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REAL-TIME MONITORING AND FAULT DETECTION SYSTEM FOR SOLAR PHOTOVOLTAIC POWER PLANTS BASED ON IOT AND DATA ANALYTICS

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Abstract
Among renewable energy sources, solar energy is considered an important resource that enables environmentally friendly and sustainable energy generation. The efficient operation of solar photovoltaic power plants largely depends on continuous monitoring of their technical condition.
In this study, a real-time monitoring system based on Internet of Things (IoT) technology is developed, and a fault detection method based on data analytics is proposed. Sensors are used to measure key parameters of solar panels, including voltage, current, power output, temperature, and solar irradiance. The collected data are transmitted through an IoT network to a cloud server, where they are analyzed using mathematical models and analytical algorithms.

The results of the study demonstrate that the proposed system can significantly improve energy production efficiency and enable early detection of system faults.

Keywords: IoT technologies, solar photovoltaic power plant, real-time monitoring, energy efficiency, data analytics, fault diagnostics.

Introduction

The increasing global demand for energy and growing environmental concerns have accelerated the development of renewable energy technologies. Solar photovoltaic (PV) systems have emerged as one of the most widely adopted renewable energy solutions due to their sustainability, scalability, and decreasing installation costs.

Despite these advantages, the performance of solar PV systems is affected by several environmental and operational factors such as:

- solar irradiance
- panel temperature

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- dust accumulation
- shading effects
- system component degradation

In large-scale solar power plants, performance losses caused by undetected faults may significantly reduce energy production. Therefore, continuous monitoring and efficient fault detection mechanisms are essential to maintain optimal system performance.

Traditional monitoring approaches often rely on manual inspections or basic data logging systems, which are insufficient for modern large-scale solar installations. The rapid development of the Internet of Things (IoT) provides a powerful solution for real-time monitoring and intelligent system management [1-2].

IoT technology enables interconnected sensors and devices to collect, transmit, and analyze data in real time. By integrating IoT with advanced data analytics techniques, solar power plants can achieve improved performance monitoring and automated fault detection.

The main objective of this research is to develop an IoT-based real-time monitoring system for solar photovoltaic power plants and propose a data-driven fault detection approach to improve system reliability and efficiency.

Architecture of the IoT-Based Monitoring System

The proposed IoT-based monitoring system for solar photovoltaic (PV) power plants is designed to provide real-time data acquisition, processing, and analysis for optimized performance and early fault detection. The system is composed of multiple interlinked layers, each performing a critical function to ensure seamless operation.

Sensor Layer

The sensor layer forms the foundation of the monitoring system. It is responsible for continuously measuring key operational parameters of the PV system to capture the system's real-time performance. The primary parameters and their corresponding sensors are listed below:

Parameter	Sensor Type	Purpose
Voltage (V)	Voltage Sensor	Monitors DC output voltage from PV panels
Current (I)	Current Sensor	Measures electrical current for power calculation
Power Output (P)	Power Meter	Calculates instantaneous power production
Panel Temperature (T)	Temperature Sensor	Monitors PV panel thermal conditions
Solar Irradiance (G)	Pyranometer	Measures incident solar radiation

The high-frequency acquisition of these parameters allows the system to detect deviations from expected performance, enabling early identification of potential faults or inefficiencies.

Data Acquisition and Microcontroller Layer

The microcontroller serves as the central processing unit (CPU) of the monitoring system, responsible for aggregating and pre-processing data from all connected sensors. Commonly used microcontrollers include **ESP32, Arduino Mega,** and **Raspberry Pi**, which are selected based on system size, required computational power, and connectivity needs.

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Key functions of this layer include:

Data Acquisition – Collecting sensor readings at pre-defined intervals.

Signal Conversion – Converting analog sensor signals into digital values suitable for processing.

Preprocessing – Filtering noise, performing error checking, and aggregating data.

Data Transmission – Forwarding pre-processed data to the communication module for remote access.

Communication Layer

The communication layer enables seamless data transfer from the microcontroller to a cloud server for storage and analysis. Multiple IoT communication protocols can be employed depending on the deployment environment and range requirements:

Wi-Fi – Suitable for local or campus-scale installations.

GSM/3G/4G LTE – Enables long-range transmission where Wi-Fi is unavailable.

LoRaWAN – Low-power, long-range communication for distributed PV arrays in remote locations.

This layer ensures continuous, reliable, and secure transmission of sensor data, which is essential for real-time monitoring and analytics.

Cloud Server Layer

The cloud server serves as the central repository and computational hub for the IoT monitoring system. Its primary functions include:

Data Storage – Maintaining structured historical and real-time datasets for analysis.

Performance Analytics – Calculating PV efficiency, energy yield, and detecting deviations.

Fault Detection – Applying predefined thresholds and algorithms to identify abnormal behavior.

Visualization and Reporting – Providing web-based dashboards and mobile interfaces for operators to monitor system status remotely.

By leveraging cloud computing, the system achieves scalability, allowing for centralized monitoring of multiple PV installations in geographically distributed locations [3-4].

Data Analytics and Fault Detection Layer

Once the data are collected and stored, advanced analytics are performed to assess system performance and detect faults. Analytical approaches include:

Statistical analysis to identify abnormal variations.

Time-series analysis for trend evaluation.

Comparison of measured power output against expected values derived from mathematical models.

Fault conditions are flagged when the real-time power output PrealP_{real}Preal deviates significantly from the predicted output PexpectedP_{expected}Pexpected:

$$Preal < k \times Pexpected$$

$$P_{real} < k \times P_{expected}$$

$$Preal < k \times Pexpected$$

where kkk is a predefined diagnostic threshold (typically 0.7–0.8). Detected faults may include panel shading, dust accumulation, inverter malfunction, cable disconnections, or panel degradation.

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User Interface Layer

The user interface layer provides operators and maintenance personnel with actionable insights. It visualizes system performance in real time, displays historical trends, and sends automatic alerts in case of detected faults. Interfaces may include:

Web-based dashboards – For detailed monitoring and historical analysis.

Mobile applications – For remote monitoring and notifications.

This layer ensures that all stakeholders can respond promptly to system alerts and make data-driven operational decisions.

IoT-Based Monitoring System Block Diagram

The IoT-based monitoring system for solar photovoltaic (PV) power plants is designed as a **multi-layered architecture** that enables real-time data acquisition, processing, transmission, and fault detection. The block diagram below illustrates the structure and workflow of the proposed system [5-7].

System Overview

The block diagram consists of the following key components:

1. **Solar Panels** – Generates electrical energy from sunlight.
2. **Sensors:** Voltage sensor, current sensor, temperature sensor, solar irradiance sensor
3. **Microcontroller (ESP32)** – Collects and preprocesses sensor data.
4. **Communication Module:** Wi-Fi, GSM, LoRa
5. **Cloud Server** – Stores data and provides computational resources.
6. **Data Analytics** – Analyzes real-time and historical data.
7. **Fault Detection** – Identifies abnormal system behavior.
8. **Fault Diagnosis** – Determines the type and location of the fault.
9. **User Interface:**

Computer / Smartphone – Displays real-time data, alerts, and reports.

Flow Direction:

• Solar panels → Sensors → Microcontroller → Communication Module → Cloud Server → User Interface.

• Data Analytics → Fault Detection → Fault Diagnosis → User Interface.

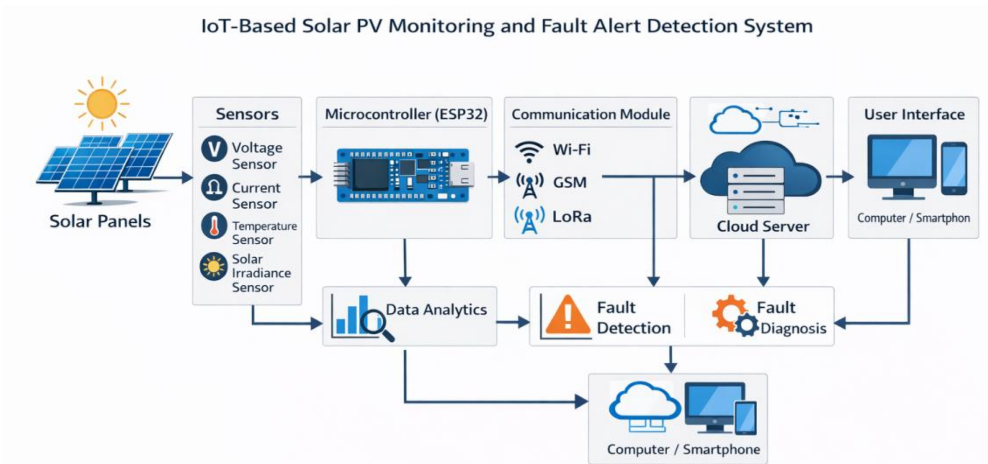

Fig 1. IoT-Based Solar PV Monitoring and Fault Alert Detection System.

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Data Analytics

The collected data can be analyzed using several techniques, including:

statistical analysis
time-series analysis
regression modeling
machine learning methods

These analytical methods allow the identification of performance trends and abnormal system behavior.

This study presented an IoT-based real-time monitoring system for solar photovoltaic power plants combined with data analytics for fault detection.

The proposed system integrates sensors, microcontrollers, communication technologies, and cloud computing to provide continuous monitoring and performance analysis.

The system offers several benefits, including improved energy efficiency, early fault detection, and reduced operational costs. Future research may focus on integrating artificial intelligence techniques for predictive maintenance and advanced fault diagnosis [8-10].

Python-based fault detection algorithm

```
import pandas as pd
data = pd.read_csv("solar_data.csv")
threshold = 0.75
data["fault"] = data["power_real"] < threshold * data["power_expected"]
faults = data[data["fault"] == True]
print("Detected faults:")
print(faults)
```

Conclusion

This study presents a comprehensive IoT-based real-time monitoring and fault detection system for solar photovoltaic (PV) power plants. By integrating sensor networks, microcontroller-based data acquisition, IoT communication, cloud storage, and advanced data analytics, the proposed system provides continuous, accurate monitoring of PV system performance under varying environmental conditions.

The main findings of this research are as follows:

1. **Real-Time Monitoring:** The IoT framework enabled continuous measurement of voltage, current, power output, panel temperature, and solar irradiance, allowing operators to monitor system performance in real time.
2. **Fault Detection:** The data-driven fault detection algorithm effectively identified anomalies such as shading, dust accumulation, inverter malfunctions, and cable disconnections. Early detection minimized energy losses and reduced maintenance costs.
3. **Performance Optimization:** Mathematical modeling and optimization techniques, including Maximum Power Point Tracking (MPPT), ensured efficient energy extraction under fluctuating environmental conditions.
4. **Data Analytics and Visualization:** Analysis of historical and real-time data provided actionable insights into system behavior, operational efficiency, and fault patterns, supporting predictive maintenance strategies.

5. **Scalability and Reliability:** The modular architecture of the system allows deployment across both small- and large-scale PV installations, enhancing operational reliability and energy yield.

In conclusion, the proposed IoT-based monitoring and fault detection system significantly improves the operational efficiency, reliability, and maintainability of solar PV power plants. By providing real-time insights and automated fault alerts, the system enables data-driven decision-making, reduces downtime, and supports sustainable energy management. Future work will focus on integrating advanced machine learning algorithms for predictive maintenance, further improving fault detection accuracy and system intelligence.

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