

# Edge-Enabled IoT Solar Grid with Autonomous Fault Detection and Adaptive Isolation

<sup>1</sup>Mr. T Chakrapani, <sup>2</sup>Maile Chandrakala, <sup>3</sup>Shaik Shahin, <sup>4</sup>Madugundu Gnaneswari, <sup>5</sup> Telugu Usha Rani, <sup>6</sup>Sandula Ribka

<sup>1</sup>AssociateProfessor, <sup>2,3,4,5,6</sup>Students

*Department of Electronics and Communication Engineering, St. Johns College of Engineering & Technology, Yerrakota, Yemmiganur, Kurnool, A.P.*

**Abstract:** This project presents an Edge-Enabled IoT Solar Grid system designed for autonomous fault detection and adaptive isolation. The system addresses the critical need for reliable and efficient solar energy management by integrating Internet of Things (IoT) technology with edge computing. It utilizes an ESP32 controller to continuously monitor key electrical parameters such as voltage, current, and temperature of solar panels and grid components via sensors. Unlike traditional cloud-dependent systems, this solution processes sensor data locally at the edge, enabling real-time fault detection. When an anomaly such as overvoltage, overcurrent, or overheating is detected, the system autonomously activates a relay to isolate the faulty section while maintaining power supply to the healthy parts of the grid. This adaptive isolation mechanism prevents system-wide failures and reduces downtime. All operational data is also transmitted to the ThingSpeak cloud platform for remote monitoring, data visualization, and long-term analysis. This technology provides an affordable, portable, and highly reliable solution for modern smart grids and decentralized solar energy infrastructures.

**Keywords:** ESP32 controller, Edge Computing, Solar Grid Monitoring, Fault Detection, Adaptive Isolation, IoT, Relay.

## I. INTRODUCTION

The global shift towards renewable energy has positioned solar power as a cornerstone of sustainable development. As solar photovoltaic (PV) installations grow from small rooftop systems to large-scale solar farms, the complexity of managing and maintaining these grids increases exponentially. Continuous monitoring of critical parameters like voltage, current, and temperature is essential to ensure optimal energy yield, component longevity, and system safety [1]. Any fault, whether from panel degradation, electrical short circuits, or overheating, can lead to significant power loss, equipment

damage, and even fire hazards if not addressed promptly.

Conventional health monitoring techniques for electrical grids often rely on centralized supervisory control and data acquisition (SCADA) systems or manual inspections [2]. While effective to a degree, these methods are inherently reactive and suffer from several limitations. The necessity for data to travel to a central server for analysis introduces latency, delaying fault detection and response. This delay can allow minor issues to escalate into major failures. Furthermore, the growing volume of data from numerous sensors creates network congestion and increases operational costs.

To overcome these challenges, the Internet of Things (IoT) has emerged as a transformative technology, enabling seamless connectivity between physical devices and the digital world [3]. However, transmitting all sensor data to the cloud for processing is not always optimal. This is where Edge Computing plays a crucial role. By bringing computation and data storage closer to the source (the solar panels), edge computing minimizes latency, reduces bandwidth usage, and enables real-time decision-making. This project introduces an ESP32-based Edge-Enabled IoT Solar Grid system that leverages these technologies to provide a smarter, more resilient, and efficient solution for solar grid management.

## II. OBJECTIVES

The primary goal of this project is to design and implement a smart solar grid monitoring and protection system that leverages IoT and edge computing for enhanced reliability. The specific objectives are as follows:

To develop a real-time monitoring system: The system will use sensors to continuously track critical

health metrics of the solar grid, including voltage, current, and temperature.

To implement edge-based data processing: The ESP32 controller will process sensor data locally to enable immediate analysis and decision-making without relying on cloud latency.

To design an autonomous fault detection mechanism: The system will identify abnormal operating conditions (e.g., overvoltage, overcurrent, overheating) in real-time by comparing sensor data against predefined safe thresholds.

To create an adaptive isolation system: Upon fault detection, the system will automatically trigger a relay to isolate the faulty section of the grid, preventing damage to other components and ensuring continuous power supply to healthy sections [5].

To enable remote monitoring and data analysis: The system will transmit processed data to the ThingSpeak cloud platform, allowing for remote visualization, data logging, and historical trend analysis.

### III. BLOCK DIAGRAM

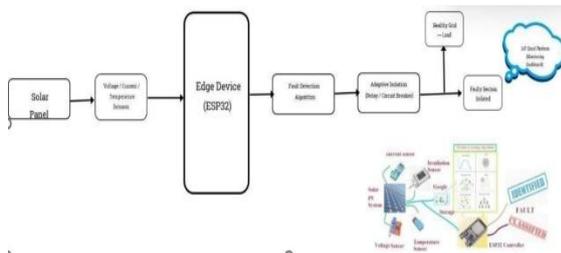


Fig.1. Block diagram of the proposed Edge-Enabled IoT Solar Grid system

### IV. WORKING PROCESS

The Edge-Enabled IoT Solar Grid system operates as a continuous loop of monitoring, processing, acting, and reporting. The process begins when the ESP32 controller is powered on and establishes a connection to the Wi-Fi network.

**Data Acquisition:** The system continuously reads data from multiple sensors. A Voltage Sensor measures the output voltage of the solar panel(s). A Current Sensor measures the electrical current flowing through the grid. A Temperature Sensor (DHT11/LM35) monitors the temperature of the solar panel and other critical components to detect overheating.

**Local Edge Processing:** The ESP32 controller acts as the edge device. It processes the raw sensor data locally. The controller runs a fault detection algorithm that compares the incoming voltage, current, and temperature readings against pre-set, safe operational limits [6].

**Display and Alert:** The real-time readings (Voltage, Current, Temperature, System Status) are displayed on an LCD I2C screen for local monitoring. This allows a technician or user on-site to see the system's health at a glance.

**Autonomous Fault Isolation:** This is the core innovative function. If any parameter—such as current exceeding the safe limit (overcurrent) or temperature rising above the threshold (overheating)—the fault detection algorithm identifies a problem. The ESP32 immediately sends a control signal to a Relay Module. This relay acts as a circuit breaker, disconnecting the faulty section (e.g., the affected solar panel string) from the main power bus. Simultaneously, a buzzer and an LED provide a local audio-visual alarm [7]. The rest of the grid continues to operate normally, thus adapting to the fault.

**Cloud-Based Remote Monitoring:** For data logging and remote supervision, the ESP32 uses its built-in Wi-Fi module to send the processed health data (status of voltage, current, temperature, and any fault events) to the ThingSpeak cloud platform. ThingSpeak archives the data and presents it in graphical dashboards. This allows engineers or grid operators to monitor the system's performance from anywhere in the world, review historical data, and analyze long-term trends [8].

### V. EXISTING SYSTEM

Traditional solar grid monitoring systems predominantly rely on centralized architectures. In such systems, sensors on solar panels transmit all raw data to a central server or cloud platform for processing and analysis. This approach often utilizes SCADA (Supervisory Control and Data Acquisition) systems or simple data loggers. Operators must monitor these central systems and, upon receiving an alert, manually dispatch technicians to inspect and rectify the fault. While this provides a level of remote visibility, it is fundamentally reactive and inefficient [9].

## VI.. DRAWBACKS

**High Latency:** The necessity to transmit data to a remote server for analysis creates a significant delay. This latency can be critical, as a fault can cause irreversible damage in the seconds it takes for the cloud to respond.

**Lack of Real-Time Response:** Existing systems lack the intelligence to act autonomously. They can only alert, not isolate. This means that until a human operator intervenes, the faulty component remains connected, potentially causing cascading failures [10].

**Network Dependency:** The entire monitoring and fault response process is entirely dependent on a stable internet connection. If the network fails, the system loses its ability to monitor and alert, rendering it blind and vulnerable.

**Data Congestion and Cost:** Transmitting the vast amounts of raw, continuous data from every sensor in a large solar farm to the cloud consumes significant bandwidth and can lead to high data storage and transmission costs.

**Delayed Maintenance:** Without immediate isolation, a minor fault can worsen, leading to more extensive damage, higher repair costs, and prolonged system downtime.

## VII.. PROPOSED SYSTEM

To overcome the limitations of traditional systems, this project proposes an Edge-Enabled IoT Solar Grid with Autonomous Fault Detection and Adaptive Isolation. This system shifts the intelligence from the cloud to the edge. It uses an ESP32 microcontroller to collect data from voltage, current, and temperature sensors. The ESP32 processes this data locally to detect faults in real-time. Upon detection, it autonomously controls a relay to isolate the faulty section [11]. Simultaneously, it uses Wi-Fi to send a summary of the system's status and alerts to the ThingSpeak cloud for remote monitoring and analysis.

## VIII. PROPOSED SYSTEM ADVANTAGES

**Real-Time Fault Detection and Response:** By processing data at the edge, the system detects and

isolates faults in milliseconds, preventing damage and power loss.

**Autonomous Operation:** The system can protect itself and maintain operation even when the internet connection is down, ensuring grid resilience.

**Reduced Network Traffic:** Only essential, processed data (e.g., alerts, average values) is sent to the cloud, drastically reducing bandwidth usage and data storage costs [12].

**Improved Grid Reliability and Uptime:** By isolating only the faulty section, the rest of the grid continues to supply power, minimizing downtime.

**Low-Cost and Scalable:** The system uses affordable components like the ESP32, basic sensors, and a relay, making it a cost-effective solution that can be scaled from a single home to a large solar farm.

**Enhanced Safety:** The immediate isolation of overheating or short-circuiting components significantly reduces the risk of fires and equipment damage.

**Intelligent Remote Monitoring:** The cloud platform provides a powerful interface for long-term performance analysis and remote supervision without the burden of processing every data point.

## IX. PROBLEM STATEMENT

Modern solar energy grids are expanding rapidly, but they are often managed by monitoring systems that are too slow to prevent faults from causing significant damage and disruptions. The reliance on centralized, cloud-only processing creates latency in fault detection. More critically, the lack of autonomous control means that systems cannot react to protect themselves during network outages or before a human operator can intervene. This results in increased downtime, higher maintenance costs, reduced energy efficiency, and safety risks. There is an urgent need for an intelligent, self-protecting solar grid monitoring system that can act instantly at the source of the problem.

## X. LITERATURE REVIEW

Al-Fuqaha et al. (2015) [13]: Provided a comprehensive survey on IoT, detailing its enabling

technologies, protocols, and applications. This foundational work highlights the potential of IoT in various sectors, including energy, and forms the basis for understanding the communication architecture of our system.

Shi et al. (2016) [14]: Introduced the vision and challenges of edge computing, emphasizing its role in reducing latency and bandwidth usage. Their work directly validates our approach of using edge processing for time-critical applications like fault detection.

Gharavi and Ghafurian (2011) [15]: Discussed the evolution and requirements of the Smart Grid, outlining the need for intelligent and automated control mechanisms for future power systems, which our project directly addresses.

Reddy et al. (2019) [16]: Demonstrated a real-time solar PV monitoring system using IoT, showcasing the effectiveness of using sensors and cloud platforms for data collection. Our project extends this concept by adding edge-based autonomous control.

Patel and Desai [Reference from your provided solar doc]: Explored gas leakage detection using IoT, demonstrating the practical application of sensors and microcontrollers for safety-critical monitoring, a principle analogous to our electrical fault detection.

S. Madakam et al. (2015) [17]: Provided a comprehensive literature review on the Internet of Things (IoT), reinforcing the paradigm of connecting physical objects to the internet, which is a cornerstone of this project.

## XI. HARDWARE DESCRIPTION

### ESP32 Microcontroller:

The ESP32 is the central processing unit of the system. It is a low-cost, low-power system on a chip (SoC) with integrated Wi-Fi and dual-mode Bluetooth. In this project, it performs all critical functions: reading data from sensors, executing the fault detection algorithm locally (edge processing), controlling the relay for isolation, displaying data on the LCD, and transmitting data to the ThingSpeak cloud via Wi-Fi [18]. Its dual-core architecture allows it to handle real-time control tasks and communication simultaneously without latency.



Fig.2. ESP32 Microcontroller  
Current Sensor (ACS712/INA219):

The current sensor, such as the ACS712 hall-effect sensor or INA219 precision sensor, measures the electrical current flowing from the solar panel to the load or battery. It provides an output (analog or I2C) proportional to the current. This is used to detect overcurrent conditions, short circuits, and to monitor overall system power output.



Fig.3. ACS712 Current Sensor

### Voltage Sensor Module (0-25V)

The Voltage Sensor Module is a simple resistive voltage divider circuit. It scales down the solar panel's output voltage to a level (0-5V) that the ESP32's analog-to-digital converter (ADC) can safely read. The module reduces the input voltage by a factor of 5, allowing measurement of DC voltages up to 25V. This is crucial for detecting overvoltage (excessive voltage) and undervoltage (insufficient voltage) condition

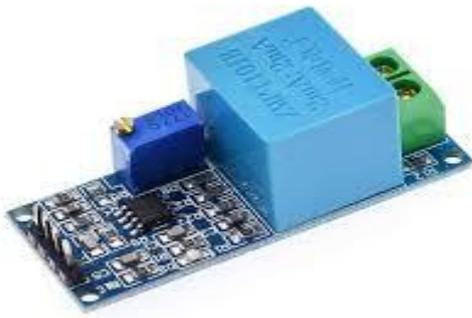


Fig.4. ACS712 Current Sensor



Fig.6. ACS712 Current Sensor

### Solar Panel

The Solar Panel is the primary power source for the system. It consists of photovoltaic (PV) cells that convert sunlight into electrical energy (DC). The output voltage and current vary depending on sunlight intensity and load conditions. The panel used in this system is a 12V/10W polycrystalline solar panel, which provides sufficient power for the monitoring system and small loads. The solar panel's output is continuously monitored by voltage and current sensors to detect faults such as underperformance, shading, or complete failure.



Fig.5. Solar panel

### 5V Relay Module:

This is the actuator for the adaptive isolation mechanism. It is an electrically operated switch. The ESP32 sends a low-power control signal to the relay module, which activates an internal electromagnet to open or close a high-power circuit. In this system, it disconnects the faulty solar panel section from the rest of the grid.

## XII. RESULTS AND DISCUSSION

The developed Edge-Enabled IoT Solar Grid system was successfully implemented and tested. The system demonstrated its ability to monitor and protect a solar panel setup effectively.

**Real-Time Monitoring:** The ESP32 successfully read data from the voltage, current, and temperature sensors. These values were accurately displayed on the LCD I2C screen, updating in real-time, allowing for effective local monitoring.

**Edge-Based Fault Detection:** The system was subjected to simulated fault conditions. Overcurrent was simulated by temporarily increasing the load, and overheating was simulated by applying localized heat to the LM35 sensor. The ESP32's algorithm detected these anomalies almost instantly (within milliseconds) by comparing readings to predefined thresholds.



**Autonomous Adaptive Isolation:** Upon detection of a fault (e.g., overcurrent > 2A), the ESP32 immediately triggered the relay module. The relay

successfully disconnected the solar panel from the load, preventing further stress. Critically, in a multi-string setup, only the faulty string was isolated, and power from the healthy panels continued to be supplied.

**Local Alert System:** Simultaneously with the isolation, a buzzer was activated, and a red LED lit up, providing clear immediate feedback. The LCD displayed a "FAULT - ISOLATED" message.

**Cloud Integration:** The ESP32 successfully transmitted key parameters (voltage, current, temperature, and fault status) to the ThingSpeak cloud platform. The data was visualized on public and private channels, confirming successful remote monitoring. The system transmitted data even during a fault event, allowing for post-incident analysis.

### XIII. ADVANTAGES

- Real-time monitoring of critical solar grid parameters.
- Edge-based fault detection for instant response.
- Autonomous adaptive isolation of faulty sections.
- Cost-effective and portable design.
- Easy to use with local display and remote dashboard.

### XIV. APPLICATIONS

- **Smart Solar Farms:** For large-scale solar installations to automate fault management and maximize uptime.
- **Industrial Solar Systems:** To protect sensitive manufacturing equipment from power fluctuations and faults.
- **Residential Rooftop Systems:** To provide homeowners with automated protection and easy remote monitoring.
- **Remote & Rural Electrification:** In areas with limited technical support, the system's autonomous capabilities ensure reliable operation.
- **Microgrids:** As a critical component in the management and protection of decentralized energy networks.

### XV. CONCLUSION

The Edge-Enabled IoT Solar Grid with Autonomous Fault Detection and Adaptive Isolation system

presents a robust, efficient, and intelligent solution for modern solar energy management. By integrating IoT sensing with powerful edge computing on an ESP32 platform, the system overcomes the critical limitations of traditional, cloud-dependent monitoring methods. It successfully achieves its objectives by providing real-time monitoring of voltage, current, and temperature; performing instantaneous, edge-based fault detection; and executing autonomous adaptive isolation of faulty sections using a relay. This prevents minor faults from escalating into major system failures, ensuring continuous power supply from healthy parts of the grid.

The system's dual-layer architecture of local edge control for immediate action and cloud-based connectivity for remote supervision creates a powerful synergy. It offers the speed required for protection and the visibility required for management. This solution is not only cost-effective and scalable but also significantly enhances the reliability, safety, and efficiency of solar energy systems, making it a valuable contribution to the advancement of smart grid technology and the broader adoption of renewable energy.

### XVI. FUTURE ENHANCEMENTS

While the current system is highly effective, several enhancements can be explored to further improve its functionality and intelligence:

**AI-Powered Predictive Maintenance:** Integrating machine learning algorithms (e.g., anomaly detection models) on the ESP32 or a companion edge device. Instead of just reacting to thresholds, the system could predict faults by learning normal operational patterns and identifying subtle, pre-failure deviations [20].

**Wireless Sensor Networks:** Using LoRa or ZigBee to connect sensors, allowing for a truly wireless and more easily deployable system over larger areas.

**Integration with Energy Storage:** Adding intelligence to control battery charging and discharging. The system could isolate a faulty panel but use stored energy from batteries to maintain critical loads, further enhancing grid resilience.

**GPS Tracking:** Incorporating GPS to automatically log the exact location of a fault, which is invaluable

for large solar farms where identifying a faulty panel among thousands can be a challenge.

Solar Panel String Optimization: Using data from individual sensors to identify underperforming panels not due to immediate faults but due to soiling or degradation, enabling targeted cleaning or maintenance.

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