Design and Implementation of Effective Real Time Monitoring System for Utility Solar Power Plant

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Abstract- This paper presents the design and implementation of a Solar PowerPlant Monitoring System using Node-RED, MySQL, RS-485communication, and industrial networking components. The objective ofthe system is to provide real-time monitoring, data logging, andintelligent analysis of various parameters of a solar power plant,including voltage, current, power output, energy generation, andequipment health status.The research utilizes RS-485-based sensors/meters connected throughRS-485 to Ethernet converters and industrial network switches toestablish long-distance and reliable communication. Node-RED servesas the central processing platform used for data acquisition, protocolhandling, workflow automation, and dashboard visualization. Thecollected data is stored in a MySQL database for long-term logging,analysis, and report generation. The system is scalable, cost-effective,and suitable for small to large grid-connected or standalone solarinstallations.This monitoring system enhances performance tracking, improves faultdetection capability, reduces downtime, and supports data-drivendecision-making for efficient solar plant operation.

Keywords: Node-RED, MySQL, RS-485communication, Ethernet

I. INTRODUCTION

The purpose of this project was to develop a real-time monitoring anddata logging system for the solar power plant. Previously, operator recorded inverter and plant data manually at fixed intervals (every hour).This process was time-consuming, prone to errors, and lacked historicaldata analysis capability. [2]The new monitoring system is designed using Node.js as the backendplatform, with MySQL database integration for reliable data storage. [3], [4] Itenables real-time monitoring, historical data visualization, and automaticdaily logging of both individual inverters and the overall planttrends as shown in Fig.1.[5]

Fig.1. Trends in the History

II. OBJECTIVE AND PURPOSE

The main objective is to implement a cost-effective and reliablemonitoring solution for a 50 kWp solar power plant that provides realtimevisibility, long-term data storage, and easy scalability for additionaldevices in the future.

III. LITERATURE REVIEW

Arman Jahan Eva et al. proposed design integrates both energy sources into a visually appealing and self-sustaining structure capable oflive monitoring and remote management. The system uses low-cost hardware (Arduino Nano, ESP8266, INA226sensors) and simulation tools (COMSOL Multiphysics forstructural integrity, HOMER Pro for cost analysis andMATLAB Simulink for performance modeling) using MPPT. A prototype was implemented for economic evaluation under site-specific conditions in Rajbari, Bangladesh (23∘40.8′N, 89∘31.3′E) demonstrating a levelized Costof Energy (LCOE) \$0.11/kWh to \$0.18/kWh for a single unit, which is approximately 50% lower than astandalone solar system. [1]

PranayPrasoon et al. presents a detailed performance assessment of a 5 MWp grid-connected solar photovoltaic (PV) power plant installed by NTPC Limited at Dadri, India. Commissioned in 2013, the facility is one of the country's early large-scale solar installations developed under Phase I of the Jawaharlal Nehru National Solar Mission. The site

records an average annual solar irradiation of 4.59 kWh/m²/day and an average temperature of about 25.13 °C. Using monitored data from the financial year 2022–23, the analysis evaluates the plant's operational performance by examining both controllable and uncontrollable factors affecting its efficiency and output. [7]

A study by Nawaz Ahmad et al. examines the site-specific feasibility, optimal system configuration, and detailed PVsyst-based performance of a 100 MWp solar photovoltaic plant proposed for Suhar Industrial City in Oman. The work is particularly significant due to its focus on aligning solar generation with industrial energy demand in the high-irradiance MENA region, where large-scale case studies remain limited. The analysis considers both technical performance and economic feasibility for partially meeting the energy requirements of the industrial zone. The optimized design, comprising over 174,432 PV modules, demonstrates the potential to supply nearly 40% of the city's annual electricity demand based on 2021 conditions. [8]

These reviews provide supporting evidence for structuring and showcasing the power plant monitoring system across its different operational stages.

IV. METHODOLOGY

The system architecture consists of four primary layers:

• Data Acquisition Layer – Collects inverter and meter data via RS-485.

• Communication Layer – Uses ATC-1000 converters to convert ModbusRTU to TCP/IP.

• Server Layer – Node.js application logs and processes incoming data, storing it in MySQL.

• Visualization Layer – Web-based dashboard accessible through anyintranet-connected PC.

The system continuously collects data from solar inverters and theACDB energy meter via RS-485 (Modbus RTU) communication. TwoATC-1000 converters are used to convert RS-485 to Modbus TCP/IP,which is then transmitted through a Planet SW-10 network switch to themonitoring PC. [6] The Node.js server reads and stores the data in theMySQL database and displays it on the dashboard as shown in Fig.2.
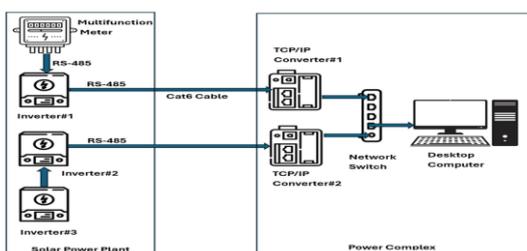

Fig. 2. System Communication Flow Diagram

The system communication flow is organized such that Inverter 1 and the Energy Meter are connected to Converter 1, while Inverter 2 and Inverter 3 are linked to Converter 2. Both converters then transmit their data to a network switch, which subsequently facilitates communication with the PC.

The system consists of several hardware components with their respective specifications. Two TCP/IP converters (Model: ATC-1000) are used to enable communication between inverters and the network. A single network switch (Model: Planet SW-10) is included to interconnect all communication devices. For data transmission, about 90 meters of Cat-6 Ethernet cable is required. Additionally, an existing PC with Windows 11 is utilized for monitoring and control purposes. Overall, these components form a cost-effective communication and monitoring setup. The software component typically includes monitoring and control applications installed on the PC, which facilitate real-time data acquisition, visualization, and system management.

The system utilizes open-source software tools to enable efficient communication, data handling, and monitoring. Node.js v20 is used as the backend server to manage communication between devices and handle data processing tasks. For data storage and retrieval, MySQL is employed as a reliable database solution. Additionally, Node-RED runtime software is used to design and manage data flows, providing an intuitive interface for integrating hardware devices, APIs, and online services.

CAT-6 (Category 6) cable is a high-speed Ethernet cable designed for reliable data communication, offering higher bandwidth, reduced crosstalk, and faster transmission speeds compared to CAT-5e. It is widely used in SCADA systems, industrial automation, LAN networks, and data centers. The cable is constructed with four twisted pairs of wires (Blue, Orange, Green, and Brown) and includes a plastic spline separator to minimize interference between pairs. It is available with different jacket types such as PVC, FRLS, LSZH, outdoor PE, and armored variants to suit various environmental conditions. For industrial applications, copper conductors are recommended over CCA due to better performance and durability. In terms of specifications, CAT-6 supports a bandwidth of 250 MHz, delivers speeds up to 1 Gbps for distances up to 100 meters and up to 10 Gbps for distances up to 55 meters, uses RJ45 connectors, and has a maximum channel length of 100 meters, complying with TIA/EIA-568 standards (T568A/T568B).

CAT-6 cable is widely used in SCADA systems due to its strong noise immunity, particularly when shielded variants such as FTP and STP are employed. It ensures reliable communication between critical devices like PLCs, IEDs, and SCADA systems, supporting industrial communication protocols such as Modbus TCP, Profinet, Ethernet/IP, and OPC UA. Additionally, it is well-suited for long-distance

data transmission up to 100 meters without significant signal loss, making it ideal for large installations. Overall, CAT-6 provides robust, industrial-grade networking performance required for efficient and stable SCADA operations.
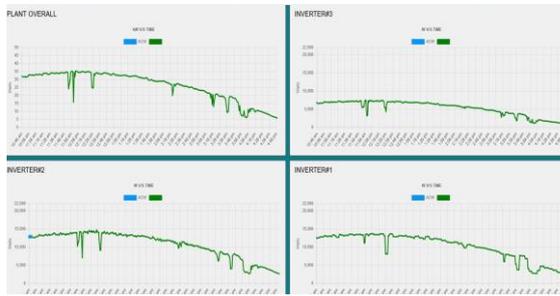

Fig. 3. Real time Trends in Various Sections

A typical CAT-6 installation in an industrial or SCADA environment follows a structured communication flow to ensure reliable data transfer. In one configuration, a PLC is connected via CAT-6 cable to a network switch, which then transmits data over fiber to the control room, where it is monitored through the SCADA system. In another setup, an RS-485 device communicates through a converter that translates signals to Ethernet, allowing connection via CAT-6 to a switch and then to the PLC. Additionally, for surveillance systems, an IP camera is connected using CAT-6 cable to a PoE switch, which supplies both power and data, and then links to an NVR for video recording and monitoring.

An RS-485 to Ethernet converter, commonly referred to as a Modbus RTU to Modbus TCP gateway, is a device that translates serial RS-485 communication into Ethernet-based communication. This enables field devices such as energy meters and sensors to interface seamlessly with PLC and SCADA systems over TCP/IP networks. In industrial applications, it plays a crucial role by transforming long-distance RS-485 signals into faster and more reliable Ethernet communication. It also allows PLC and SCADA systems to access Modbus RTU devices using the Modbus TCP protocol, thereby simplifying integration. Additionally, the use of such converters minimizes complex wiring requirements while improving overall system stability, making them highly suitable for connecting energy meters, sensors, and other industrial instruments.

The converter operates by translating RS-485 serial data frames into Ethernet TCP/IP frames, enabling seamless communication between serial devices and network-based systems. It typically supports Modbus gateway functionality, allowing bidirectional conversion between Modbus RTU and Modbus TCP protocols. In addition, it can function in multiple modes such as Virtual COM, TCP server, and TCP client, providing flexibility for different industrial communication setups. By utilizing Ethernet or fiber networks, the converter ensures stable, noise-resistant communication over long distances. In terms of features, the device is designed with an industrial-grade build, including surge protection and operation on a 24V DC power supply, making it suitable for harsh environments. It often includes multiple RS-485 ports for connecting several devices.

A network switch is a device used to connect multiple devices within a local area network (LAN), enabling efficient and reliable communication. It operates by using MAC addresses to ensure that data is transmitted only to the intended destination, thereby improving network performance and reducing unnecessary traffic. Network switches are widely used in industrial systems, office environments, and SCADA applications to provide stable, high-speed data transfer.

There are several types of network switches based on application and functionality. Unmanaged switches are simple plug-and-play devices suitable for small networks and basic SCADA panels. Managed switches offer advanced features such as VLAN, QoS, IGMP, and redundancy protocols like RSTP, PRP, and MRP, making them ideal for industrial automation and power systems. Industrial switches are specifically designed for harsh environments, featuring rugged metal enclosures, wide temperature tolerance, and DIN-rail mounting for use in PLC and SCADA systems. PoE (Power over Ethernet) switches provide both power and data through CAT-6 cables, commonly used for devices like IP cameras and WiFi access points.

In industrial and managed switches, important features such as VLAN (Virtual Local Area Network) allow network segmentation, helping to isolate different sections of the network for improved security, performance, and reliability.

In a typical industrial communication setup, PLCs or RTUs are connected to an industrial switch, which then transmits data over a fiber optic link to a main switch, ultimately reaching the SCADA server for monitoring and control. Energy meters are integrated into the system through an Ethernet switch, which communicates their data to the PLC. For surveillance, IP cameras are connected to a PoE switch that provides both power and data, and the video feed is sent to an NVR for recording and monitoring. Additionally, in large facilities, multiple buildings are interconnected through switches forming a fiber optic ring network, which links back to the control room switch, ensuring reliable and redundant communication across the entire system.

A Surge Protection Device (SPD) for RS-485 communication lines is essential for safeguarding serial communication equipment from transient overvoltages caused by lightning strikes, electrical faults, switching surges, and ground potential differences. It helps prevent damage to critical components such as sensors, energy meters, PLC communication ports, RS-485 converters, and other field devices. Since RS-485 networks often span long distances—up to 1200 meters—they are more susceptible to

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lightning-induced surges, especially when cables run outdoors or between buildings. Additionally, field panels are frequently exposed to electrical noise from motors, VFDs, and heavy loads, increasing the risk of voltage spikes. Sensitive devices like power meters, temperature sensors, and IEDs can be easily affected by such disturbances, making SPDs vital for improving reliability and extending equipment lifespan.

The SPD operates by being installed in series with the communication line, where it detects excessive voltage and safely diverts it to the earth ground. It effectively clamps the voltage to safe levels using fast-acting protective components such as TVS diodes, MOVs, and gas discharge tubes (GDTs). For optimal protection, SPDs should be installed at both ends of the RS-485 network—near the device and control panel—as well as at building entry points where cable routing changes, and close to RS-485 to Ethernet converters to ensure comprehensive protection across the communication system.

Node-RED is a flow-based visual programming platform originally developed by IBM that enables users to connect hardware devices, APIs, databases, and online services through an intuitive drag-and-drop interface. Running on Node.js, it is widely applied in IoT, automation, and industrial integration. It offers a browser-based flow editor, supports multiple protocols such as MQTT, Modbus, HTTP, TCP, OPC UA, and WebSocket, and can operate on platforms like Windows, Linux, Raspberry Pi, and servers. It also provides easy integration with PLCs, sensors, and cloud systems, along with a dashboard interface for web-based monitoring and control.

Node.js, built on Google Chrome's V8 engine, is a powerful JavaScript runtime that enables execution of JavaScript outside the browser, primarily for server-side applications. It is known for its event-driven architecture and non-blocking I/O model, which ensures high performance and scalability. With a vast NPM library ecosystem, Node.js is ideal for developing APIs, IoT gateways, and backend systems, and can run on cloud platforms, servers, and edge devices. Node-RED is built on top of Node.js, where Node.js provides the runtime environment, while Node-RED adds a graphical interface and prebuilt nodes, making the combination highly effective for developing IoT and industrial automation solutions.

MySQL is a widely used open-source relational database management system that operates using Structured Query Language (SQL). It is commonly implemented in web applications, industrial systems, SCADA data logging, IoT platforms, and enterprise-level software due to its efficiency, reliability, and strong community support. MySQL is designed to deliver high performance with minimal memory usage and can handle very large datasets containing millions of records. It is compatible with multiple operating systems

such as Windows, Linux, macOS, and cloud environments, and supports advanced features like replication, clustering, and high availability. Additionally, it integrates seamlessly with technologies such as Node-RED, Python, Java, C#, PHP, and PLC gateways.

In operation, MySQL organizes data into tables consisting of rows and columns, where SQL commands are used to insert, retrieve, and manage information. The database engine processes query efficiently, optimizing performance for fast data access. Data can be accessed through applications, APIs, or visualization dashboards, and the system includes essential capabilities such as backup and recovery, indexing, triggers, and stored procedures to ensure robust and reliable database management.

V. RESULTS

The system provides real-time monitoring of solar power generation along with key performance parameters, ensuring continuous visibility of plant operations. It automatically logs data into a MySQL database with accurate timestamps, enabling reliable record-keeping and analysis. A user-friendly dashboard displays both overall plant performance and detailed information for individual inverters, along with real-time trend charts that refresh automatically. The system supports comprehensive energy reporting on a daily, monthly, and yearly basis, with historical data available from 2015 onwards. Its modular architecture allows easy expansion by adding new devices, while dependable data acquisition is achieved using ATC-1000 Modbus converters.

Additionally, the platform includes interactive charts for energy comparison and performance evaluation, and the web-based dashboard can be accessed from any PC within the intranet. Users can retrieve historical data and export it to CSV or Excel formats for further analysis. The system is scalable, allowing future integration with weather sensors and DG monitoring, and ensures data reliability through automatic recovery during communication failures. The values of various parameters in Fig. 4 in the overview of the solar plant monitoring system.

Fig.4. Overview of Plant Monitoring System

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Fig.5. Data of Inverter 1 Monitoring System

Fig.6. Data of Inverter 2 Monitoring System

Fig.7. Data of Inverter 3 Monitoring System

It is designed for efficient operation with low system resource usage and quick response times as shown in Fig. 5,6 and 7. Being fully based on open-source software, it incurs no recurring license costs and can function effectively in both standalone and network-based environments.

VI. CONCLUSION

The developed Solar Power Plant Monitoring System successfullyautomates the performance tracking of the 50 kWp solar plant. Itoffers real-time data visualization, historical trend analysis, andreliable automatic data logging. The system enhances theoperational transparency of the plant while reducing manualintervention and maintenance efforts. The modular structure allowsfuture scalability with minimal modification.

The system functions within a secure local intranet environment without any external access, ensuring enhanced data protection and system integrity. The MySQL database can be configured to perform automatic daily backups, safeguarding critical information against data loss. The Node.js application is designed to restart automatically after a power failure, maintaining system continuity with minimal manual intervention. Additionally, access to the dashboard is restricted to authorized systems connected to the network, providing controlled and secure usage.

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