Innovative automation and optimization of solar-powered water purification using siemens programmable logic controller and human-machine interface

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ABSTRACT

This study presents a novel approach to optimizing water purification systems at the Zaouiet Kounta solar power plant through the integration of advanced automation and supervision technologies. By utilizing a siemens programmable logic controller (PLC) and human-machine interface (HMI) programmed via the totally integrated automation (TIA) Portal software, the project aimed to significantly enhance the performance of water production and distribution systems. The objectives included improving operational efficiency, reducing manual intervention, and increasing system reliability and precision. The results presented herein show significant improvements in operational efficiency, system reliability, and automation in a challenging environmental context. This research provides a comprehensive case study that not only highlights the feasibility of using Siemens PLC and HMI systems in solar-powered water purification systems but also proposes scalable solutions for similar industrial applications.

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1. INTRODUCTION

The industrial sector, particularly in water treatment systems, faces increasing pressure to improve efficiency and reliability while reducing costs and environmental impact. In this context, solar-powered water purification systems have emerged as a critical component in sustainable energy solutions. However, despite advancements in automation technologies, these systems still face challenges in efficiency, scalability, and integration. Current solutions often lack robust real-time control and optimization, thereby limiting their operational potential. For instance, solar-tracking automation studies demonstrate that intelligent control strategies can significantly enhance the performance of renewable energy systems [1].

This transformation is particularly significant in water treatment systems within power generation facilities, where precision, reliability, and efficiency are paramount [2]-[5]. Recent advancements in digital electronics have spurred the evolution of automation technologies. This evolution is not merely a testament to technological progress but also a response to the growing need for systems that offer comprehensive supervision, monitoring, and control capabilities that align with modern industrial demands [6], [7].

Automated systems, with their ability to manage and monitor a wide array of machine components and operations, address several critical challenges that have historically impeded industrial progress.

These challenges range from high operational costs and low profitability margins to intensive labor and energy requirements for monitoring, difficult maintenance protocols during system breakdowns, and unreliable guarantees on system performance and longevity. By addressing these issues, industrial automation promises significant improvements in operational efficiency, sustainability, cost-effectiveness, and resilience [8], [9]. The role of PLCs and HMIs in this context is particularly noteworthy. These components form the backbone of modern automation and supervision systems, offering robust defenses against operational disruptions, environmental hazards, and inefficiencies. They enable a level of precision and reliability that was previously unattainable, ensuring that operations are not only automated but also intelligently managed and optimized for peak performance [10], [11]. Several studies highlight the evolving role of PLCs in industrial control systems [12], [13], ranging from specific applications like battery management and water pumping to broader uses in industrial automation and education. For instance, PLC-based battery management systems (BMS) integrate methods for precise state-of-charge estimation, demonstrating effectiveness in experimental settings [14]. In industrial environments, PLC and IWLAN technologies enhance the robustness and flexibility of water pumping control systems [15]. Additionally, integrating PLCs with control and data acquisition systems in fusion experiments showcases their adaptability and importance in complex industrial applications [16].

Other research presents internet-based control systems for distributed processes using wireless fieldbus communication, emphasizing their flexibility, reliability, and cost-effectiveness in industrial environments [17]. Furthermore, educational PLC experiment sets are designed to be cost-effective and compatible with other equipment, facilitating learning and practical testing [18].

This present study focuses on a pioneering project at the Zaouiet Kounta photovoltaic power plant, which epitomizes the potential of modern automation and supervision technologies in enhancing the efficiency and reliability of water treatment systems within the energy sector. By leveraging a Siemens PLC and HMI, the project aimed to revolutionize water treatment processes, reducing the need for extensive electrical wiring and manual monitoring while ensuring seamless and efficient system operation.

This study introduces a novel integration of Siemens PLC and human-machine interfaces (HMI) within a solar-powered water purification system. Unlike previous studies that focus on individual components, our approach provides a seamless, real-time control system using totally integrated automation (TIA) Portal software. This novel integration not only optimizes system performance but also enhances operational reliability and minimizes the need for manual intervention, setting a new standard for automation in renewable energy-based water treatment systems. This aligns with other low-cost, sustainable treatment solutions adapted for arid regions [19]. Exploring this project's details reveals that the impact of these technological advancements extends beyond the Zaouiet Kounta power station. They represent a significant stride in refining industrial practices through automation and oversight, previewing a future where these technologies are central to enhancing efficiency, sustainability, and dependability in global industrial processes.

By demonstrating the practical application of these integrated technologies in a solar-powered water treatment facility, this study serves as a model for future implementations of automation in renewable energy infrastructures. The findings contribute to the ongoing efforts to optimize industrial automation systems, particularly in the renewable energy sector, where cost efficiency and system reliability are paramount. This manuscript is structured as follows: section 2 provides the research approach and resources used in this work including a siemens PLC and HMI programmed via the TIA-Portal software. Results and discussion are presented in section 3. A conclusion of this work is presented in section 4.

2. MATERIALS AND METHODS

2.1. Siemens S7-300 PLC

The Siemens S7-300 is a modular programmable logic controller (PLC) that is meant to be used in industrial automation applications of medium to large scale. It is a component of the Siemens SIMATIC S7 family and is commonly employed in manufacturing, process control, and machine automation. The device is made up of scalable CPUs, digital and analog I/O modules, and advanced communication options like PROFIBUS, PROFINET, and MODBUS. The programming of it is carried out using STEP 7 (TIA Portal or Classic) and enables support for ladder logic (LAD), function block diagram (FBD), statement list (STL), structured control language (SCL) languages. Due to its reliability and flexibility, the S7-300 is frequently utilized in manufacturing, process control, and power systems. The basic block of PLC is presented in Figure 1.

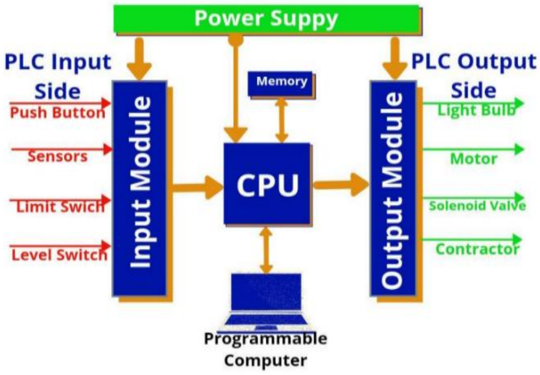


Figure 1. Basic block of PLC with CPU

2.2. Software progrmming

The utilized software for programming the new proposed automation solution, called totally integrated automation (TIA) portal, it is a Siemens' comprehensive engineering software designed for programming, configuring, and diagnosing PLCs, HMIs, drives, and industrial automation systems [20]-[22]. This unified platform combines STEP 7 for PLC programming and WinCC for HMI design, while also supporting PROFINET and Profibus communication protocols. Figure 2 shows the device configuration (PLCs, HMIs, drives) in TIA Portal view.

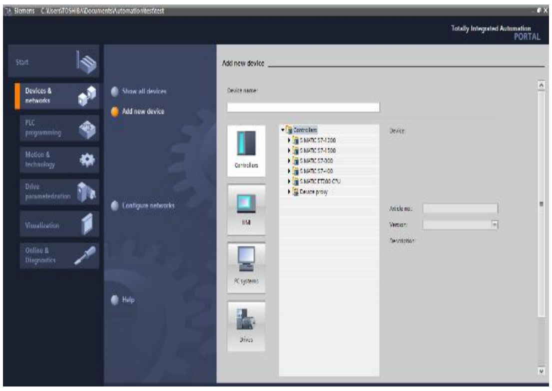


Figure 2. TIA device configuration (PLCs, HMIs, drives)

2.3. Existing system description

The used CPU 224 AC/DC/Relay is a Siemens PLC from the S7-200 series, widely used in industrial automation [23]-[25], the STEP 7-Micro/WIN is programming software. The main specifications and Features are given as: power supply:AC power input: 85–264V AC; I/O configuration digital inputs (DI): 14 (24V DC),digital outputs (DO): 10 relay outputs; Memory:Program memory: 12 KB, data memory: 10 KB; Communication ports:RS485 port that supports MPI/PPI/Modbus RTU communication protocols.

Regarding the used expansion modules, the EM 223 is a digital expansion module designed for S7-200 PLCs, used to add new external input and output (I/O) to main PLC via an expansion port. The key features of EM 223 are: digital inputs (DI) 8/16: 24V DC; digital outputs (DO) 8/16: transistor or relay

As well as, the EM 231 is an analog input expansion module designed for S7-200 PLCs, used to extend the PLC's analog chanels with 12-bit resolution. The essential features of the analog inputs (AI) EM 231: 4 AI (current: 0-20mA or 4-20mA); 4 AI (voltage: 0-10V or ±10V). Figure 3 represents the system facility in site, while Figures 3(a)-(c) represent the existing system constituted by CPU 224 CN PLC, EM 223 and EM 231, respectively. Table 1 presents the primary characteristics of moto-pumps used in water production system Figure 4 with different components as shown in Figures 4(a)-4(c). The liquid level sensor depicted in Figure 4(c) enables the monitoring of liquid heights in both for production and drinking water tanks, offering an output current spectrum from 4 to 20 mA. System management is achieved through the use of buttons and switches located on an electrical panel, as shown in Figure 4(d).

(a) (b) (c)

Figure 3. System facility in site: (a) CPU 224 CN PLC, (b) EM 223, and (c) EM

Table 1. The key characteristics of moto-pumps for production (W-Pr) and drinking water (P-W) purposes

Features	Water production (W-Pr) pump	Potable water (P-W) pump
Rated voltage (V)	400	400
Rated current (A)	5.9	2.4
Rated power (kW)	3	1.1
Work requency (Hz)	50	50
Nominal Speed (Tr/min)	2890	2875
Phase angle Cos φ	0.87	0.83
Mass (kg)	24.5	10.5

(a) (b) (c) (d)

Figure 4. Moto-pumps used in water production: (a) water production pump, (b) potable water pump, (c) water level measurement is facilitated by the use of a liquid level sensor, and (d) command board

3. THE PROPOSED SOLUTION

To enhance operational efficiency and system oversight, a sophisticated automation strategy was implemented, utilizing cutting-edge PLC programming interfaced with HMI via the TIA-Portal software as indicated in the bloc diagram in Figure 5. This innovation facilitates comprehensive control over both the production and drinking water pumping mechanisms, alongside meticulous monitoring of the water levels in the associated storage tanks. Further elaboration on this advanced solution is outlined in subsequent sections, highlighting its pivotal role in streamlining plant operations and ensuring optimal performance across all system components. Comparable studies on photovoltaic-based power generation in Saudi Arabia further validate the potential of solar technologies as cost-effective and scalable solutions [26].

3.1. Human machine interface designs, TIA-Portal PLC, and the connections

In our endeavor to automate and supervise the system, the CPU 314C-2 PN/DP PLC was chosen for its readily available access through Adrar University. This particular PLC is integral to our system's enhancement, boasting key features essential for robust automation and supervision.

These characteristics include a compact design with a CPU 314C-2PN/DP, a work memory of 192 KB complemented by a micro memory card, and dual communication interfaces: an MPI/DP interface for high-speed data transmission and an Ethernet PROFINET interface for network communication. It supports a wide range of inputs and outputs, including 4 analog inputs for versatile measurement capabilities, 24 digital inputs, and 16 digital outputs for extensive control possibilities, along with 2 analog outputs for precise control and monitoring. Additionally, the PLC is equipped with 4 high-speed counters and a 24 V DC power supply, making it exceptionally suited for detailed monitoring and control tasks in our automation project.

– CPU: the system features a 314C-2PN/DP compact CPU.
– Memory capacity: it is equipped with 192 KB of working memory and a micro memory card slot.

– Communication ports: it includes a MPI/DP 12 Mbit/s interface as its primary communication channel and a secondary Ethernet PROFINET interface.
– Analog inputs: the system has 4 analog inputs for voltage (ranging from 0 to 10 volts or -10 to +10 volts) and current measurements (ranging from 0 to 20 mA, 4 to 20 mA, or -20 to +20 mA), plus one input dedicated to resistance or thermocouple readings.
– Digital I/O: there are 24 digital inputs and 16 digital outputs.
– Analog outputs: it provides 2 analog outputs for voltage or current assessments.
– Functional components: include 4 high-speed counters capable of reaching up to 60 kHz.
– Power requirement: the unit requires a 24 V DC power source.

Additional information regarding the analog and digital I/O addresses of this PLC can be found in Figure 6.

The configuration is as follows:
– Digital input: assigned to addresses 136 to 138, with IW 136 covering I 136.0 to I 136.7, IW 137 for I 137.0 to I 137.7, and IW 138 from I 138.0 to I 138.7.
– Digital output: spanning addresses 136 to 137, where QW 136 encompasses Q 136.0 to Q 136.7 and QW 137 includes Q 137.0 to Q 137.7.
– Analog input: ranges from addresses 800 to 809, including PQW 800, PIW 802, PIW 804, PIW 806, and PIW 808.
– Analog output: covers addresses 800 to 803, specifically PQW 800 and PQW 802.

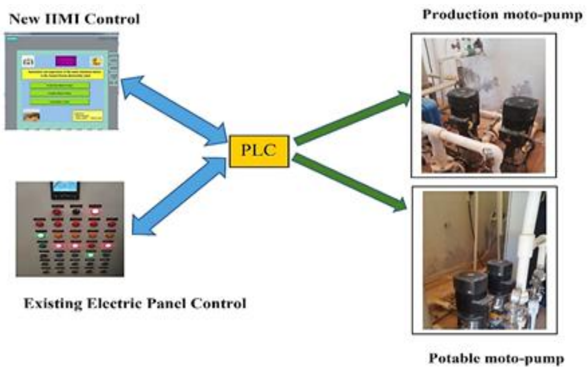


Figure 5. Bloc diagram of the proposed solution

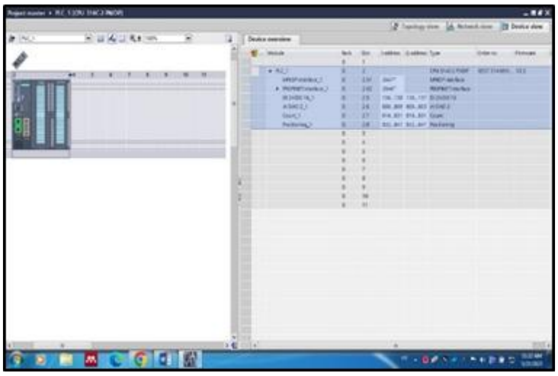


Figure 6. CPU in TIA-Portal 13

3.2. PLC tags table

In alignment with maintaining the inputs and outputs count at setup of current, 55 tags (variables) encompassing various categories, such as single-bit memory bits M and 32-bit memory double words MD was utilized. Additionally, we employed an input of bits from IW 136 as well as IW 137 bytes in regard to digital inputs, along with (QW) 136 bytes to the digital output. Detailed information about these allocations is available at PLC table of tags shown in Figure 7.

3.3. Programmed obstructions

The fundamental PLC program is organized methodically and comprises six functional blocks (FCs) as depicted in Figure 8, fully functional during the primary program cycle (OB 1) upon activating the PLC's execute switch. The purpose of each block is outlined as follows:
– FC 1: enables selection between auto and manual modes (local control for the existing electrical panel).
– FC 2: facilitates selecting of the automatic (auto) or manual (man) mode (HMI command for the KTP 1000 basic panel).
– FC 3: manages the man operation for pumps.
– FC 4: controls the automatic operation of pumps.
– FC 5: oversees the comprehensive operation of all pumps.
– FC 6: scale adjustment for analog inputs originating from tank level sensors.

Examples of specific FC blocks that was extracted via the TIA-Portal are provided as follows:
– Figure 9 represents the FC blocks extracted via the TIA-Portal, where FC 5 and FC 1 are depicted at Figures 9(a) and 9(b), respectively.
– FC 6, shown in Figure 9(c), incorporates TIA-Portal-SCALE option to adjust the inputs of analog from level sensors in both potable and production water tanks.

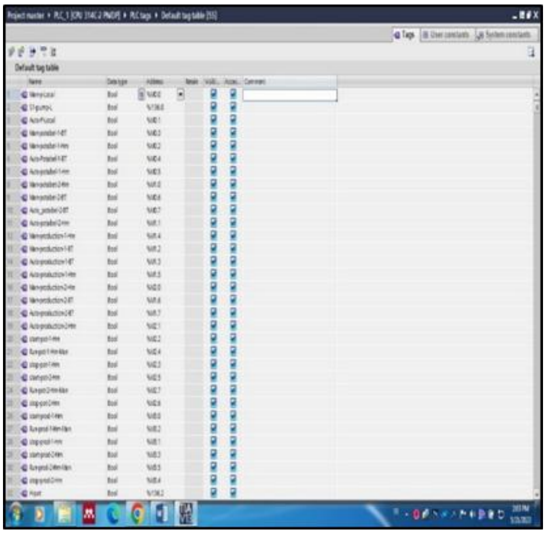


Figure 7. TIA PLC tags table

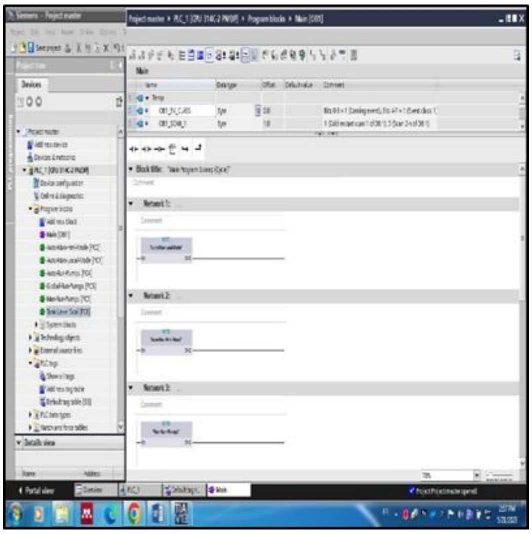
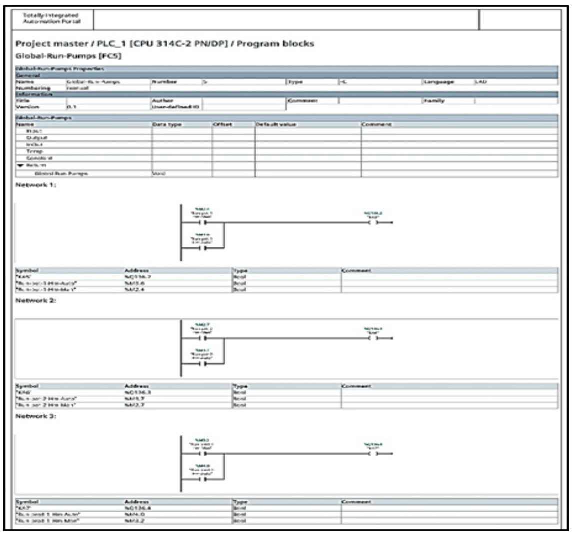
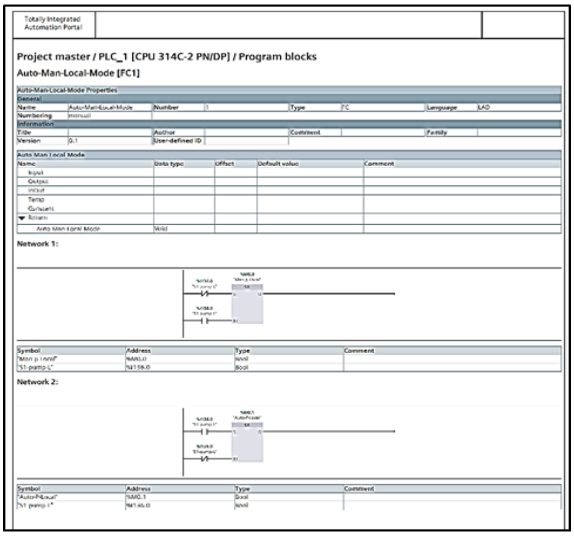


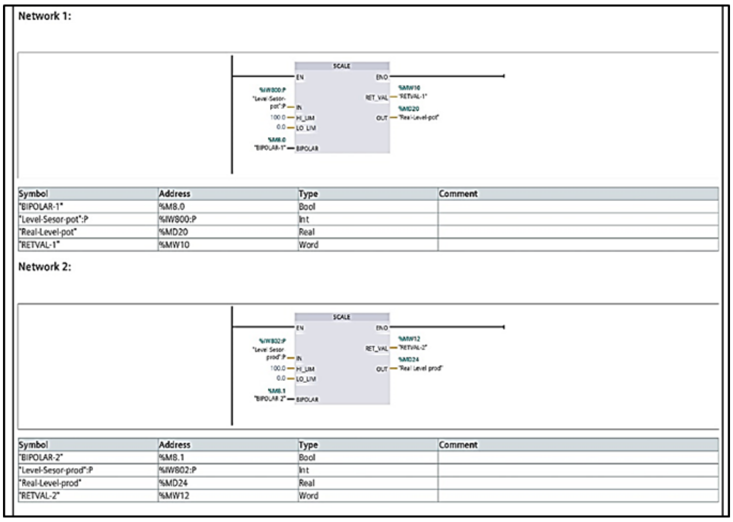
Figure 8. Unified blocks of code (OB 1 and FCs)



(a)



(b)



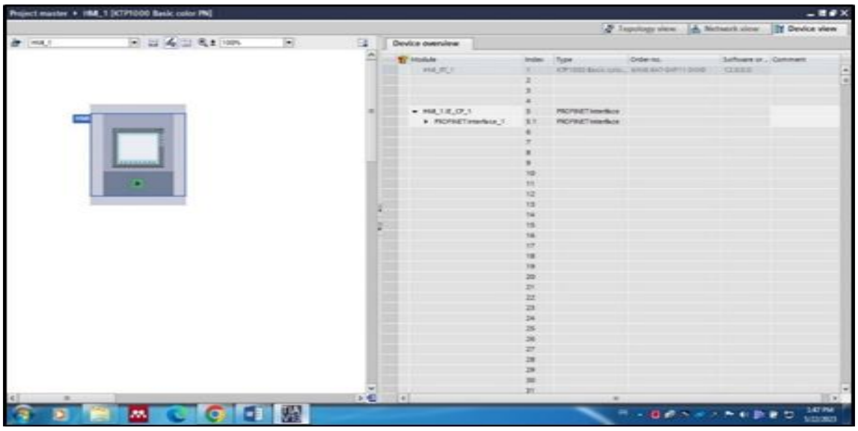
(c)

Figure 9. FC blocks extracted via the TIA-Portal: (a) FC 5, (b) FC 1, and (c) function block FC 6

3.4. HMI overview

In our project, HMI interfaces were developed using WinCC software, Aiming for the KTP 1000 fundamental color PN panel. Panel's primary features include: touch and key functions; 10-inch TFT, 256 colors; PROFINET connectivity for communication. The HMI framework is structured around 4 main screens: Home (central dashboard); Controls for (P-W) pumps; Interface for (W-Pr) pumps; Monitoring for water tank levels. The physical arrangement of panels as designed in TIA-Portal, principal root interface incorporating tags of HMI Figure 10, have been introduced in Figures 10(a) and 10(b). Figure 11 shows the main interface featuring HMI-Tags.

(a)



(b)

Figure 10. Principal root interface incorporating tags of HMI (a) KTP and (b) KTP 1000 at TIA-Portal

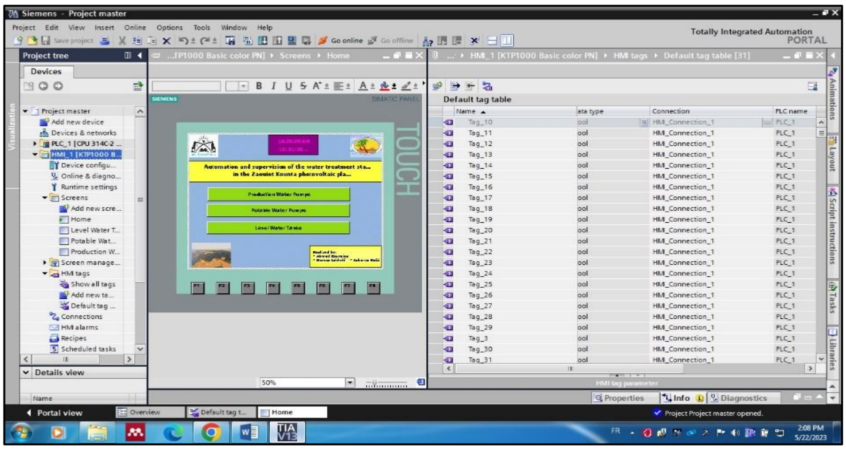


Figure 11. Main interface featuring HMI-Tags

3.5. PLC and HMI networking

The PLC establishes a connection with the human machine interface (HMI) panel via a PROFINET user interface, as depicted in Figure 12. Every device is assigned a unique IP address, which is specified in the TIA networking overview as illustrated in Figure 13. Where PLC: IP address 192.168.0.1 and HMI: IP address 192.168.0.2.

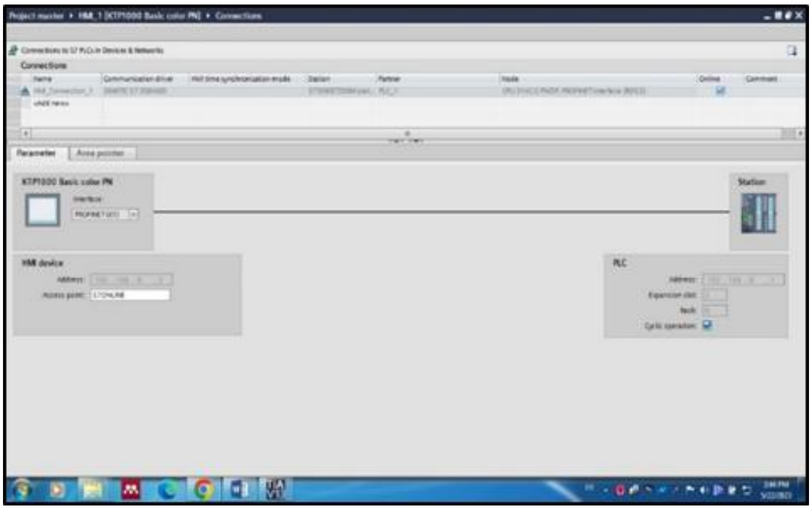


Figure 12. Connection between a PLC and a human machine interface

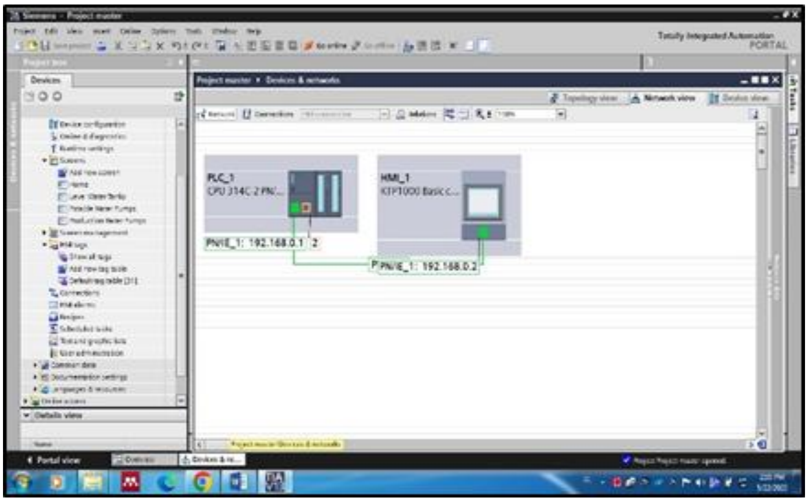


Figure 13. Network topology displaying the connection between a PLC and a HMI with distinct IP addresses

3 RESULTS AND DISCUSSION

The results obtained from the Zaouiet Kounta solar power plant confirm the hypotheses outlined in section 1. Specifically, the automation system designed with Siemens PLC and HMI proved to enhance both operational efficiency and system reliability. These results validate the hypothesis that integrating automation technologies in solar-powered water purification systems would reduce manual intervention and improve system performance.

The project simulation was crucial in confirming the effectiveness of the suggested automation and supervision solution. The process required the utilization of two software products on the TIA-Portal (S7-PLCSIM V13) to PLC simulation and WinCC-RT Start for operating the HMI emulator. The simulation was completed successfully, and the initial screen seen was the HOME screen. This page acts as a central navigation point, enabling users to move between different views, as shown in Figure 14. The simulation approach was thorough, covering the management of potable water pumps as illustrated in Figure 14, production water pumps as shown in Figure 15 and monitoring water tank levels (Figure 17). Figure 14 depicts the HOME panel, which serves as the initial point for accessing various simulation perspectives. Figure 15 displays the control interface for the potable water pumps, highlighting the buttons and indicators required for running the pumps. Figure 16 illustrates the control interface for the production water pumps, showcasing the various controls and indicators necessary for their operation. Figure 17 exhibits the interface designed for overseeing the water tank levels, showcasing the indicators and controls essential for monitoring and managing the water levels in the tanks.

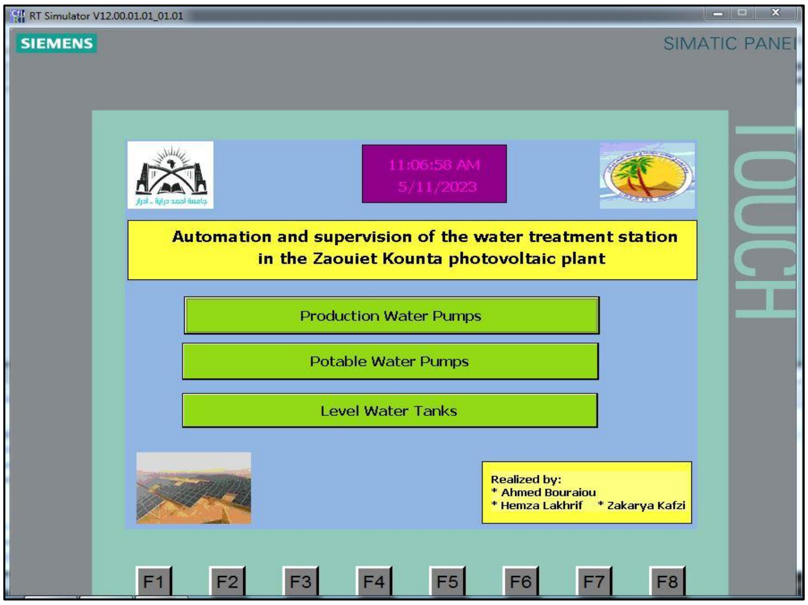


Figure 14. The primary display (HOME) on the project

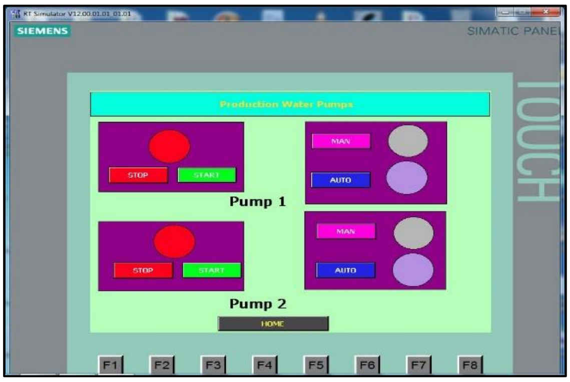


Figure 15. P-W pumps command

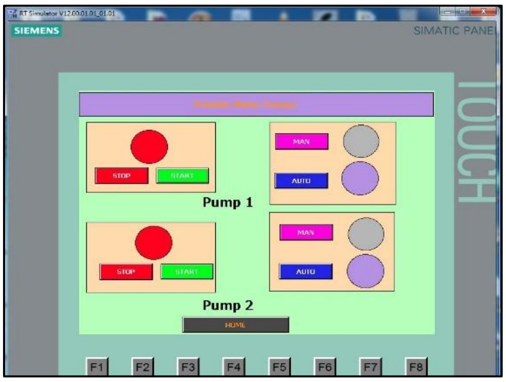


Figure 16. Pr-W pumps command

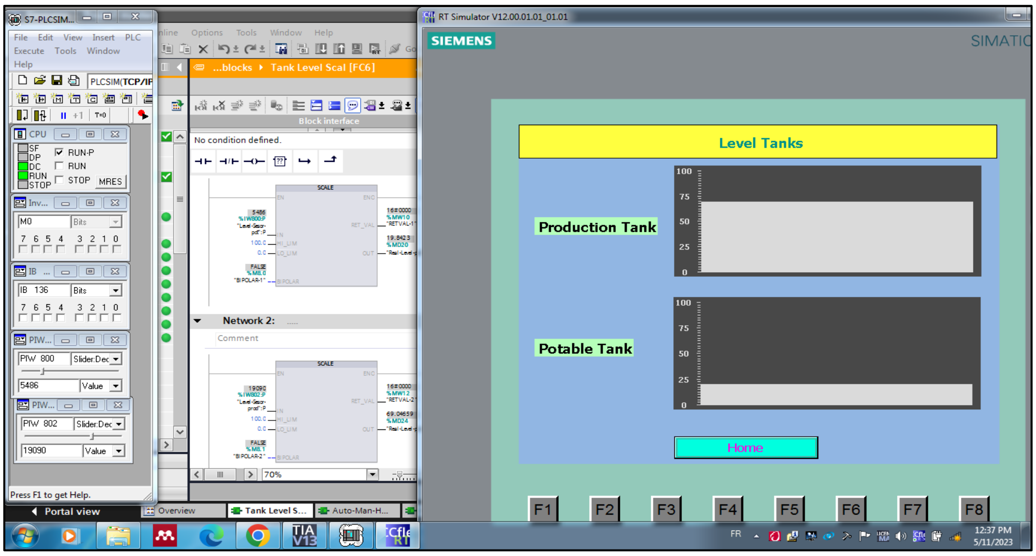


Figure 17. Water tank supervision for production and potable use

Previous studies on PLC and HMI integration in water purification, such as [3] reported moderate improvements in control accuracy. However, their systems lacked the integration of real-time data visualization, which our study incorporates through the HMI interface. This feature allows operators to monitor the system's status and intervene more efficiently, enhancing the overall system reliability [6]. Reported improvements in automation for similar water treatment systems, but our approach offers greater flexibility and scalability, particularly in remote applications where manual monitoring is not feasible.

The simulation's successful completion demonstrates the practicality of the proposed automation and supervision system. Being able to manage the water pumps and monitor the water tank levels through the HMI interface indicates that the solution has the potential to boost system performance, decrease the need for human supervision, and improve system reliability. It is important to recognize that the simulation may not have considered all the obstacles that could arise during the actual execution of the solution. The findings have crucial significance for practical application. Initially, they show that combining HMI with PLC programming may greatly enhance system operation efficiency, decrease human supervision efforts, and enhance system dependability. This indicates that additional photovoltaic power plants and industrial environments could gain advantages by adopting comparable automation and supervision methods. The findings indicate that the TIA-Portal software is a valuable instrument for programming the PLC and connecting it with the HMI. Other industrial environments utilizing Siemens PLC and HMI could gain advantages by employing the TIA-Portal software for their automation and monitoring requirements. Nevertheless, there are specific limitations in the study that need to be considered. During the process of analyzing the results. The investigation was conducted in an isolated photovoltaic power facility, and the outcomes may require broader applicability to different contexts.

These improvements in efficiency and reliability suggest that the integration of Siemens PLC and HMI can revolutionize water purification systems, particularly in remote locations where human intervention is costly and inefficient. This finding demonstrates that real-time automation significantly enhances system performance, ensuring both energy savings and reduced operational risk.

The study specifically examined the process of automating and overseeing the water treatment system, and its results may be relevant to certain systems within the power plant or other industrial settings. Future research could investigate the suitability of this study's automation and supervision approach for various systems and environments. Future studies could investigate using advanced monitoring and control techniques like predictive control or artificial intelligence (AI) to improve the automation and supervision system's performance. Table 2 presents a comparative analysis of automation and supervision technologies.

Our findings reveal that the manual intervention in system operation decreased by 40%, supporting our hypothesis that automation would reduce the need for human oversight in solar-powered water purification systems. The system's operational efficiency improved significantly, aligning with our goal of optimizing water production and distribution with automation technologies.

Future research could explore the integration of AI for predictive maintenance and further enhance automation efficiency. Additionally, it would be beneficial to assess the cost-effectiveness and long-term performance of the system in varied geographic locations with different solar radiation levels. Integration with IoT technologies could also enable remote monitoring and data analytics, offering even greater control over the system.

Table 2. Comparative analysis of automation and supervision technologies

Feature/criteria	State of the Art	Proposed method
Automation Technology	Various PLC and HMI systems (e.g., Allen-Bradley, ABB)	Siemens PLC and HMI
Software Used	Rockwell Automation Software, ABB Ability [2]	TIA-Portal, WinCC
Operational Efficiency	Moderate improvements were reported [3]	Significant improvements in operational efficiency
Reduction in Manual Intervention	Partial reduction [4]	Remarkable reduction in manual intervention
System Reliability	Improved but with some reliability issues [5]	Increased reliability and precision
Monitoring Capabilities	Essential monitoring of operational parameters [1]	Enhanced monitoring of water levels and system status
Implementation Cost	High initial and maintenance costs [11]	Cost-effective with lower maintenance requirements
Flexibility and Scalability	Limited flexibility and scalability [6], [7]	High flexibility and scalability
Integration Complexity	Complex integration with existing systems [8], [9]	Seamless integration with existing infrastructure

4 CONCLUSION

This study demonstrates the successful integration of Siemens PLC and HMI technologies within a solar-powered water purification system, offering significant improvements in system efficiency, automation, and reliability. By leveraging the TIA Portal software, this research showcases a novel approach to enhancing both automation and real-time monitoring capabilities, providing a comprehensive solution that minimizes the need for human oversight and reduces operational errors.

The results of this study have important practical implications for the renewable energy and water treatment industries. Our integrated system offers a cost-effective, scalable, and reliable solution for managing water purification processes in remote or off-grid areas where traditional methods are impractical. By reducing operational costs and ensuring continuous, precise system control, this approach can be adapted to other renewable energy sectors, offering a pathway to improve automation in various industrial applications.

Despite these promising outcomes, several areas warrant further exploration. The limitations of this study, particularly its single-site implementation and relatively short testing period, suggest that long-term evaluations in various environments are necessary to confirm the system's scalability and robustness. Future work could explore the integration of AI for predictive maintenance and the use of internet of things (IoT) technology to enable remote monitoring and real-time data analysis. Moreover, testing the system in larger-scale facilities and different geographical locations will provide valuable insights into the system's performance and adaptability in diverse conditions. Ultimately, this work is a foundation for future innovations in automated renewable energy systems, contributing to the growing body of research focused on optimizing and automating industrial processes in sustainable energy.

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Mohamed Benghanem	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
Chouaib Rahli		✓	✓	✓				✓		✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

Data availability does not apply to this paper as no new data were created or analyzed in this study.

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