An Intelligent Inspection System for PV Power Generation Based on AIOT

Meng-Hui Wang*, Zong-Han Lin

ABSTRACT

The aim of this study is to develop a real-time operation monitoring and fault diagnosis system for solar photovoltaic power generation systems to improve their safety and stability. The study believes that the traditional method of periodic maintenance is no longer sufficient to meet the needs of the current energy shortage, and thus, the development of a real-time monitoring system is necessary to grasp the power generation situation in a timely manner, improve the stability of the power supply system, and prevent unexpected damage caused by system failures. The intelligent inspection technology developed in this study can monitor the electrical signals of the solar photovoltaic power generation system, and transmit the monitoring data to the MySQL cloud database for storage. It can also be monitored and analyzed in real-time by the online status intelligent monitoring data system developed in this study. Through the system developed in this study, the operation status monitoring and fault diagnosis of solar photovoltaic power generation systems can be achieved, improving the reliability and stability of the system, and meeting the needs of modern energy development.

Keywords: Solar Photovoltaic Power Generation System, Intelligent Inspection System, Internet of Things (IoT), Programmable Logic Controller (PLC), Human-Machine Interface.

I. INTRODUCTION

In recent years, there has been an increasing frequency of extreme weather events worldwide, leading to governments around the world actively seeking to reduce greenhouse gas emissions. The 26th Conference of the Parties to the United Nations Framework Convention on Climate Change adopted a new agreement known as the "Glasgow Climate Pact," which calls for limiting the global average temperature increase to within 2 degrees Celsius. To achieve this goal, countries are investing in renewable energy, particularly solar and wind power between 2020 and 2030, it is projected that there will be an annual addition of 630 GW of solar photovoltaic capacity and 390 GW of wind power capacity, a fourfold increase compared to the levels in 2020. The global energy demand proportion has been reduced by 8%, with approximately 90% of electricity generation coming from renewable sources. The aim of this initiative is to achieve global decarburization within a short period of 30 years [1].

In our country, there are four main directions in energy transition: reducing coal consumption, increasing natural gas usage, promoting renewable energy, and establishing a nuclear-free homeland. Among these, solar photovoltaic and wind power are the primary renewable energy generation methods being promoted. It is projected that by 2025, the installed capacity of solar photovoltaic systems will reach 20 GW, and offshore wind turbines will have an installed capacity of 5.7 GW [2]. Energy security, green economy, environmental sustainability, and social equity are the core values of our country's energy transition. To achieve sustainable development goals, the government has launched several related initiatives. For example, the two-year plan for solar photovoltaic power generation aims to install solar photovoltaic systems on rooftops or idle spaces of public facilities to achieve the 20 GW installation target by 2025 [3]. In light of the global nuclear disaster incidents [4], our country has reassessed the positioning of nuclear energy and advocated for a nuclear-free homeland. Green nurturing of nuclear power has become one of the important goals in Taiwan's energy development [5].

According to domestic reports on renewable energy accidents, the main causes of solar photovoltaic (PV) power generation accidents include inverter failures, damage and contamination of PV modules, components of the AC/DC distribution panel, and detachment of PV array circuits [6]-[7]. Among them, construction deficiencies and product defects account for 38% and 35% respectively. In terms of product defects, most of them are due to loose circuits or improper wiring [8], and inspection patrols are currently a commonly used solution. Therefore, we propose an intelligent remote inspection method that enables rapid maintenance of solar PV power plants, aiming to reduce operational costs.

Today, the maintenance of green energy power plants has evolved from traditional post-maintenance or regular inspections to proactive maintenance, which involves

Corresponding Author: Meng-Hui Wang (E-mail: wangmh@ncut.edu.tw).
Zong-Han Lin (E-mail: 4b012120@gm.student.ncut.edu.tw)
Department of Electrical Engineering, National Chin-Yi University of Technology, 57, Sec.2, Chung Shan Rd., Taichung, 106, Taiwan.

developing comprehensive maintenance strategies through real-time monitoring of equipment. By developing an efficient intelligent inspection technology for solar photovoltaic (PV) power systems and utilizing the high-speed and low-latency transmission of 5G [9]-[10] along with intelligent edge computing platforms, regular inspection procedures can be conducted. This approach not only ensures the safety of solar PV power systems but also significantly reduces labor costs [11]. Since solar PV power systems are often installed in open and unobstructed areas, they are susceptible to weather conditions, especially during typhoons. Factors such as insufficient structural strength, loose screws, and corrosion of the support structure can also lead to accidents. Therefore, a support structure strength warning system is also an important research topic within the intelligent inspection system.

II. Analysis of Fault States in Solar Photovoltaic Systems

In the current global context, where countries around the world are increasingly emphasizing the development of green energy, solar photovoltaic power generation has emerged as an environmentally friendly and renewable energy source, attracting the attention of many nations for promotion and development. However, due to limited manpower resources for operating and maintaining solar photovoltaic systems, effectively utilizing intelligent systems for the maintenance of solar photovoltaic power generation has become an important issue for improving efficiency.

Analyzing the failure data of solar photovoltaic systems domestically and internationally further confirms the significance of this issue. According to a report by TÜV Rhineland Energy, the causes of fire incidents in solar photovoltaic power generation systems are distributed [12] as shown in Figure 1. Among the main causes of accidents resulting from fire incidents in solar photovoltaic systems, installation errors (38%) and product failures (35%) together account for seventy percent of the fires. This indicates that the majority of the incidents are caused by the failure of maintenance and inspection work by operation and maintenance personnel.

According to reports on renewable energy power generation accidents in the country, the causes of fire incidents in solar photovoltaic power plants are distributed [6]-[7] as shown in Figure 2. The largest proportion of failures in solar photovoltaic systems is attributed to inverters (37%), followed by damages to solar photovoltaic modules (29%), AC/DC distribution panel components (11%), loose connections (5%), and others (9%). To improve the impact of system failures in current solar photovoltaic power plants, all of the aforementioned issues need to be addressed.

Therefore, regarding the maintenance of solar photovoltaic power generation systems, this paper focuses on exploring the application of effective and safe detection methods. By utilizing an intelligent inspection and monitoring system, real-time monitoring and fault warning of solar photovoltaic power plants can be achieved, assisting operation and maintenance personnel in prompt response and handling, thereby improving the efficiency of solar photovoltaic power generation systems.

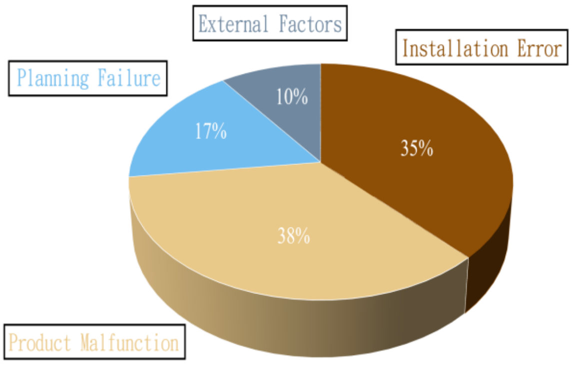

Figure 1 Distribution Map of Solar Photovoltaic Fire Incidents in Germany

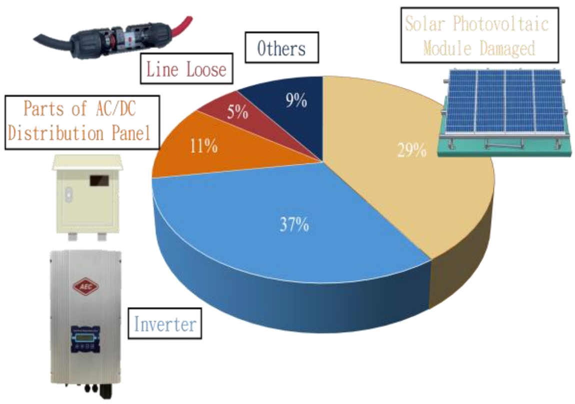

Figure 2 Domestic Solar Photovoltaic System Fault Distribution Chart

III. Research System Architecture

In this study, a solar power generation system was used for experimental testing, and an online condition monitoring data platform was established. The platform consists of four main components. The first component is the solar power generation testing platform and PLC for reading electrical signals, which is used to collect real-time operational data of the solar power generation system. The second component is the LabVIEW remote graphical control system and electrical signal transmission, which is responsible for transmitting electrical signals and monitoring the real-time performance of the solar power generation system. The third component is the IoT smart cloud remote monitoring system, which uploads the collected data to the cloud for analysis, allowing for a better understanding of the operation of the solar power generation system. The fourth component is the solar panel mounting structure monitoring system, which monitors the operation of the solar panel mounting structure to ensure the stable operation of the solar power generation system. For detailed descriptions of the four components mentioned above, please refer to Figure 3.

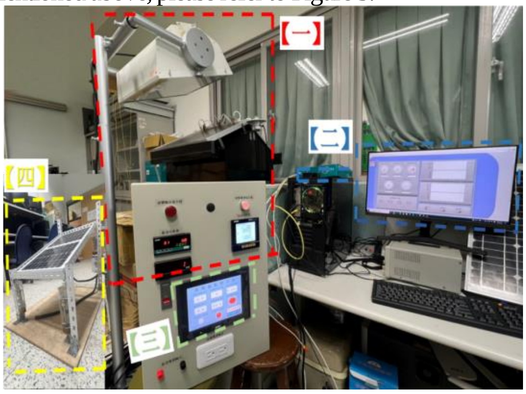

Figure 3 Online Status Smart Monitoring Data Platform

This article describes the architecture of a monitoring system for operational status, as shown in Figure 4, which can effectively detect the operational status of solar power generation systems. The entire system is primarily divided into four main components, including the solar power generation measurement platform and PLC signal acquisition, LabVIEW remote graphical control system and signal transmission, Internet of Things smart cloud monitoring system, and solar panel mounting monitoring system.

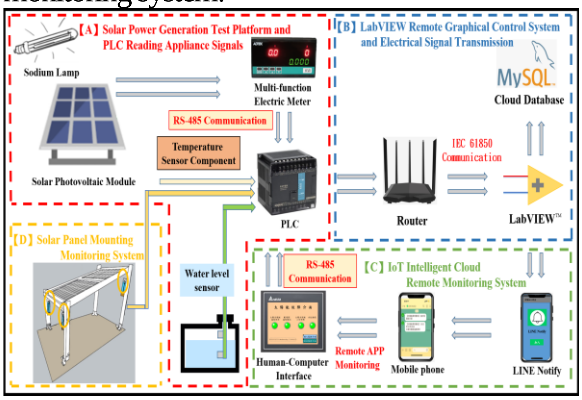

Figure 4 Architecture of Operation Status Monitoring System

3.1 Solar Power Generation Testing Platform and PLC Reading Appliance Signals

As shown in Figure 4, Block A is a solar photovoltaic power generation test platform. The platform uses sodium lamps to simulate sunlight irradiation and uses a multifunctional meter to read various electrical equipment data, transmitting the signal to the PLC controller for monitoring and control. The platform uses PT100 temperature sensing elements for solar photovoltaic module temperature detection. When the temperature is abnormal, a water pump motor with a high-pressure nozzle is used for spraying the module to reduce temperature and extinguish fires. In addition, the regular cleaning function is also available to solve problems caused by foreign objects and excessive dust accumulation on the modules, thereby improving the efficiency of solar photovoltaic module power generation.

To prevent accidents such as motor idling or burning due to low water level or water outage, the system uses a water level sensor to monitor the water level, adjusting the motor pumping status according to the high or low water level of the water tank. In addition, the temperature inside the distribution box and the arc monitoring of the solar inverter are also collected and analyzed. Once an abnormality is detected, a carbon dioxide fire extinguisher is immediately used to extinguish the fire, thereby protecting the equipment and items. Compared with other types of fire extinguishers, carbon dioxide does not leave residue, does not have corrosiveness, and has less impact on the environment, making it very suitable for use in computer rooms and places for storing valuables.

3.2 LabVIEW Remote Graphical Control System and Electrical Signal Transmission

As shown in Figure 4, Block B consists of the LabVIEW remote graphical control system and the Ethernet PCT/IP protocol electrical signal transmission system. Through this system, data on power generation and operational status can be accurately read and monitored. Additionally, this data can be uploaded to a MySQL cloud database for storage and management, enabling real-time tracking and visualization of the system's operational status. The system also incorporates an important functionality, which is the feedback of actual operational data to the PLC controller to achieve corresponding control actions. For instance, when the system temperature exceeds a certain threshold, the PLC controller can receive relevant information in a timely manner and implement control strategies such as watering for cooling, thereby reducing the risk of system failures and extending the lifespan of the solar photovoltaic system.

3.3 IoT Intelligent Cloud Remote Monitoring System

As shown in Figure 4, Block C represents the Internet of Things (IoT) smart cloud remote monitoring system, which enables real-time monitoring and centralized management through an app-based human-machine interface. This system significantly reduces the manpower costs associated with inspections. Furthermore, the system can connect to the LINE Notify alert status feature through LabVIEW remote graphical control system, allowing abnormal system signals to be sent to the mobile phones of maintenance personnel, enabling them to promptly receive notifications and facilitate troubleshooting and maintenance.

The system consists of three layers: the perception layer, the network layer, and the application layer. The first and second layers are responsible for collecting and transmitting sensor data, while Block Three serves as the core of the system, responsible for remote monitoring and management. By utilizing an app as the remote human-machine interface, the operation becomes more convenient and intuitive, providing the ability to monitor the system's operation status and data, as well as perform control and settings.

The system also incorporates an alert function. When the system encounters abnormal conditions, the LabVIEW remote graphical control system will send alert messages to LINE Notify, notifying maintenance personnel to take appropriate actions. This enables prompt response and troubleshooting, reducing system downtime and maintenance costs while enhancing system reliability and stability.

3.4 Solar Panel Mounting Monitoring System

As shown in Figure 4, Block D of this study developed a solar photovoltaic panel mounting structure monitoring platform to ensure the normal operation of the solar power generation system. Water level sensors were placed around the solar panel mounting structure, as shown in Figure 5, to monitor the integrity of the structure. This enables the timely detection of any abnormal conditions, such as tilting or instability of the mounting structure, ensuring the safe operation of the system.

The monitoring platform implemented in this study utilizes water level sensors to achieve high reliability and precision in monitoring the solar photovoltaic panel mounting structure. When abnormal horizontal alignment of the structure is detected, the monitoring platform immediately triggers an alarm and notifies relevant personnel for inspection or repair. Additionally, the monitoring platform records the operational status of the mounting structure for subsequent analysis and optimization.

The solar photovoltaic panel mounting structure monitoring platform developed in this study enhances the stability and safety of the system, while also improving monitoring and maintenance efficiency. This is of significant importance for the long-term stable operation and sustainable development of solar power generation systems.

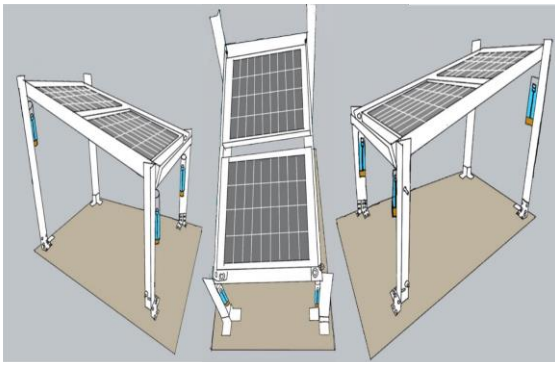

Figure 5 Design of Mounting Bracket Perspective View

IV. Experimental Results and Discussion

The proposed method in this paper enables effective condition monitoring of solar photovoltaic power generation systems. Therefore, an experimental platform for solar photovoltaic power generation systems was established in this study. In addition to the on-site human-machine interface for operational personnel, remote monitoring can also be carried out through a smartphone application system. Furthermore, this paper constructs a remote communication framework using Modbus TCP and RS-485 protocols and integrates all the monitoring systems to form an integrated solar photovoltaic power generation intelligent monitoring system. The functionalities of the developed solar photovoltaic power generation intelligent monitoring system are described below:

A. On-site and Remote Human-Machine Interfaces

In order to allow maintenance personnel of the solar photovoltaic power generation system to have real-time access to system status information, a human-machine interface has been designed in this system. By using a mobile app, users can remotely monitor the operating status and power generation of the solar photovoltaic power generation system, as well as perform manual cleaning and other controls. If any abnormality occurs in the equipment, the system will notify the relevant maintenance personnel through the LINE Notify alarm function. The design of this interface is shown in Figures 6 to 11. The interface for remote monitoring through the mobile app is shown in Figure 12. The solar photovoltaic system status information provided by this interface includes the generated voltage, load current, and power generation.

Figure 6 System Homepage

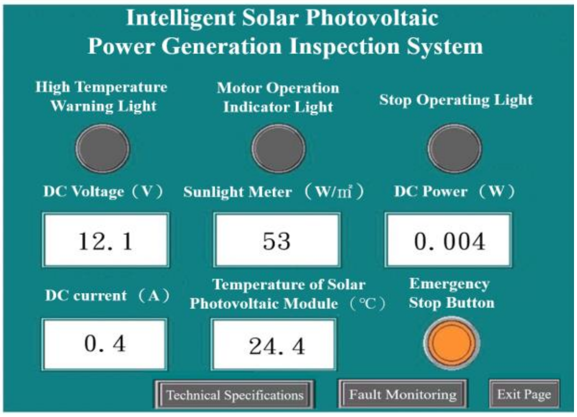

Figure 7 Solar Photovoltaic Power Generation Monitoring Interface

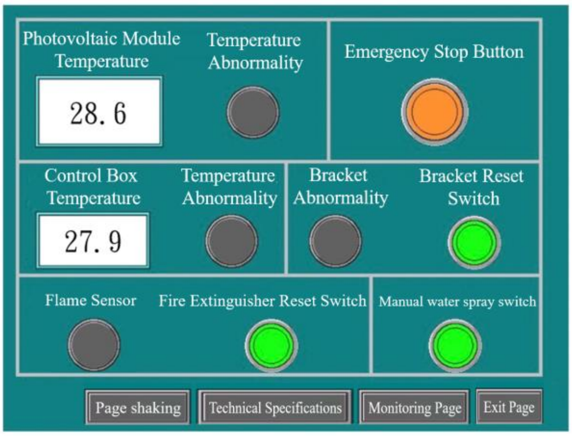

Figure 8 Solar Photovoltaic Power Generation Control Interface

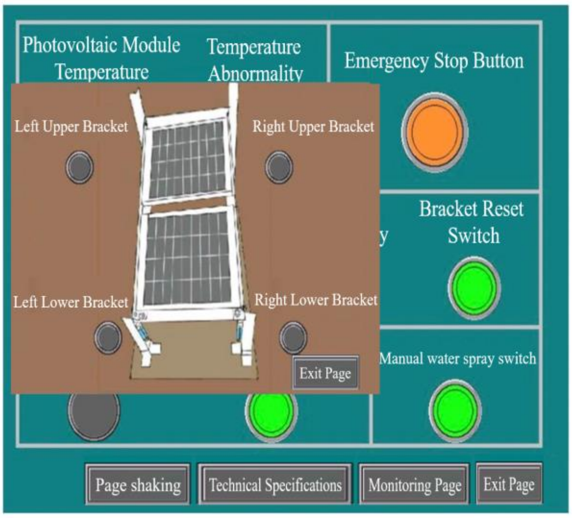

Figure 9 Solar Photovoltaic Mounting System Vibration Monitoring Interface

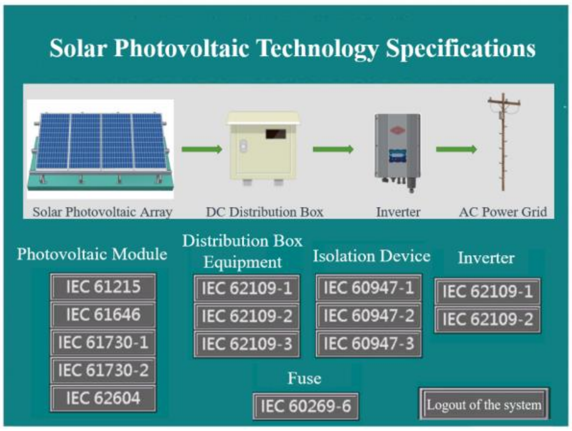

Figure 10 Solar Photovoltaic Technology Specifications Page

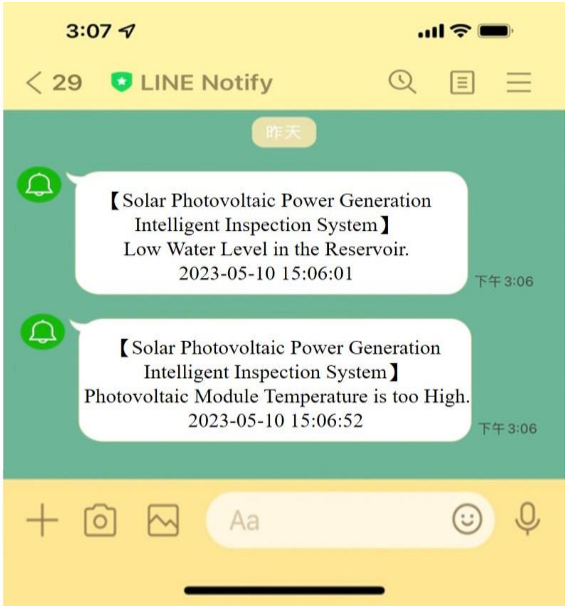

Figure 11 Warning Status Message Alert

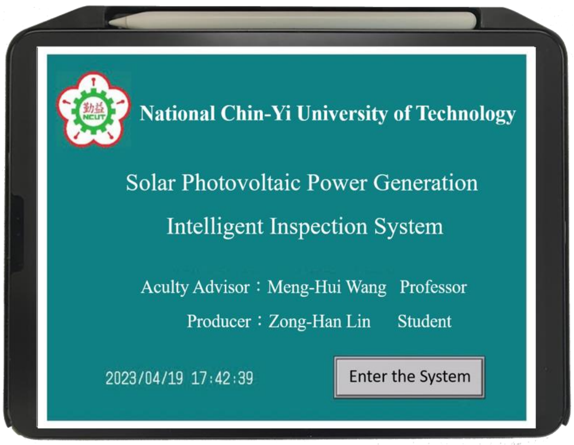

Figure 12 Mobile App System

B. LabVIEW Detection and Monitoring System Interface

The intelligent inspection technology for solar photovoltaic power generation system developed in this thesis utilizes LabVIEW graphical interface software to create a remote graphic control system, as shown in Figures 13 to 14. Figure 13 presents various status monitoring interfaces of the system. By monitoring the basic electrical signals of the solar photovoltaic power generation system, including voltage, current, power, temperature, solar radiation, and real-time messages of the solar photovoltaic module array, the system achieves monitoring capabilities. Block A in Figure 13 displays various basic signals of the solar photovoltaic module array. Block B shows the interface for monitoring the support structure and various indicator lights. Block C contains various buttons, such as the manual water spray switch, support structure reset switch, fire extinguishing system switch, and emergency stop button.

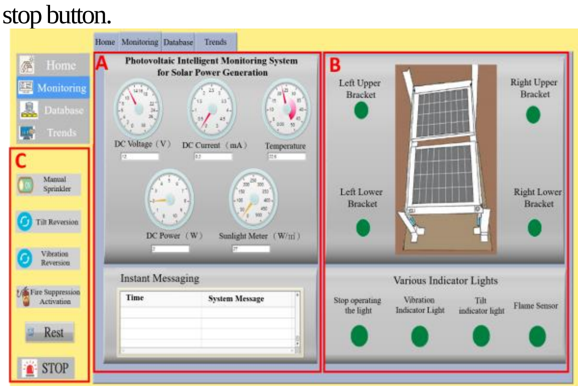

Figure 13 Solar Power Generation Operation Status Monitoring Interface

Figure 14 displays the database query interface of our system, which provides a clear representation of the historical data regarding solar photovoltaic power generation. Users can input specific criteria to retrieve relevant historical information, facilitating maintenance personnel in conducting regular maintenance and troubleshooting more effectively. Additionally, this interface enables the scheduling of necessary maintenance tasks while the solar power generation system continues to operate, ensuring uninterrupted system functionality.

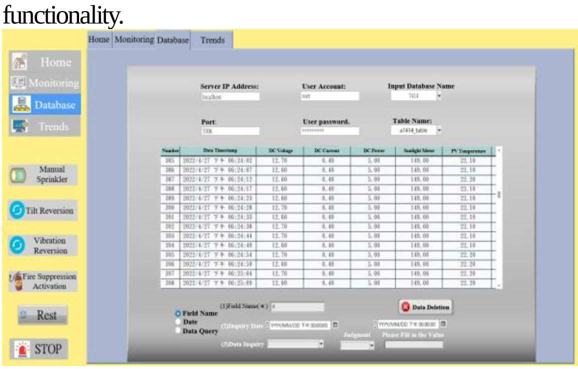

Figure 14 MySQL Database Query Interface

Figure 15 shows the database query interface of our system, which provides a clear display of the historical information of the solar photovoltaic (PV) power generation system. Users can input specific conditions to query relevant historical data, which helps maintenance personnel to perform regular maintenance and troubleshooting more effectively. Additionally, this interface enables the scheduling of necessary maintenance and repairs while the solar PV system continues to generate power, ensuring uninterrupted operation of the system.

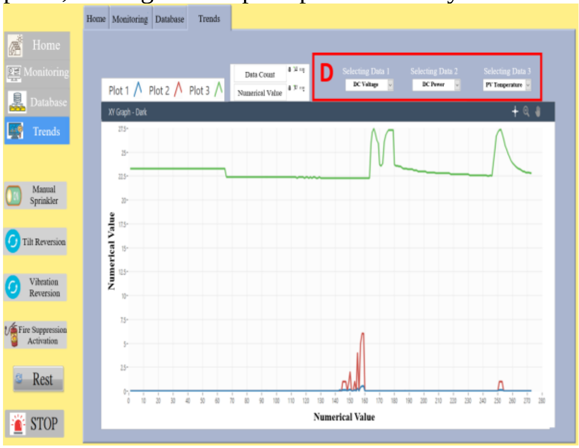

Figure 15 Solar Power System Electrical Signal Trend Chart

V. CONCLUSIONS

The main research focus of this study is the development of an intelligent inspection technology system for solar photovoltaic power generation systems, which includes a real-time condition monitoring and detection system for solar photovoltaic systems. The research primarily focuses on online state-of-health monitoring data, specifically real-time remote monitoring of the operation status of solar photovoltaic systems. Through a series of planned performance tests described in this paper, the research findings can be summarized as follows:

A. This paper establishes a solar photovoltaic system experimental platform and a state monitoring system, in which the signal acquisition and measurement system are primarily controlled and monitored using a PLC. Through the integration of the on-site human-machine interface terminal and the online LabVIEW software, it can be used as a monitoring and operating device for the entire system. Additionally, a multi-functional meter collection meter is installed at the on-site end to read relevant electrical data, which is then connected to the PLC via Modbus TCP and RS-485 communication methods. As a result, not only does it enhance the operational safety of the solar photovoltaic system, but it also enables round-the-clock monitoring of the system and improves operational and maintenance efficiency.

B. The present study focuses on the continuous monitoring of electrical signals, utilizing a MySQL database to access and store large-scale data. In the event of system anomalies, a remote monitoring human-machine interface (HMI) is employed to display real-time notifications, ensuring prompt response from the maintenance personnel to address any incidents that may occur at the solar photovoltaic power plant.

ACKNOWLEDGMENTS

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Meng-Hui Wang is a Distinguished professor at National Chin-Yi University of Technology, and his major areas of research include renewable energy systems, power systems, extension theory, and AI applications.

Zong-Han Lin is a student at National Chin-Yi University of Technology, and his major areas of research include renewable energy systems, interests include artificial engineering and fault diagnosis.