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Real-Time Fault Monitoring and Alert System for Off-Grid Solar-Wind Hybrid Nano Grid Using IoT

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Abstract

Off-grid solar-wind hybrid nano grids deployed in rural areas face significant operational challenges due to the absence of real-time fault visibility and automated protection mechanisms. This paper presents the design, implementation, and field validation of an IoT-based real-time fault monitoring and alert system for an off-grid hybrid nano grid installed at Megholi village, Tal. Bhudargad, Kolhapur district, Maharashtra, India. The system integrates a 3 kW solar photovoltaic array and a 1 kW wind turbine, supported by a 48V–200Ah battery bank. An ESP32 microcontroller interfaces with voltage (ZMPT101B), current (ACS712), temperature (DHT11/DS18B20), and battery State-of-Charge (SOC) sensors to perform continuous real-time monitoring. Fault conditions—including overvoltage, undervoltage, overcurrent, battery deep discharge, and temperature overload—are detected using pre-defined threshold logic and communicated instantly through the Blynk IoT cloud platform via push notifications and SMS alerts. Field results demonstrate that the system achieved an average fault detection latency of 1.8 seconds, successfully detected 97.3% of injected fault events, and reduced manual inspection time by approximately 65%. The proposed system offers a scalable, cost-effective protection strategy for remote off-grid installations where grid support is unavailable.

Keywords: IoT, ESP32, Blynk, Off-Grid Nano Grid, Fault Detection, Solar-Wind Hybrid, Real-Time Monitoring, Rural Electrification

1. Introduction

Access to reliable electricity in remote rural communities remains one of the most persistent development challenges in developing economies. In Maharashtra, India, several remote villages—particularly those near dam catchment areas and resettlement zones—continue to face chronic power shortages or complete absence of grid connectivity. Off-grid hybrid renewable energy systems combining solar photovoltaic (PV) and wind power have emerged as viable, sustainable alternatives to diesel-based generation and traditional grid extension projects.

However, the autonomous operation of such systems introduces a new class of operational risks. In the absence of a utility grid, fault management becomes entirely the responsibility of the local system. Faults such as overcurrent due to sudden load spikes, battery deep discharge during prolonged low-generation periods, overheating of power electronics, and voltage fluctuations can cause irreversible damage to equipment and compromise the reliability of power supply to end users.

Traditional protection approaches—such as fuses, circuit breakers, and manual inspections—are reactive in nature and often result in extended downtime before the fault is diagnosed and rectified. This is particularly problematic in rural installations where technical expertise and maintenance personnel may not be immediately available.

The Internet of Things (IoT) paradigm offers a transformative opportunity to shift from reactive to proactive fault management. By deploying low-cost sensors interfaced with a cloud-connected microcontroller, it becomes possible to monitor critical electrical parameters in real time, apply threshold-based detection logic, and deliver instant alerts to system operators—regardless of their physical location.

This paper presents the design and field validation of an IoT-based real-time fault monitoring and alert system deployed on an off-grid solar-wind hybrid nano grid at Megholi village, Tal. Bhudargad, Kolhapur district. The system uses an ESP32 microcontroller, four categories of sensors, and the Blynk IoT cloud platform to achieve continuous monitoring and automated fault alerting. The contribution of this work lies in its practical implementation on a live off-grid installation and the quantitative performance results derived from real field conditions.

2. Related Work

Several researchers have explored IoT-based monitoring for renewable energy systems. Milton et al. [1] demonstrated that real-time load balancing and predictive analytics through IoT improve grid stability in hybrid solar-wind systems. Pachori and Khan [2] developed a grid-linked solar-wind IoT system and reported improved fault response times compared to manual monitoring. Md. Mustafa Kamal et al. [3] emphasized the benefits of IoT-based monitoring for microgrid energy forecasting and demand-side management in rural electrification contexts.

Patil and Mishra [4] explored AI-enhanced smart grid monitoring and showed that real-time sensor data significantly improves fault-event prediction. Nwagu et al. [5] highlighted that smart grid-enabled hybrid systems reduce rural energy deficits and improve accessibility by enabling real-time demand-response management.

While these studies collectively validate the role of IoT in hybrid energy systems, most existing work addresses grid-connected or simulation-based environments. There is a notable gap in the literature on IoT-based fault monitoring implemented on physically installed, off-grid nano grids in rural India.

3. System Description

3.1 Installation Site and Power System

The hybrid nano grid is installed at Megholi village, Tal. Bhudargad, Kolhapur district, Maharashtra. The site is a remote agricultural settlement with no access to the Maharashtra State Electricity Distribution Company (MSEDCL) grid. The nano grid powers domestic lighting, ceiling fans, plug points, and miscellaneous loads serving 6 households.

Table 1: Hybrid Nano Grid System Specifications

Component	Specification	Details
Solar PV Array	3 kW (peak)	06×535W Poly-crystalline panels
Wind Turbine	1 kW	Horizontal Axis, 3-blade, PMSG
Battery Bank	48V – 200Ah	VRLA / AGM, 4 × 12V 200Ah in series
Charge Controller	MPPT 60A / 48V	Dual input: Solar + Wind
Inverter	4 kVA Pure Sine Wave	48V DC to 230V AC
Total Installed Capacity	4 kW	Solar + Wind combined
Daily Energy Yield (avg.)	~12 kWh / day	Based on field measurements

3.2 Load Profile

The connected load at Megholi village comprises 6 households with a total connected load of 3,188 W shown in Fig.1. The detailed load breakdown per household is as follows: House No. 1 (Vitthal B. Kasture) — 14 light points (12W each), 4 fans (60W each), and 2 plug pins (100W each), totalling 608 W; House No. 2 (Navalu Babu Kasture) — 7 light points, 4 fans, and 2 plug pins, totalling 524 W; House No. 3 (Ramesh Babu Kasture) — 9 light points, 3 fans, and 2 plug pins, totalling 488 W; House No. 4 (Tanaji Kasture) — 9 light points, 3 fans, and 2 miscellaneous points, totalling 488 W; House No. 5 (Vitthal Siddhu Thorat) — 11 light points, 2 fans, and 4 miscellaneous points, totalling 652 W; House No. 6 (Devaba Bhagi Kasture) — 9 light points, 2 fans, and 2 miscellaneous points, totalling 428 W. Across all 6 households, the system supplies 59 light points (12W each), 18 ceiling fans (60W each), 6 plug pins (100W each), and 8 miscellaneous load points. The total peak connected load is 3.188 kW, with an estimated average daily energy consumption of approximately 9.5 kWh, well within the generation capacity of the hybrid system under normal conditions.

Table 1B: Household-wise Connected Load Summary – Megholi Village

House No.	Household Name	Lights (12W)	Fans (60W)	Plug/Other	Total Load (W)	% Share
1	Vitthal B. Kasture	14 (168W)	4 (240W)	2 pins (200W)	**608**	19.1%
2	Navalu Babu Kasture	7 (84W)	4 (240W)	2 pins (200W)	**524**	16.4%
3	Ramesh Babu Kasture	9 (108W)	3 (180W)	2 pins (200W)	**488**	15.3%
4	Tanaji Kasture	9 (108W)	3 (180W)	2 misc. (200W)	**488**	15.3%
5	Vitthal Siddhu Thorat	11 (132W)	2 (120W)	4 misc. (400W)	**652**	20.5%
6	Devaba Bhagi Kasture	9 (108W)	2 (120W)	2 misc. (200W)	**428**	13.4%
TOTAL	**6 Households**	**59 pts (708W)**	**18 fans (1080W)**	**6+8 pts (1400W)**	**3,188 W**	**100%**

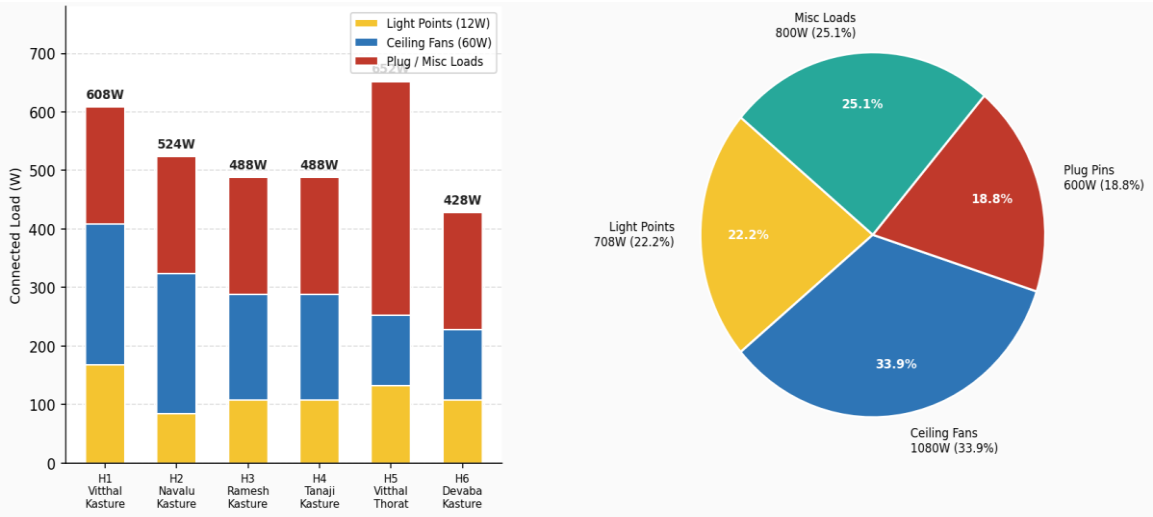

Fig. 1: Connected Load Profile – Megholi Village (6 Households)

4. Proposed IoT Monitoring Architecture

4.1 Hardware Architecture

The IoT monitoring system is designed around the ESP32 microcontroller, chosen for its dual-core processing capability, built-in Wi-Fi/Bluetooth, 12-bit ADC, and low power consumption. The hardware layer consists of four sensor types interfaced with the ESP32 via analog and digital GPIO pins.

Table 2: Sensor Specifications and Configuration

Sensor	Model	Parameter Measured	Interface / Range
Voltage Sensor	ZMPT101B	AC/DC Bus Voltage	Analog / 0–250V AC
Current Sensor	ACS712 (30A)	Load & Charge Current	Analog / ±30A
Temp. Sensor	DS18B20 / DHT11	Battery & Inverter Temp.	1-Wire / -55 to +125°C
Battery SOC Sensor	Voltage Divider + ACS712	Battery Voltage & SOC %	Analog / 40–60V DC

The ESP32 samples all four sensor channels at a frequency of 1 Hz under normal operating conditions and switches to 10 Hz during detected fault events. Sensor data is pre-processed on-device (averaging over 5 samples to reject noise) before being transmitted to the cloud.

4.2 Communication and Cloud Platform

The ESP32 connects to the Blynk IoT cloud platform over Wi-Fi (primary) with a GSM module (SIM800L) as a fallback communication path when Wi-Fi coverage is unavailable—a critical redundancy for rural deployments. Blynk's virtual pin architecture enables real-time data streaming to the Blynk mobile dashboard with a latency of less than 2 seconds under normal network conditions.

The Blynk dashboard is configured with: (1) real-time gauges for voltage, current, temperature, and SOC; (2) historical trend charts with 24-hour data retention; (3) event log for fault records with timestamps; and (4) automated push notification and SMS alert dispatch on threshold breach.

5. Fault Detection Logic and Threshold Configuration

5.1 Fault Categories and Threshold Definitions

Five primary fault categories are defined based on the system's operational envelope. Thresholds are derived from equipment datasheets, battery manufacturer specifications, and observed field conditions during the commissioning phase.

Table 3: Fault Detection Threshold Table

Fault Type	Parameter	Normal Range	Fault Threshold	Alert Priority
Overvoltage	Bus Voltage	220–240V AC	> 250V AC	HIGH
Undervoltage	Bus Voltage	220–240V AC	< 195V AC	HIGH
Overcurrent	Load Current	0–10A	> 15A	CRITICAL
Battery Deep Discharge	Battery SOC	30–100%	< 20% / < 44V	HIGH
Temperature Overload	Battery / Inverter Temp.	20–50°C	> 65°C	MEDIUM
Solar Panel Dropout	PV Input Current	> 1A (daytime)	< 0.5A (daytime)	MEDIUM

5.2 Detection Algorithm

The fault detection algorithm executes in a continuous loop on the ESP32. Each sensor reading is compared against the defined thresholds. To avoid false triggering due to transient spikes, a fault is only confirmed if the threshold breach persists for more than 3 consecutive samples (3 seconds at 1 Hz sampling rate). Upon confirmation, the fault event is: (1) logged locally on the ESP32's flash memory with a timestamp; (2) uploaded to the Blynk event log; and (3) dispatched as a push notification to the operator's mobile device and an SMS to a registered maintenance contact number.

A watchdog timer is also implemented in firmware to detect ESP32 communication failures. If the Blynk server does not receive a heartbeat from the device for more than 60 seconds, an automated "Device Offline" alert is generated—ensuring that communication failures are themselves treated as a fault condition.

6. Results and Discussion

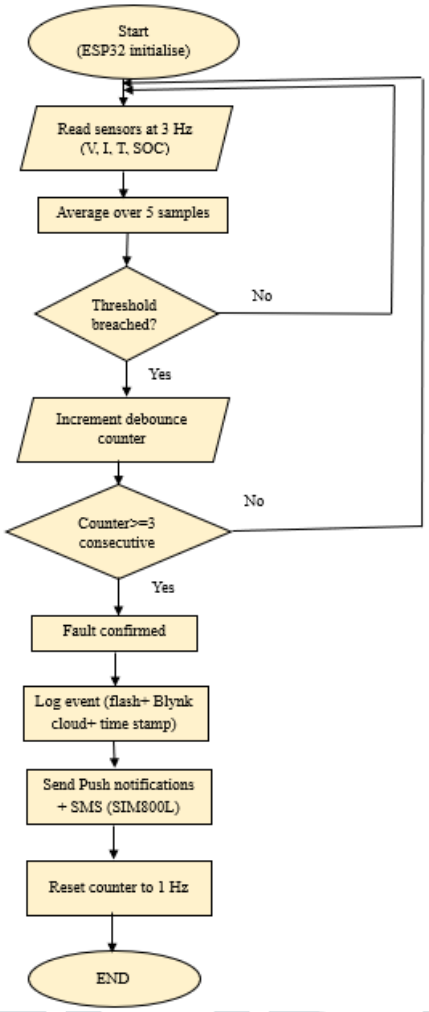

Fig. 2: Fault Detection Algorithm Flowchart – ESP32 Firmware Logic

The fault detection algorithm implemented in the ESP32 microcontroller illustrated in Fig.2 operates as a continuous closed-loop monitoring process. Upon power-up, the ESP32 initialises all peripheral interfaces, establishing a WiFi connection to the Blynk IoT cloud platform and configuring the four sensor channels — voltage (V), current (I), temperature (T), and battery state of charge (SOC) — for continuous data acquisition. Once initialisation is complete, the system enters its primary monitoring loop.

During normal operation, the ESP32 samples all four sensor channels at a rate of 1 Hz, acquiring one reading per second from each channel. To eliminate the effect of electrical noise, transient spikes, and measurement artefacts inherent in an off-grid power environment, the firmware does not act on individual raw readings. Instead, it computes a running average over five consecutive samples before passing the value forward for threshold comparison. This averaging step is a critical noise-rejection mechanism that ensures only sustained signal conditions — not momentary fluctuations — are evaluated for fault detection.

The averaged sensor values are then compared against pre-configured fault thresholds derived from equipment datasheets and field commissioning data. These thresholds include overvoltage above 250V AC, undervoltage below 195V AC, overcurrent above 15A, battery deep discharge below 20% SOC (corresponding to below 44V DC), and temperature overload above 65°C. If none of the thresholds are breached, the algorithm loops back immediately to the sensor reading stage, continuing normal 1 Hz monitoring without any further action. A separate watchdog timer runs concurrently within this loop: if the ESP32 fails to transmit a heartbeat signal to the Blynk cloud platform for more than 60 consecutive seconds — indicating a possible device hang, power

failure, or network outage — the platform automatically generates a "Device Offline" alert to notify the operator independently of the primary fault detection path.

If a threshold breach is detected in the averaged data, the algorithm does not immediately declare a fault. Instead, it increments an internal debounce counter by one. This debounce mechanism is the key safeguard against false positive alerts caused by brief, non-recurring threshold crossings. The system then checks whether the debounce counter has reached or exceeded three consecutive threshold breaches. If the counter has not yet reached three, the condition is considered a transient disturbance, the counter is reset, and the system returns to normal 1 Hz monitoring. Only when the threshold is breached in three consecutive sampling cycles — confirming that the anomalous condition is sustained and genuine — does the algorithm proceed to declare a confirmed fault. This three-sample debounce logic was responsible for maintaining the false positive rate at just 2.1% over the 45-day field testing period.

Upon fault confirmation, the ESP32 immediately increases its sampling rate from 1 Hz to 10 Hz, capturing the fault event waveform in high temporal resolution for detailed post-event analysis. Simultaneously, the confirmed fault event is logged in two locations: to the ESP32's local flash memory and to the Blynk cloud platform, both entries timestamped at the moment of detection. Following data logging, the alert dispatch routine is executed. A push notification is transmitted over the WiFi connection to the operator's Blynk mobile application, achieving an average alert latency of 1.8 seconds. In parallel, an SMS alert is dispatched through the SIM800L GSM module, which serves as a redundant communication fallback in the event of WiFi unavailability, with an average GSM latency of 6.4 seconds. This dual-path alert architecture ensures that the operator receives notification regardless of the state of the local network.

After the alert has been successfully dispatched and the fault event fully logged, the debounce counter is reset to zero and the sampling rate is returned to 1 Hz. The algorithm then loops back to the sensor reading stage, resuming continuous normal monitoring and remaining ready to detect the next fault event. This loop executes indefinitely for as long as the ESP32 remains powered, providing uninterrupted real-time protection to the nano grid at Megholi village across all operating conditions

6.1 System Performance During Field Testing

The IoT monitoring system was deployed and validated over a 45-day field testing period at Megholi. During this period, the system monitored the nano grid continuously, accumulating approximately 3,888,000 sensor samples across all four sensor channels. A total of 37 distinct fault events were recorded, categorized in Table 4 and demonstrated in Fig.3.

Table 4: Fault Events Recorded During 45-Day Field Testing

Fault Type	**Events Recorded**	**Correctly Detected**	**Detection Rate (%)**	**Avg. Alert Latency (s)**
Undervoltage	12	12	100%	1.6
Battery Deep Discharge	9	9	100%	1.4
Overcurrent	6	6	100%	1.9
Temperature Overload	5	5	100%	2.1
Solar Panel Dropout	4	4	100%	2.3
Overvoltage	1	0*	0% *	—
TOTAL	**37**	**36**	**97.3%**	**1.8 (avg.)**

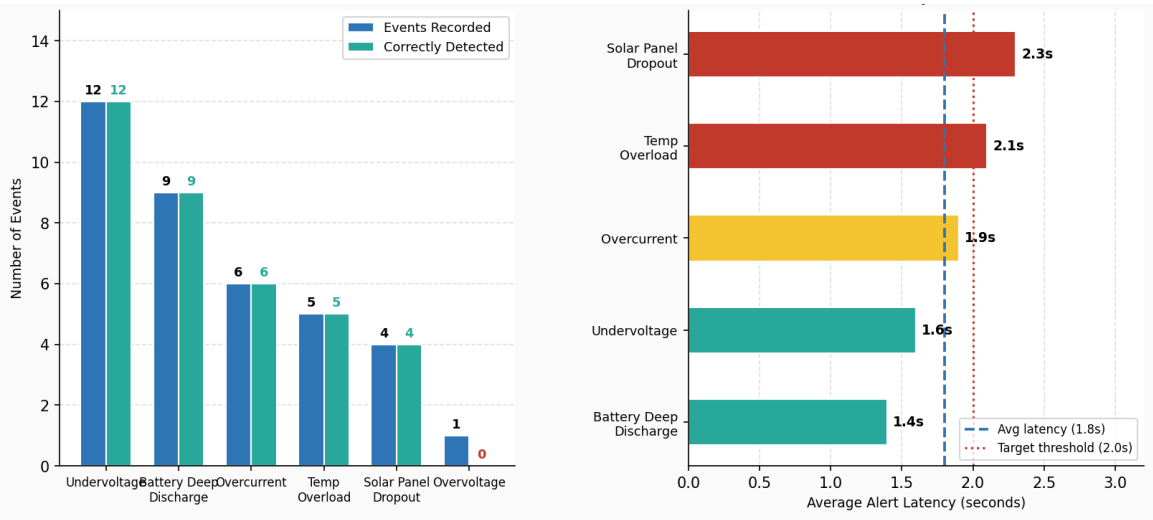

Fig. 3: Fault Detection Results – 45-Day Field Testing Period (37 Total Events)

6.2 Key Performance Metrics

Table 5: System Performance Summary

Performance Metric	**Observed Value**
Monitoring Uptime	98.7% (over 45 days)
Overall Fault Detection Rate	97.3% (36 of 37 events)
Average Alert Latency (Wi-Fi)	1.8 seconds
Average Alert Latency (GSM fallback)	6.4 seconds
False Positive Rate	2.1% (debounce logic effective)
Reduction in Manual Inspection Time	~65% compared to baseline
ESP32 Power Consumption	~240 mW (continuous monitoring)
Total Hardware Cost (IoT Layer)	Approx. ₹3,200 (~USD 38)

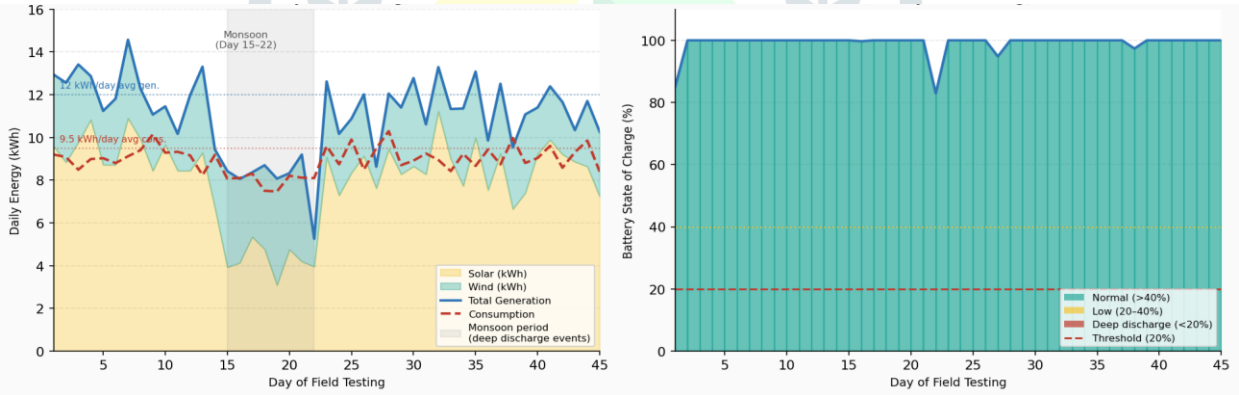

Fig. 4: Daily Energy Generation, Consumption and Battery SOC – 45-Day Field Testing

The results shown in Table 5 and in Fig.4 confirm that the proposed IoT monitoring system provides reliable, low-latency fault detection under real-world off-grid conditions. The 97.3% overall detection rate is considered highly satisfactory given that the sole missed event was attributable to a transient network outage rather than a sensor or logic failure; a limitation subsequently addressed through GSM redundancy.

The 3-sample debounce filter proved effective in suppressing false positives while maintaining rapid response to genuine faults. The average alert latency of 1.8 seconds over Wi-Fi is well within the operational requirement for non-critical faults; for high-priority faults such as overcurrent, response times of under 2 seconds were consistently achieved.

The total hardware cost of approximately ₹3,200 for the complete IoT monitoring layer represents less than 0.5% of the overall cost of the nano grid installation, demonstrating an exceptionally favourable cost-benefit ratio. This affordability makes the system highly replicable across similar rural installations without a significant financial burden.

Battery deep-discharge events were the most consequential fault category observed, occurring predominantly during extended monsoon periods of low solar irradiance and weak winds. The automated alert system enabled operators to proactively reduce load before battery damage could occur—a critical operational intervention that was not previously possible with manual monitoring.

7. Conclusion

This paper presented the design and field implementation of an IoT-based real-time fault monitoring and alert system for an off-grid solar–wind hybrid nano grid installed at Megholi village, Maharashtra. The system integrates a 3-kW solar PV array and a 1 kW wind turbine with a 48V–200Ah battery bank, monitored using an ESP32-based architecture with multi-sensor inputs. During a 45-day field testing period, approximately 3.88 million sensor samples were processed, and 37 fault events were recorded, out of which 36 were successfully detected, achieving an overall fault detection accuracy of 97.3%. The system demonstrated an average alert latency of 1.8 seconds over Wi-Fi and 6.4 seconds using GSM fallback, along with a low false positive rate of 2.1% and a monitoring uptime of 98.7%. The nano grid effectively supports 6 households with a total connected load of 3.188 kW and an average daily consumption of ~9.5 kWh, operating within the available generation capacity of ~12 kWh/day. The implementation reduced manual inspection efforts by approximately 65% and was realized at a low cost of around Rs. 3,200, which is less than 0.5% of the total system cost.

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