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RESEARCH ARTICLE

Design Integration of SCADA, PLC, and IoT Systems for Optimizing Solar Photovoltaic Power Plant

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Abstract

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This study discusses the integration of Supervisory Control and Data Acquisition (SCADA), Programmable Logic Controller (PLC), and Internet of Things (IoT) systems to optimize the operation of photovoltaic solar power plants (PLTS). By implementing three main operating modes: Battery to PLC, PV to PLC, and Utility to PLC, the proposed system can improve energy management efficiency, system reliability, and power management flexibility. Battery to PLC mode allows optimal use of battery power when solar energy sources are limited, such as during rainy conditions or at night. PV to PLC mode maximizes the use of solar energy during the day when there is an abundant solar energy source. Utility to PLC mode maintains the continuity of electricity supply from the PLN network when energy from batteries and solar panels is insufficient. These three operating modes create a very beneficial system for its users because it can complement all the shortcomings of conventional solar power generation systems. IoT integration also provides added value in predictive maintenance, reducing operational costs and minimizing the risk of system failure. In addition, IoT integration also makes this system perfect, with remote monitoring that can provide benefits for users, namely time efficiency and ease of system control. The test results show that the integration of SCADA, PLC, and IoT can handle large data volumes and is adapted for larger generating capacities. From an environmental perspective, using this system reduces carbon emissions by maximizing renewable energy. This study provides a framework for applying more efficient and environmentally friendly technologies in renewable energy management. This research can help the development of solar power generation systems that use clean energy sources to be developed further.

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Introduction:

Global demand for renewable energy, primarily Solar Photovoltaic Power Plants (PV), continues to increase as part of efforts to reduce the negative impacts of climate change and dependence on fossil fuels. Solar energy is recognized as a sustainable energy source. It has excellent potential to provide clean energy, especially in areas with high sunshine intensity, such as Peru, which has around 300 sunny days yearly [1]. Despite economic challenges, global renewable energy capacity continues to increase significantly. According to the International Renewable Energy Agency (IRENA) report, global renewable energy capacity increased by more than 260 GW in 2020, around 50% compared to the previous year [2]. However, operational efficiency and maintenance of PV are still significant challenges that must be overcome. The application of advanced technology and appropriate control systems is required to optimize PV performance. For example, an automatic solar tracking system can increase energy capture by up to 20% [3]. Overcoming these operational challenges is crucial so that PV can sustainably meet the increasing energy needs of the system [4].

One of the technologies that can be utilized to increase efficiency is SCADA (Supervisory Control and Data Acquisition), which is vital in monitoring and controlling Photovoltaic Solar Power Plants (PLTS) in real time. SCADA allows data collection from various components in PLTS so that operators can monitor overall conditions, from energy output to solar module status. This capability will enable operators to respond quickly to problems and maintain optimal PLTS performance. Research shows that implementing a SCADA system can significantly improve PLTS operational efficiency through effective data visualization and appropriate control strategies [5]. SCADA also enables the implementation of advanced monitoring techniques to enhance decision-making and operational efficiency, ultimately maximizing energy production [5],[6].

In addition to SCADA, PLC (Programmable Logic Controller) plays a crucial role in PLTS automation by controlling physical equipment such as inverters and motors. A well-designed PLC program can adjust PLTS operations responsively to changes in the environment and electrical loads, thereby increasing operational efficiency. Research shows that PLCs can streamline processes and improve reliability in solar power generation, especially in dynamic conditions that require rapid adjustments [7].

This adaptability is essential to maintain high energy output levels and the longevity of solar energy production equipment [7]. Furthermore, the potential of IoT (Internet of Things) in optimizing PLTS is also increasingly prominent. IoT technology allows various devices in PLTS to be connected to the internet, facilitating remote monitoring and more profound control. With this connectivity, deeper data analysis and predictive maintenance can be performed, allowing the identification of potential problems before they cause significant damage [7],[8]. IoT in photovoltaic systems has improved performance monitoring, impacting energy management and operational efficiency [7],[8]. By leveraging IoT, operators can ensure that solar panels operate at maximum efficiency, reduce downtime due to maintenance issues, and increase overall energy output [7],[8].

Integrating SCADA, PLC, and IoT technologies in Solar Photovoltaic Power Plant (PLTS) systems is key to improving operational efficiency and energy management. SCADA enables real-time monitoring and control, accelerating response to potential problems, while PLC ensures adaptive automation to environmental changes and electrical loads. On the other hand, IoT provides more efficient remote monitoring and predictive maintenance opportunities, thereby preventing significant breakdowns and reducing downtime. With the adoption of these technologies, PLTS can operate optimally, maximize energy output, and support the transition to more sustainable renewable energy [5],[6],[7],[8].

Integrating SCADA, PLC, and IoT systems in Solar Power Plants (PLTS) presents complex challenges related to coordination between hardware and software and data security. Effective coordination is needed to ensure these three systems work synergistically and optimize operational efficiency and reliability. Complex system architectures often become obstacles in integration, especially ensuring smooth communication between components. The complexity of modern software applications can also exacerbate operational inefficiencies if integration is not done correctly ("Innovative SCADA-Based Oil Refinery Control with Arduino Integration Using Labview", 2023; Tükez & Kaya, 2022). In addition, the implementation of IoT increases the risk of cyber attacks, so the system needs to be designed with strong security protocols to protect critical infrastructure. Dynamic IoT data requires continuous monitoring and the development of adaptive security protocols to prevent operational disruptions and adverse impacts on the reputation of renewable energy systems [9]. Therefore, overcoming these integration and security challenges is the key to implementing SCADA, PLC, and IoT systems in PLTS.

Supervisory Control and Data Acquisition (SCADA) systems are crucial in energy management, especially in renewable energy applications such as solar power plants (PV). SCADA is an industrial control system that enables monitoring and control of large-scale infrastructure, including power plants and distribution networks. In the context of PV, SCADA collects and analyzes data from various components, such as solar panels and inverters, to ensure optimal operational performance and efficiency [10],[11]. The system also monitors other vital parameters, including weather conditions, module temperature, and network status, which affect the PV output and overall plant performance [11],[12]. The implementation of SCADA in PV improves operational efficiency through advanced monitoring capabilities. Studies have shown that SCADA enables the tracking of critical parameters essential for predicting PV output more accurately. With proper data integration, SCADA helps operators make more informed decisions regarding energy production and management, improving overall performance [13],[14]. SCADA's ability to monitor real-time conditions also enables better management in the face of changing environmental conditions and electrical loads.

In addition, SCADA offers significant advantages in renewable energy management through its remote monitoring capabilities. This feature allows operators to quickly identify and resolve issues, reduce downtime, and increase plant productivity [11],[13]. The ability to continuously monitor energy production and operational status improves efficiency and contributes to energy security by ensuring that potential issues are detected and addressed promptly [11],[15]. In addition, integrating SCADA with other technologies, such as IoT and machine learning, optimizes energy management through predictive maintenance and real-time data analytics [16].

Programmable Logic Controllers (PLCs) are essential in operating and managing solar power control systems, especially in solar power plants (PLTS). PLCs are electronic devices designed to automate industrial processes, allowing the integration of various components in solar energy systems, such as solar panels and inverters, automatically and efficiently. PLCs facilitate increased operational efficiency and reliability, essential to maximizing energy production from solar sources [17],[18]. In the context of PLTS, PLCs are used to control the electricity generation process by adjusting the position of the solar panels through a tracking system, which adjusts the angle of the panels to receive sunlight optimally throughout the day. This capability significantly increases the energy output of photovoltaic (PV) systems, with studies showing that solar tracking systems can increase energy capture efficiency by up to 40% compared to fixed installations [19],[20]. PLCs also maintain the stability of the voltage and current generated, ensuring that the power output meets the standards required for integration into the grid or local consumption [21].

The advantages of PLC in PV systems include high execution speed, ease of programming, and good resilience in industrial environments. PLCs are designed to adapt quickly to changing operational conditions and can withstand harsh environmental conditions, providing critical durability and reliability to maintain continuous operation [22]. Integration of PLC with Supervisory Control and Data Acquisition (SCADA) systems further enhances its functionality, enabling real-time monitoring and control of solar energy systems [18]. It allows operators to make more informed decisions based on data collected from various sensors, thereby improving energy management and operational efficiency [23]. The implementation of PLC in solar power control systems also contributes to the sustainability of energy production by optimizing solar panel performance and reducing energy waste, which is critical as the demand for renewable energy sources continues to grow in response to environmental concerns and the need for sustainable energy solutions [24],[25]. Overall, the role of PLC in solar power control systems is critical to improving the efficiency, reliability, and sustainability of solar energy production. Its ability to automate processes, optimize energy output, and integrate with advanced monitoring systems underscores the importance of PLCs in the renewable energy sector.

The Internet of Things (IoT) plays a key role in monitoring and optimizing solar power plants (PLTS) by connecting devices via the Internet to enable real-time data exchange. This technology allows for remote monitoring of the performance of solar panels, inverters, batteries, and other components by collecting and transmitting data to a control center or cloud [7]. With critical data such as voltage, current, and light intensity collected and analyzed, IoT helps optimize energy output and ensures the effective functioning of solar power infrastructure [26],[27]. Studies have shown that IoT integration can improve data collection efficiency, enable system adjustments based on environmental conditions, and optimize the use of generated energy [26],[28].

A significant advantage of IoT in PV systems is the ability to perform predictive maintenance by continuously analyzing sensor data. It allows the detection of potential problems before they develop into severe damage, which reduces operational costs and minimizes downtime [7]. For example, monitoring photovoltaic panels can detect inefficiencies due to environmental factors such as dust or shading [7]. In addition, IoT allows dynamic adjustment of energy production strategies based on weather patterns and other external factors, as well as optimizing panel angles to maximize sun exposure [29]. The flexibility and capabilities of IoT in energy management increase the operational efficiency and sustainability of solar power systems, as well as support effective energy utilization and waste reduction [30].

Optimization of Solar Power Plants (PLTS) is essential to increase the contribution of renewable energy in the national energy mix and support energy sustainability goals. The use of advanced technologies such as SCADA, PLC, and IoT allows for the maximization of PLTS operations, thus supporting the efficiency and effectiveness of the system as a whole. The integration of this technology not only plays a role in maximizing PLTS performance but is also expected to reduce operational costs through increased efficiency, predictive maintenance, and reduced downtime. Thus, this integrated system provides excellent economic value for operators and energy consumers, contributing to developing more sustainable and efficient renewable energy.

This study aims to design a practical integrated system design for integrating SCADA, PLC, and IoT in a photovoltaic solar power plant and to improve the operational efficiency of the solar power plant through these technologies. This study aims to develop an optimal communication structure and data flow between the three systems and identify methods to utilize the capabilities of each system to improve real-time monitoring, automatic control, and data analysis, with the ultimate goal of improving the performance and energy efficiency of the solar power plant.

2. Materials and Methods

In this section, the methodology will explain how the tool system used in this research works and the process carried out, which can be seen in Figure 1. It shows the work process in the system in this research, which has four inputs, and then two processes occur until the output from this system can be produced. Figure 2. shows the flow of the research carried out, which is divided into five parts: first, preliminary study; second, Objectives; third, research location; fourth, system design and monitoring; and finally, final output. Then, several parts will be emphasized in this methodology, which will be divided into the following paragraphs;

2.1 Literature Review

A literature review was conducted to understand the concepts and applications of SCADA, PLC, and IoT in the context of photovoltaic solar power plant management. This activity involved gathering literature from various scholarly journals, textbooks, articles, and credible online sources related to control and monitoring technology in renewable energy. The research team conducted in-depth discussions and analyses to build a solid theoretical framework and identify relevant technological solutions.

2.2 System Integration and Design

The integration design of SCADA, PLC, and IoT was developed to create a unified system that optimizes PV solar power plant operations. This phase includes:

- Needs Analysis: Identifying system requirements, including technical specifications for SCADA, PLC, and IoT devices.
- System Architecture Design: Developing a system architecture that outlines interactions between SCADA, PLC, and IoT. This includes communication schemes, data flow, and user interfaces.
- Prototype Implementation: Building an integrated system prototype for preliminary testing, including the hardware and software to test the system design.

2.3 System Testing and Evaluation

System integration testing was conducted to ensure the performance and reliability of the proposed design. This phase includes:

- Functional Testing: Testing the system to verify that all SCADA, PLC, and IoT components function as designed, covering real-time monitoring, automated control, and data analysis.

- Performance Evaluation: We analyzed test results to evaluate the system's operational efficiency and reliability. Test data were collected and analyzed to identify areas for improvement.
- Documentation of Results: Preparing detailed documentation of the test results, including a comprehensive report on system performance and recommendations for further improvements. The research findings will also be structured in a paper tailored for publication.

2.4 Report Preparation and Evaluation

All stages of the research, from literature review, design, testing, and evaluation, will be compiled into a comprehensive final report. This report will cover the methodology, test results, data analysis, and practical implementation recommendations. The research findings will also be published as a scientific paper for dissemination within the academic and professional renewable energy technology community. The proposed system design and test results will provide an overview of SCADA, PLC, and IoT integration in optimizing PV solar power plant operations.

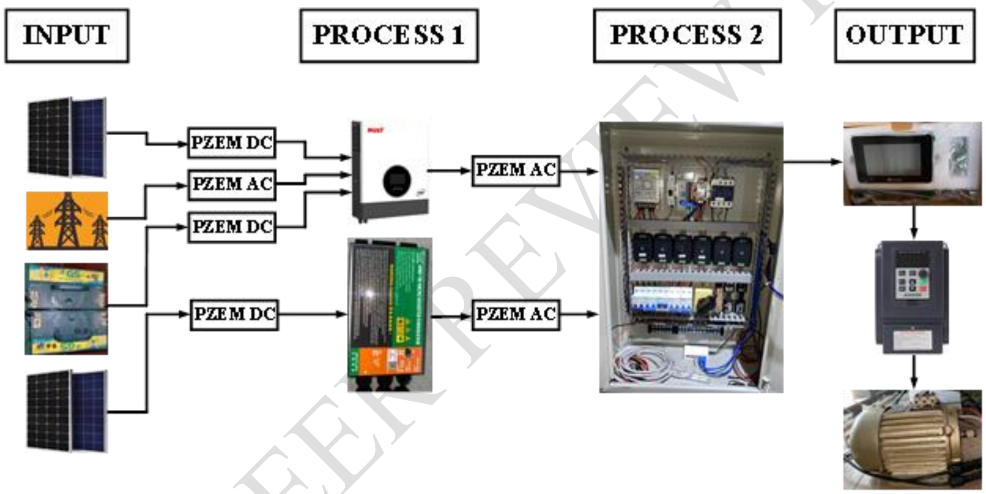

Figure 1. Integration Design of SCADA, PLC, and IoT Systems for Optimizing Solar Photovoltaic Power Plant Operations

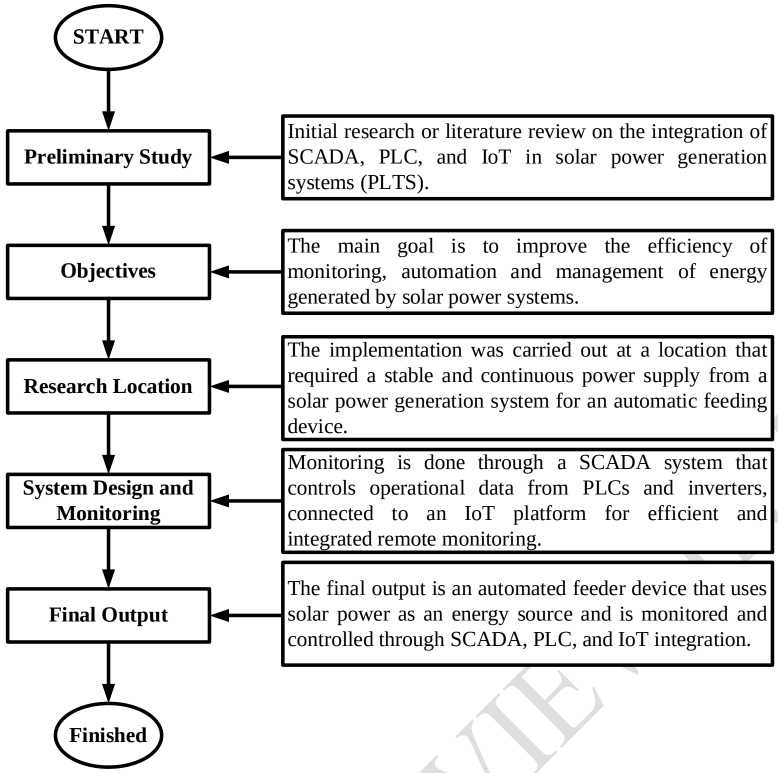

Figure 2. Research Flow Chart Diagram

2.5 Component and Program

Once it is known that the system plan will be like Figure 1, then it will be determined for all the components used and the values used for the tool construction plan in the field, which can be seen in Table 1, which displays all the tool components used to assemble the system carried out in this study.

Table 1. Components Specification

Component	Specifications
PV (Photovoltaic)	- 550 Wp x 2 (Seri 2)
	- Monocrystalline: Surya Chint Astro 5 Energy / JA Solar
Battery	- 2 x 12V/100AH
Hybrid Inverter	- 5.5KW/48V MUST PV1800VHM (145 Vdc)
Inverter (1 Phase to 3 Phase)	- Input: 1PH 176-264V, 50/60HZ
	- Output: 3PH 0-220V, 1.5KW, 8.2A
	- Frequency Range: 0.01-400HZ
Photovoltaic On-Grid	- Maximum Power (Pmax): 100W
	- Voltage at Pmax (Vmp): 18.6V

	- Current at Pmax (Imp): 5.37A
	- Open-Circuit Voltage (Voc): 22.8V
	- Short-Circuit Current (Isc): 5.71A
On-Grid Inverter	- AC Output Voltage: 180-280VAC
	- PV Input Voltage: 18-50VDC
	- Maximum Input Power: 260W
	- Rated Output Power: 250W
	- AC Frequency: 47.5Hz-52.5Hz / 57.5Hz-62.5Hz
Motor 3 Phase Asynchronous	- Voltage: 380V
	- Current: 1.08A
	- Speed: 1400 RPM
	- Frequency: 50Hz
	- Power: 1/2 HP
	- Noise Level: 70 dB(A)
HMI	HMI Haiwell 4,3 inch
PLC	PLC Haiwell AC10S0R
Sensor AC	PZEM 016 + CT
Sensor DC	PZEM 017 + Shunt
MCB AC + DC	-MCB AC 6A 2P
	-MCB DC 32A 2P

Knowing all the components will make assembling the system in the field easy. After collecting the components and assembling the system in the field, the next thing to do is program the SCADA as the central control. Figure 3 shows a program made according to the user's wishes.

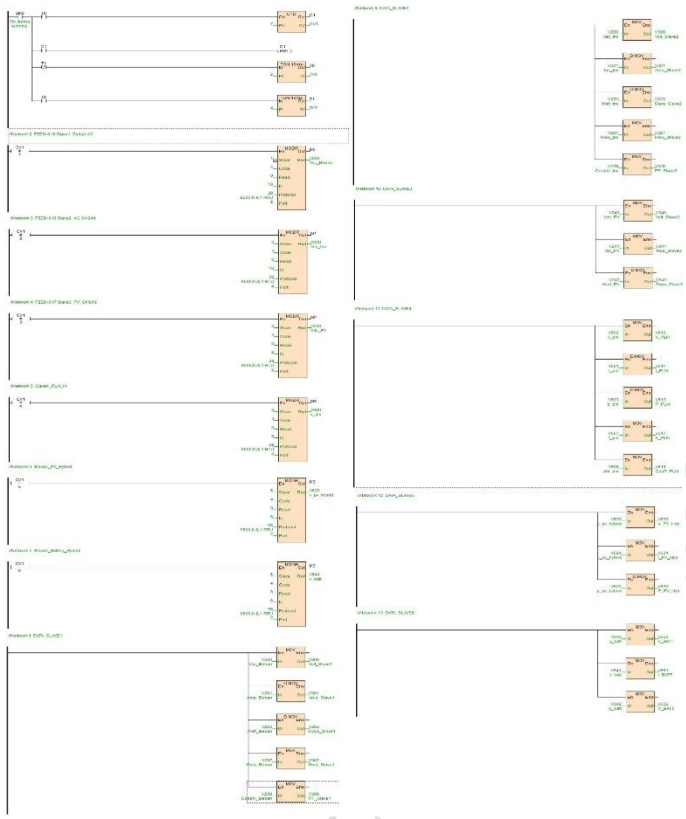

Figure 3. Programs used SCADA

2.6 Mode Sistem

The tool design in the "Design Integration of SCADA, PLC, and IoT Systems for Optimizing Solar Photovoltaic Power Plant Operations" consists of three main operational modes to manage energy resources efficiently. These modes are: Battery to PLC Mode: Utilizes stored energy in the battery to supply power when the solar panel output is insufficient. This ensures power continuity and taps into backup resources when renewable energy availability is low. PV to PLC Mode: Prioritizes using energy generated by the solar panels to meet load demands, thereby maximizing the use of renewable energy sources and reducing dependence on stored or utility power. Utility to PLC Mode: Provides additional power from the utility provider (PLN) when energy from solar panels and batteries is insufficient to meet the load requirements. Integrating these three modes allows the system to operate flexibly and efficiently, maximizing the available energy resources while ensuring a reliable power supply through continuous monitoring and control by SCADA and IoT technologies.

3. RESULTS AND DISCUSSIONS

This section will discuss the results of the field tool trials, with the results taken in the field directly determining whether this system can work well. So, the data is taken from each operating mode mentioned before, and there is one more piece of data taken to prove with real-time data taken by the system that shows the energy sources often used.

3.1 System Block Diagram for Utility to PLC Mode (Total Control System Technology - TCST)

The Utility to PLC Mode activates when the solar panel and battery supplies are insufficient. In this mode, the system shifts to draw energy from the utility provider (PLN) to fulfill the power deficit. The PLC (Programmable Logic Controller) manages the energy flow from the utility to the load, ensuring a stable and adequate power supply. SCADA monitors energy consumption and associated costs, enabling users to make informed energy management decisions. The integration of IoT allows real-time monitoring of energy usage, empowering users to identify consumption patterns and seek cost optimization opportunities.

The initial design concept is a Total Control System Technology (TCST) Block Diagram, which outlines an integrated control system that enables comprehensive monitoring, control, and optimization of industrial processes or specific operations. The system block diagram can be seen in Figure 4. This diagram represents the connections between components in each operational mode, demonstrating the flow and control of energy sources to ensure an optimal and reliable power supply.

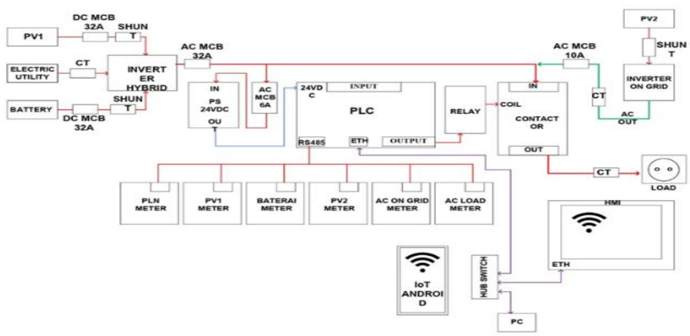

Figure 4. Block Diagram of Total Control System Technology (TCST)

The TCST design of utility integration to PLC in this solar power system allows significant energy monitoring, control, and management optimization. This design increases efficiency, reduces dependence on external resources (PLN), and provides remote monitoring capabilities, making it a flexible and reliable solution for renewable energy management. This can be seen in Figure 5. which shows the TCST output results in PLN mode as a source.

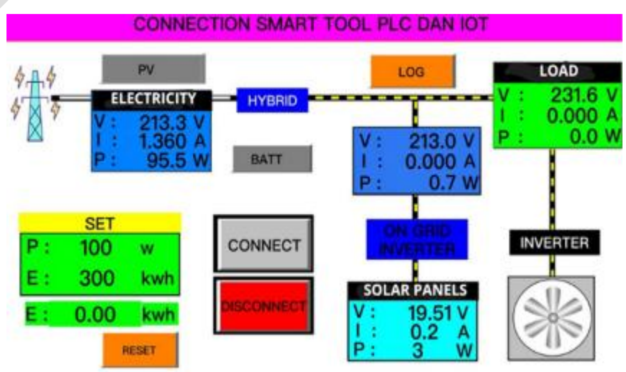

Figure 5. Output of Total Control System Technology (TCST) Block Diagram

For the "Utility to PLC Mode Block Diagram" in the designed application, the output will display a comprehensive interface for users to monitor and control the solar power generation system. In this mode, information from PLN (State Electricity Company) will be displayed, including voltage (V), current (I), and power (P) generated, with values such as 216.4 V, 0.491 A, and 9.0 W. This data will integrate with information from the load consuming power, allowing users to view real-time performance, with load indicators showing 215.9 V voltage and 0.038 A current with a power of 2.5 W. The application also enables users to set energy usage thresholds (SET) and view energy consumption in kilowatt-hours (kWh). Users can effectively manage operational modes (Hybrid, Battery, or PV) with connection and disconnection functionality. This design provides a clear and easily understood overview of system performance, helping users make decisions to optimize energy usage from renewable sources.

3.2 Battery to PLC Mode Block Diagram

In Battery to PLC Mode, the energy stored in the battery is used to supply power to the system. This mode is advantageous when the energy production from the solar panels does not meet the load requirements, such as at night or during adverse weather conditions. The PLC will control the energy flow from the battery, ensuring efficient and stable distribution to meet the current power demand. Integration with SCADA and IoT allows real-time monitoring of the battery status, allowing users to view the capacity and health of the battery and make more informed decisions regarding charging and energy usage. Figure 6. is the block diagram for the battery to PLC operation mode.

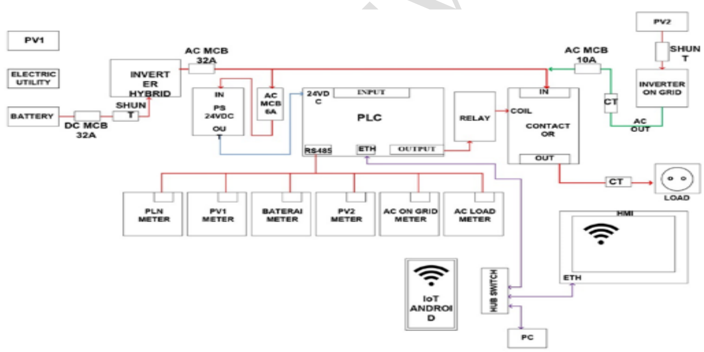

Figure 6. Block Diagram of Battery to PLC Mode

Figure 7. shows the output of the battery mode system as a source. This block diagram illustrates a well-integrated system design, combining renewable energy with advanced control and monitoring capabilities. Using PLC for automation, IoT, and SCADA for remote monitoring ensures that this solar power system can be managed efficiently and reliably. The system is also flexible, allowing for future upgrades or changes in power sources, battery capacity, and communication interfaces (Ethernet, RS485). This design supports real-time monitoring, protection, and control, making it ideal for optimizing solar power plant operations.

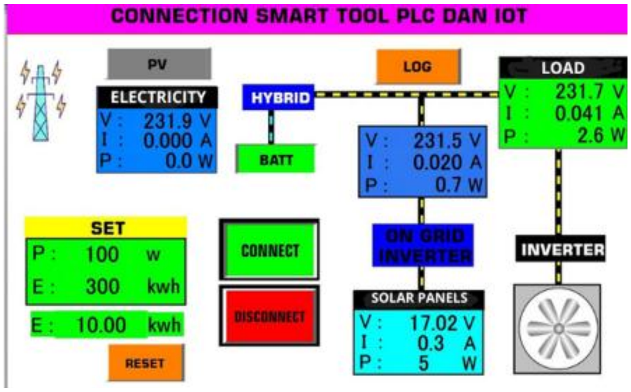

Figure 7. Output Block Diagram of Battery to PLC Mode

The output from the Battery to the PLC Mode Block Diagram displayed on the application screen reflects the interconnection of various elements within the PLC and IoT-based photovoltaic system. The diagram shows the PLN (power grid) connected in Hybrid mode, along with the battery and grid-tied inverter, which regulates the power flow. The PLN does not supply power in the diagram, with measured current and power recorded as zero, while the battery log shows an output of 231.5 V, 0.02 A, and 0.7 W. The system load receives a voltage of 231.7 V and a current of 0.041 A with a power consumption of 2.6 W. The solar panel supplies 17.02 V and a current of 0.3 A with a power output of 5 W. The application control allows users to adjust power and energy and connect or disconnect the system using the "CONNECT" and "DISCONNECT" buttons, supporting energy management in battery mode.

3.3 Block Diagram of Photovoltaic (PV) Panel to PLC Mode

The Utility to PLC mode works when the supply from the solar panels and batteries is insufficient to meet the energy needs, and the system switches to the utility provider (PLN) to cover the power shortage. In this mode, the PLC manages the energy flow from the utility to the load, ensuring that the power supply remains stable and sufficient. SCADA can provide data on energy consumption and costs, helping users make more intelligent decisions about energy management. IoT integration allows real-time energy usage monitoring, allowing users to identify consumption patterns and explore ways to optimize costs. The block diagram shown in Figure 8 shows the connection of each component.

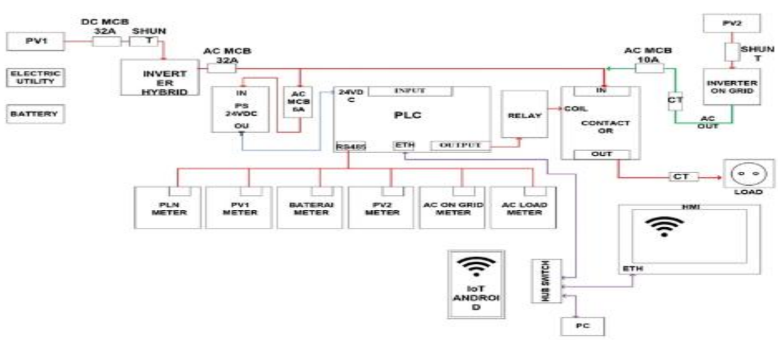

Figure 8. Output Block Diagram of PV to PLC Mode

This block diagram illustrates a comprehensive and efficient system design that combines PLC, IoT, and SCADA technologies to optimize solar power generation operations. With automatic power management, integrated metering, and remote monitoring capabilities, the system enables reliable and efficient solar power generation operations with battery storage and grid support. As demonstrated in Figure 9. the output results can be easily controlled.

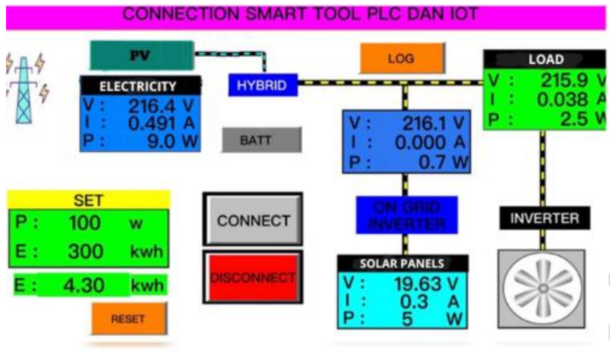

Figure 9. Output from PV to PLC Mode Block Diagram

The output from PV to PLC Mode Block Diagram on the application screen shows the interconnection of the photovoltaic system managed through PLC and IoT. The solar panel (PV) produces a voltage of 19.63 V with a current of 0.3 A, producing a power of 5 W. On the other hand, PLN still supplies a voltage of 216.4 V with a current of 0.491 A and a power of 9.0 W. This data flows through the Hybrid mode that connects the power source to the battery and inverter. In the log, a voltage of 216.1 V is monitored without any current flowing, with a power of 0.7 W. The load receives 215.9 V, a current of 0.038 A, and consumes 2.5 W of power. The application control panel allows power (P) settings up to 100 W and energy (E) up to 300 kWh, as well as power connection ("CONNECT") and disconnection ("DISCONNECT") features, allowing efficient management of power distribution from PV to the system.

3.4 System Performance Analysis

Table 2. Data Log System

Time	V Slave1 (V)	I Burden (A)	P Burden (W)	KWh	V PV HYB (V)	I PV HYB (A)	P PV HYB (W)	Wh PV1 (Wh)
8/31/2024 12:25	2240	239	240	2.81	4409	247	1089	0
8/31/2024 12:25	2241	244	240	2.85	4440	243	1078	0
8/31/2024 12:25	2242	244	238	2.88	4446	239	1062	0
8/31/2024 12:25	2242	244	240	2.91	4460	243	1083	0
8/31/2024 12:25	2242	242	242	2.95	4470	240	1072	0
8/31/2024 12:26	2242	241	243	2.98	4470	239	1068	0
8/31/2024 12:26	2241	245	239	3.01	4468	238	1063	0
8/31/2024 12:26	2240	240	240	3.05	4466	235	1049	0
8/31/2024 12:26	2239	245	241	3.08	4466	228	1018	0

8/31/2024 12:26	2239	244	241	3.11	4467	228	1018	0
8/31/2024 12:26	2243	240	243	3.15	4468	227	1014	0
Mean	**2241**	**242.55**	**240.64**	**2.98**	**4457.27**	**237**	**1055.82**	**0**
Std Dev	**1.34**	**2.21**	**1.57**	**0.11**	**18.88**	**6.75**	**27.36**	**0**

Table 2. shows the log data taken in real-time on the device. Based on the log data and performance above, several important points can be presented:

- The voltage of Slave1 (V Slave1) is relatively stable, with an average of 2241 V and a standard deviation of 1.34 V, indicating minimal voltage fluctuations.
- The burden current (I Burden) shows slight variation with an average of 242.55 A and a standard deviation of 2.21 A, reflecting that the burden current is relatively consistent.
- The burden power (P Burden) is around 240.64 W with minimal variation (standard deviation of 1.57 W).
- The energy used (KWh) increases gradually, with an average of 2.98 KWh and a standard deviation of 0.11.
- The voltage of the PV Hybrid (V PV HYB) varies more significantly, with an average of 4457.27 V and a standard deviation of 18.88 V.
- The current of the PV Hybrid (I PV HYB) has an average of 237 A and more significant fluctuations with a standard deviation of 6.75 A.
- The power of the PV Hybrid (P PV HYB) is around 1055.82 W, with moderate variation (standard deviation of 27.36 W).

Based on the integration testing of the SCADA, PLC, and IoT systems in solar power plant operations, data indicates the stability and consistency of several key parameters. The voltage on Slave1 (V Slave1) averages 2241 V with minor fluctuations, as indicated by the standard deviation of 1.34 V. The burden current (I Burden) shows an average of 242.55 A with minimal variation, reflecting the stability of the power supply. The burden power (P Burden) averages around 240.64 W with a standard deviation of 1.57 W, indicating that the system can maintain a consistent power output. Additionally, the voltage and current from the hybrid solar panels (V PV HYB and I PV HYB) show more significant variation than other parameters, although still within an acceptable range for optimal system operation. This indicates that the integration of this system is functioning well, with stability supporting the overall performance of the solar power plant.

The conclusion from testing the SCADA, PLC, and IoT system integration in solar power plants indicates that the system operates stably and consistently. The voltage and current on the burden and the burden power have small fluctuations, reflecting stability in energy distribution. Although there are more significant variations in the voltage and current from the hybrid solar panels, these values remain within reasonable limits and do not affect the overall system performance. Therefore, the integration of SCADA, PLC, and IoT has proven capable of optimizing the operation of solar power plants, maintaining consistency in energy distribution, and effectively monitoring performance.

3.5 Process Optimization

Integrating SCADA, PLC, and IoT systems in the operation of solar power plants significantly optimizes operational processes. Real-time data allows for more efficient monitoring and management of power production. Data collected from IoT sensors, directly connected to the PLC, enables SCADA to make automated decisions to maximize solar power production based on actual conditions. For example, the system can automatically adjust output based on sunlight intensity or electricity demand burden. This helps reduce reliance on energy from the PLN grid while maximizing energy from solar panels. Additionally, continuous data collection provides in-depth insights for maintenance and overall operational efficiency improvement.

3.6 Improvement of Preventive Maintenance

IoT integration allows for predictive maintenance by continuously monitoring component performance. Voltage, current, and temperature data can be analyzed in real-time to detect anomalies indicating potential failures. In this study, the integrated IoT system detected performance declines in several solar panels before reaching critical failure levels, allowing for timely preventive maintenance actions. Based on historical data, the system detected up to 20% of potential failures before significant damage occurred, helping reduce operational downtime and higher repair costs.

Testing showed that the integrated system can stably and accurately handle large volumes of data generated from various components, such as inverters, batteries, and solar panels. The PLC system, the control center, processes data from IoT sensors and provides instructions for high-speed power regulation without significant delays. When tested in scenarios of scaling up the power plant, the system could accommodate an increased number of solar panels and other components without a decrease in performance. This indicates that the system can be easily scaled to support power plants with larger capacities.

4. CONCLUSIONS

This research demonstrates that integrating SCADA, PLC, and IoT systems in solar power plants significantly enhances operational efficiency and system reliability, especially using three main operating modes: Battery to PLC, PV to PLC, and Utility to PLC.

- Battery to PLC Mode allows the plant to efficiently manage the power stored in batteries during limited solar energy availability or at night. Real-time data from the PLC helps optimize the power distribution from the batteries to the loads, reducing dependence on the PLN grid and enhancing the utilization of stored energy.
- PV to PLC Mode regulates the flow of power directly from the solar panels to the load systems and batteries, maximizing the use of solar energy during the day. The PLC automatically controls power distribution between immediate load demands and battery charging based on solar panel energy production, thus avoiding energy waste.
- Utility to PLC Mode is utilized when the plant requires power supply from the PLN grid, such as when energy from the solar panels and batteries is insufficient. The PLC manages when the system should switch to PLN power to maintain a continuous power supply to the loads, ensuring uninterrupted system operation.

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