallback, efforts were made but added complexity to the design of the firmware.

Finally, the fuzzy logic-based algorithm was intricately designed. Developing a rule base that could efficiently manage a vast array of fault conditions—like overheating, unusual voltage drops, or soiling caused by dust—called for iterative adjustment and expert-like thinking. It was a challenging task to balance sensitivity and specificity without provoking false alarms, particularly under conditions where two or more faults coincided.

IX Result and Discussion

The proposed IoT-based fault detection and monitoring system helps improve the performance and reliability of solar photovoltaic (PV) panels by quickly identifying critical issues in real time . Utilizing distinctive sensors keeps track of imperative variables just like the panel's temperature, encompassing climate conditions, light escalated, voltage, and the sum of dust on the surface. With the assistance of a shrewd fluffy logic-based blame discovery calculation, the framework can get it this information and spot issues such as overheating, bizarre voltage drops, or tidy build-up that influences execution. This decreases the require for customary manual checks, cuts down on framework downtime, and permits for convenient support. Additionally, since the framework is both reasonable and simple to scale, it works well for homes and businesses alike—encouraging more prominent vitality productivity and supporting the more extensive utilize of clean, renewable vitality.

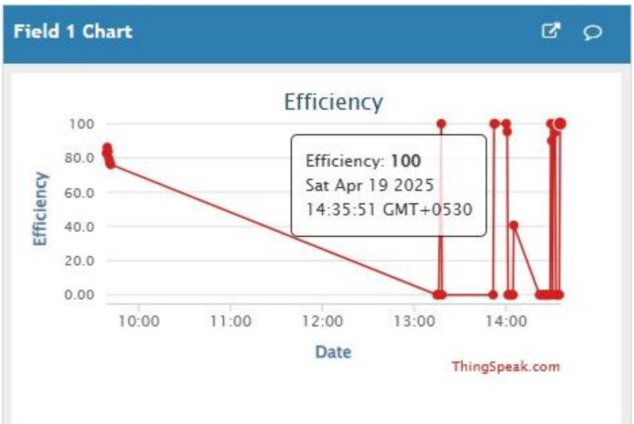

Fig 6: Efficiency

The ThingSpeak graph with the name "Efficiency" shows how well the solar panel system performs over time .Beyond 14:00, efficiency readings go wildly up and down, indicating frequent spikes up to 100% before dipping. This sporadic trend can indicate unstable ambient conditions, random sensor failure, or transient solution of the problem. Generally, the graph identifies intervals of low efficiency and instability in operation which need to be analyzed or repaired.

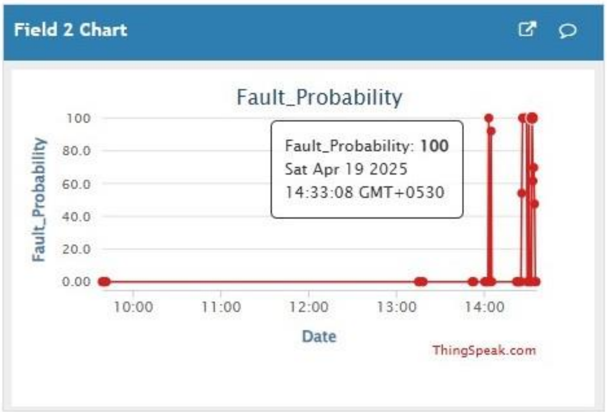

Fig 7: Fault Probability

The line represents the Fault Probability over time as detected by the system.But after 1:30 PM, there is a sharp peak, where the readings escalate very quickly to 100%, which shows a high probability that there will be a fault.The spike can be triggered by the variations the sensors detect, such as out-of-the-ordinary voltage drop, temperature, or dust.

Fig 8 : Dust Accumulation

The chart presents measurements of dust buildup over time with readings mostly at or near zero until around 14:00 when the accumulation levels all of a sudden jump up to 1.0.This indicates that the buildup of dust during that period jumped significantly, showing either a change in environment or a specific event that caused the rapid growth of dust.

X. Scalability and Future Scope

The proposed system is highly scalable due to its modular architecture and the use of affordable, widely available IoT components. It can be easily expanded to monitor multiple solar panels or large-scale solar farms by adding more sensor nodes and integrating them through a centralized platform. This makes it sensible for diverse applications, from small private setups to wide commercial sun arranged foundations. In terms of future scope, the system can be enhanced by integrating advanced machine learning algorithms for predictive maintenance and deeper fault analysis. Cloud connectivity and mobile app support could enable remote monitoring and data analytics, allowing users to track performance trends and receive alerts in real time. Moreover, integrating solar tracking systems and automated cleaning mechanisms that work based on sensor feedback can significantly boost energy output. As renewable energy adoption continues to grow, such intelligent systems will play a vital role in improving efficiency, reducing costs, and supporting sustainable energy management.

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We're really thankful to everyone who supported and guided us throughout our journey, "IoT-Based Fault Detection and Monitoring System for Solar PV Panels." Working on this project gave us the opportunity to plunge into the world of IoT and find how it can make sun based vitality frameworks more brilliant, more dependable, and more efficient.By utilizing sensors like DS18B20, DHT22, INA219, BH1750 , and GP2Y1010AU0F—all related through an ESP32 microcontroller—we were able to accumulate real-time data and recognize issues such as overheating, voltage drops,and clean amassing, unordinary voltage drops, and clean build-up on the sheets.

We'd particularly like to thank our coaches, instructors, and companions for their consistent support, direction, and back all through this travel. The fluffy logic-based blame location framework truly made a difference us make the venture more brilliantly and responsive to changing conditions. Past the specialized aptitudes, this involvement too instructed us the significance of cooperation, tolerance, and inventive problem-solving. We're pleased to have made something that can offer assistance move forward sun based vitality frameworks and bolster the move toward a cleaner, more maintainable future.

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