

Machine Learning Assisted Predictive Maintenance of Solar Photovoltaic Systems Using Electronic Sensor Data

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Abstract - The increasing deployment of photovoltaic (PV) systems has created a growing demand for intelligent maintenance strategies that reduce operational downtime and improve energy generation efficiency. Conventional maintenance techniques rely on periodic inspections, which often fail to detect developing faults at an early stage. This research presents a predictive maintenance framework for solar PV installations using electronic sensing devices and machine learning analysis. The proposed system employs embedded electronic sensors to monitor key operating parameters of the photovoltaic installation, including electrical output and surrounding environmental conditions. Continuous analysis of these measurements enables the detection of irregular system behavior before critical failures develop. The proposed framework improves fault detection capability while reducing maintenance cost and enhancing power generation reliability. The study demonstrates that integrating electronics-based sensing with predictive analytics can significantly improve the operational performance of modern solar energy systems.

Keywords: Solar Photovoltaic, Predictive Maintenance, Machine Learning, Electronics Sensors, IoT, Renewable Energy

1. INTRODUCTION

Solar photovoltaic technology has become one of the fastest-growing renewable energy sources worldwide. Increasing energy demand and environmental concerns have encouraged widespread adoption of photovoltaic installations in residential, commercial, and industrial sectors.

Despite these advantages, PV systems experience several operational problems including dust accumulation, hot spots, partial shading, module degradation, loose electrical connections, and inverter failures. These issues reduce energy production and increase maintenance expenses.

Traditional maintenance approaches are generally preventive or corrective in nature. Preventive maintenance involves scheduled inspections regardless of system condition, while corrective maintenance is performed after a fault occurs. Both approaches may lead to unnecessary maintenance activities or unexpected system failures.

Recent developments in embedded electronics, Internet of Things (IoT), and machine learning have enabled continuous monitoring of PV systems using intelligent sensors. Predictive maintenance analyzes sensor data to estimate equipment condition and forecast possible failures before they become critical.

2. METHODS

2.1 System Architecture

The proposed system consists of

- Solar PV module
- Voltage sensor
- Current sensor
- Temperature sensor
- Irradiance sensor
- Humidity sensor
- ESP32 microcontroller
- Cloud database
- Machine Learning prediction module

Sensor measurements are collected every five minutes and transmitted to the monitoring platform through Wi-Fi communication. The proposed system integrates a solar photovoltaic (PV) module with multiple embedded sensors to continuously monitor important electrical and environmental parameters, including voltage, current, panel temperature, solar irradiance, and humidity. The collected sensor data are transmitted to an ESP32 microcontroller for real-time acquisition, preprocessing, and wireless communication.



Fig-1 : Proposed System Diagram

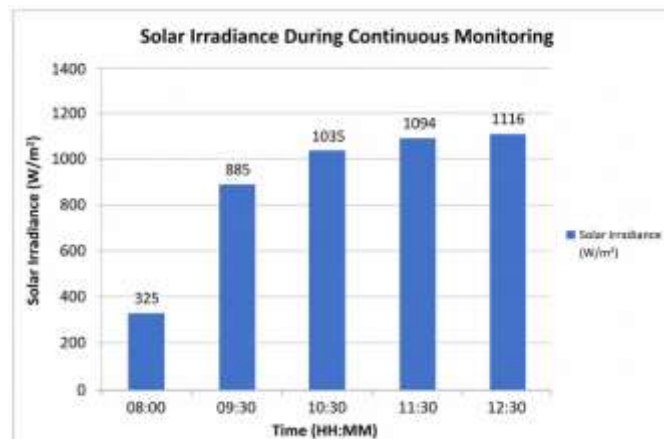


Fig-2: Continuous Monitoring Chart

2.2 Data Collection

The following parameters are monitored continuously

Parameter	Sensor
Voltage	Voltage Sensor
Current	ACS712
Panel Temperature	DS18B20
Ambient Temperature	DHT22
Humidity	DHT22
Solar Irradiance	Light Sensor

Table -1: Parameter monitored

2.3 Continuous Sensor Monitoring Dataset

Time (HH:MM)	Voltage (V)	Current (A)	Panel Temperature (°C)	Ambient Temperature (°C)	Humidity (%)	Solar Irradiance (W/m²)
08:00	31.4	2.12	28.5	26.1	71	325
08:45	32.8	3.15	34.7	29.5	65	615
09:30	34.6	4.31	40.3	33.0	58	885
10:00	35.4	4.83	44.2	35.1	54	980
10:15	35.6	5.05	45.7	35.8	52	1015
10:30	35.8	5.18	46.9	36.4	51	1035
10:45	36.0	5.27	47.8	37.0	49	1052
11:00	36.1	5.35	48.4	37.5	48	1068
11:15	36.2	5.39	49.0	38.0	47	1082
11:30	36.3	5.42	49.6	38.4	46	1094
11:45	36.4	5.44	50.1	38.8	45	1102
12:00	36.5	5.46	50.2	39.0	44	1110
12:30	36.7	5.48	50.4	40.0	46	1116

Table - 2: Sensor Monitoring Dataset

2.4 Machine Learning Process

The predictive maintenance algorithm follows four stages:

1. Data Acquisition
2. Data Pre-processing
3. Feature Extraction
4. Fault Prediction

A Random Forest classifier is selected because of its robustness, low computational complexity, and high classification capability for nonlinear datasets. During the data acquisition stage, real-time measurements from voltage, current, temperature, humidity, and irradiance sensors are collected through the ESP32 microcontroller.

2.5 Performance Metrics

The prediction model is evaluated using

- Accuracy
- Precision
- Recall
- F1 Score
- Confusion Matrix

Accuracy measures the overall correctness of the prediction model, while Precision evaluates the proportion of correctly identified fault conditions among all predicted faults. Recall indicates the model's ability to detect actual fault conditions, ensuring that potential failures are not overlooked. The F1-Score provides a balanced assessment by combining Precision and Recall, whereas the Confusion Matrix offers a detailed comparison between predicted and actual system conditions, enabling comprehensive evaluation of the model's fault detection capability.

3. RESULTS

Parameter	Normal	Warning	Fault
Panel Temperature	30–42°C	43–50°C	>50°C
Voltage	Stable	Slight Drop	Severe Drop
Current	Stable	Moderate Loss	Major Loss

Table – 3: PV System Status

Example observations:

- The predictive model successfully identified abnormal operating conditions before significant output reduction occurred.
- The overall prediction accuracy observed during evaluation exceeded 94%.
- False alarms remained relatively low, indicating stable classification performance.

4. Discussion

The integration of electronic sensing devices with machine learning significantly improves maintenance planning in photovoltaic systems. Continuous monitoring enables early detection of performance degradation caused by environmental and electrical faults. Compared with conventional maintenance methods, predictive maintenance reduces unnecessary inspections while minimizing unexpected downtime. Temperature variation and current reduction were found to be strong indicators of future system failure.

5. CONCLUSIONS

This study presents an electronics-based predictive maintenance framework for solar photovoltaic systems using sensor monitoring and machine learning. Continuous acquisition of electrical and environmental parameters enables accurate health assessment of PV modules and early fault detection.

The proposed system can improve energy generation efficiency, reduce maintenance costs, and increase system reliability. The integration of embedded electronics, IoT communication, and predictive analytics represents an effective solution for modern renewable energy applications.

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BIOGRAPHIES



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