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Advanced SCADA-PLC S7-1200 Communication System for Aeration Unit in Wastewater Treatment Stations

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ABSTRACT

The efficient operation of aeration units is crucial for the biological treatment process in wastewater treatment plants (WWTPs), as they play a pivotal role in supplying the necessary oxygen for microbial activity. This study focuses on designing and implementing an automated aeration system utilizing Programmable Logic Controllers (PLC S7-1200) and Supervisory Control and Data Acquisition (SCADA) systems. Integrating PLC and SCADA ensures precise control, real-time monitoring, and operational flexibility, enhancing process efficiency and reducing energy consumption. The methodology involved designing a control algorithm for the PLC S7-1200 to regulate aeration based on dissolved oxygen levels and flow rates. The SCADA system provides a user-friendly interface for visualization, data logging, and remote operation. The proposed system was tested under simulated and operational conditions to validate its performance. Results indicated significant improvement in oxygen transfer efficiency, stability of the process, and energy savings compared to traditional conventional aeration control methods. This study presents the role that automation technologies may play in modernizing WWTP operations regarding sustainable environmental management. The findings set a framework for further research and implementation of advanced control strategies in aeration and other critical WWTP processes.

1. INTRODUCTION

Wastewater treatment is essential to water resource protection and environmental and public health protection. In a sequence of wastewater treatment processes, aeration has been one of the most widely used techniques for enhancing the biological decomposition of organic pollutants, mainly by microorganisms, under oxygen. An efficient aeration unit is essential for optimizing the removal of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved Oxygen Level (DOL), and Total Suspended Solids (TSS), which are key indicators of water quality [1, 2].

BOD describes the amount of oxygen that is needed by bacteria to break down organic wastes in water and describes organic pollution in the waste. COD measures all the oxygen absorbed in oxidizing the non-biodegradable and biodegradable organic matter, which describes a more realistic picture of water quality. DO is the oxygen concentration dissolved in water and is among the most important parameters related to aquatic life and aquatic ecosystem well-being. TSS is suspended solids concentration in water [3], which can affect aesthetic and environmental quality. Proper decrease of these parameters is important given the target water quality requirements and the various environmental regulation needs [4].

In the last decade, the integration of PLC and SCADA systems has transformed the operation and optimization of aeration systems in wastewater treatment plants. PLCs provide reliable and automated control of aeration equipment, with the ability to precisely regulate aeration rates based on real-time conditions [5, 6]. At the same time, SCADA systems enable continuous monitoring and data acquisition for operational efficiency and decision-making [7]. The synergy between automation technologies increases performance, reduces energy consumption, and enhances regulatory compliance in wastewater treatment [8].

Contribution of the paper: The following design is intended to implement aeration units for a wastewater treatment plant using Siemens PLC S7-1200; the design of this system is according to environmental standards. The ability of the PLC to integrate with signals system and actuators via communications protocols in real-time, together with the advanced control algorithms that have been designed, improve and reduce energy consumption and maintain the water quality in this plant is essential and thus achieve an accurate microbial monitoring system.

Kadhim and Mohammed [9] designed an incoming sewage treatment process using a Programmable Logic Controller (PLC S7-300). PLC and SCADA systems enhance the automation and monitoring of this process. Additionally, the study considers the learning potential of basic automation through PLC. The biochemical treatments within this system are designed and operated using PLC technology.

Ardi et al. [10] developed a system that operates automatically using PLC, incorporating the necessary inputs and outputs for sedimentation processes. The program includes two operational modes: a manual menu and an automatic menu. As a result, the washing process is accelerated by two minutes per cycle. Moreover, the deployed used oil and water washer eliminates the need for treatment by a waste company, allowing the company to dispose of only the used oil, thereby reducing wastewater disposal costs.

Artiom [11] explored the implementation of a SCADA and automation system in a wastewater treatment plant, demonstrating its ability to reduce maintenance costs and improve energy efficiency. Following the implementation of this automated SCADA system, the treated water became free of microorganisms and parasites. The study emphasizes energy efficiency as a crucial factor in the design and development of electromechanical systems.

Tokos et al. [12] focused on enhancing SCADA systems for small-zone wastewater treatment plants in remote areas, ensuring autonomous control and remote monitoring. The research highlights key challenges, including ensuring operational safety and reducing energy consumption. However, rising costs led to a reduction in the number of sensors, which in turn decreased the amount of collected data.

Rajhans et al. [13] examined an integrated wastewater treatment system combining PLC and SCADA for operational control. However, the study noted increased costs and the automatic operating system's software commands were sometimes difficult to respond to.

OV et al. [14] presented a case study on the integration of SCADA and PLC in a power distribution system, emphasizing reliability through the use of Optical Fiber Communication (OFC) cables and redundant Ethernet switches. However, the study did not provide a quantitative performance analysis, innovation insights, or a critical evaluation of technical challenges. The research primarily utilized Open-SCADA and PLC, incorporating advanced communication technologies to ensure service continuity.

The proposed control algorithm demonstrates its effectiveness in operating aeration basins in wastewater treatment plants using an S7-1200 programmable logic controller and a supervisory control and data acquisition (SCADA) system, ensuring precise and efficient control of dissolved oxygen levels. However, the primary objective of the research was to present a practical approach applicable in industrial settings, focusing on reliability and ease of implementation rather than comparing performance with advanced control strategies such as fuzzy control (FLC) or model-based predictive control (MPC). Although these approaches may offer additional improvements in some aspects, their implementation in industrial systems requires computational complexity and software resources that may not be available in every treatment plant and are expensive. Nevertheless, evaluating these algorithms in future studies would be useful to determine the extent to which system efficiency and effectiveness improve compared to the current algorithm.

2. PROGRAMMABLE LOGIC CONTROLLER (PLC)

Figure 1 presents the Siemens S7-1200 Programmable Logic Controller, a compact and versatile automation device used for precise control and monitoring in industrial processes [15]. The S7-1200 has a scalable modular design that allows users to tailor the configuration to particular system requirements. It can support numerous communication protocols like PROFINET, thus giving it great flexibility for integration within other devices or systems in the industrial network framework [16]. The PLC incorporates a high-performance processor and extensive advanced programming possibilities using the TIA Portal, which guarantees the efficient processing of complex applications. The PLC S7-1200 is a reliable solution for industries with robust diagnostic tools and safety functionalities, which enable enhanced operational efficiency, flexibility, and support for Industry 4.0. With wide applications in machine control, process automation, and energy management, it has become one of the most important parts of modern industrial systems [17].

Figure 1. PLC hardware configuration

3. INDUSTRIAL COMMUNICATION PROTOCOLS

In industrial applications, illustrated in Figure 2, communication protocols enable efficient and reliable data exchange between devices, systems, and networks. These protocols ensure interoperability, standardization, and real-time communication, essential for the seamless operation of industrial automation and control systems. Below are detailed explanations of key communication protocols widely used in industrial applications [18, 19]:

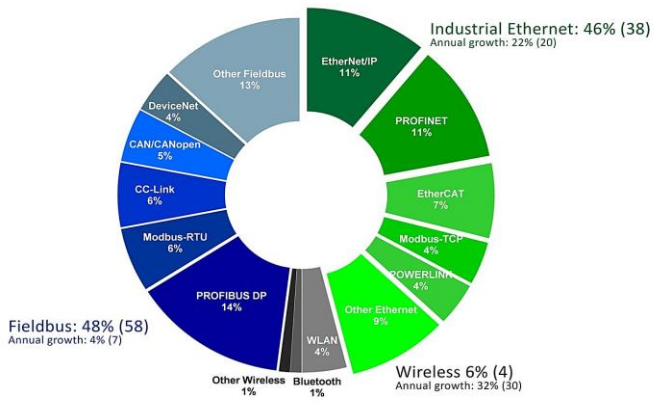


Figure 2. Industrial communication protocols

PROFINET (Process Field Net)

PROFINET is an Ethernet-based, real-time, and determinist industrial fieldbus. It permits high-speed information exchange among controllers (PLCs), field devices, and enterprise systems. Three communication classes—non-real-time, Real-Time, and Isochronous Real-time—can thus be realized by PROFINET to meet manifold automation needs. In this respect, it offers modular architecture for configuration, diagnostics, and device integration into Industry 4.0 environments.

MODBUS

MODBUS is a serial communication protocol that works on RS-232, RS-485, or TCP/IP networks. Its simplicity and reliability allow communications between devices such as programmable logic controllers, human-machine interfaces, and SCADA systems. The protocol uses a master-slave model and supports data types, discrete inputs, holding registers, and input registers.

EtherNet/IP

EtherNet/IP is the enhanced industrial protocol standard for industrial automation. The Common Industrial Protocol (CIP) develops seamless communication regarding control, safety, and diagnostics and is applied to any device over the industrial network. Such protocols build modern industrial communication with specific features and abilities, making different nodes of each interoperable to enhance productivity by supporting innovative automation solutions.

4. SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA)

The SCADA system is represented in Figure 3. It impacts the efficient and reliable running of WWTPs [3, 20]. A SCADA is a centralized control system that relies on sensors, PLCs, HMIs, and communication networks to monitor, control, and optimize plant operations using a human-machine interface [15]. A WWTP will be capable of real-time data acquisition and processing from critical components of the treatment plant through SCADA, such as pumps, aerators, sedimentation tanks, and chemical dosing units. It enables operators to visualize system performance, detect anomalies, and take corrective actions promptly, making operations efficient and compliant with environmental regulations [21]. Besides, the systems come fitted with predictive maintenance through analysis for trends that may indicate potential equipment failures before they actually happen [22]. Other advanced functionalities include remote access and integration with IIoT devices that are now available to constantly monitor and optimize plant performance. By automating routine tasks and providing comprehensive data insights, SCADA ensures that wastewater treatment facilities operate safely, cost-effectively, and sustainably [23, 24].

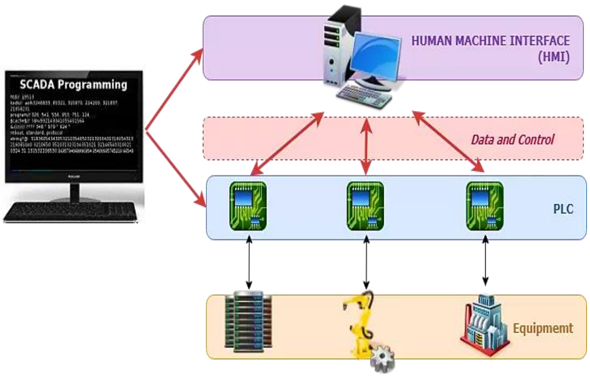


Figure 3. SCADA system

5. DESIGN AND IMPLEMENTATION OF THE PROPOSED SYSTEM

There are many advantages of using an integrated monitoring and control system to automate aeration units as a part of wastewater treatment plant usage the SCADA with programmable logic control (PLC S7-1200) by enhancing all operation stages as reduced operation coast, minimize human risks for the personal running these units, increase accuracy and highly efficiency with reducing consumption of the power, because of using the PLC ensures precise control for tracking the dissolved oxygen levels (DOL) required for the growth of bacteria and matching the operation of the aerators to increase this level when it decrease also enhance the data acquisition in real-time for specialist sensor. Figure 4 shows the communication between programmable Logic Control (PLC), Personal Computer System (PC-System), and Humen Machine Interface (HMI) via process field net (PRONET) according to suitable internet protocol (IP).

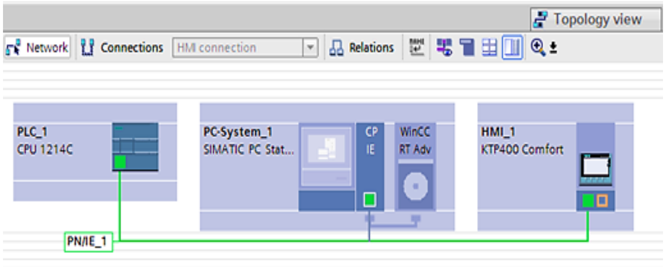


Figure 4. Industrial automation system topology

This diagram represents a typical topology view of an industrial automation system using the Siemens TIA gateway. It shows the connection between a SIMATIC S7-1200 PLC (PLC_1), a personal computer terminal (PC-System_1) running WinCC RT Advanced for SCADA or HMI applications, and a KTP400 Comfort panel (HMI_1). The PN/IE network (PN/IE_1) provides Ethernet-based connectivity between the devices. The green lines indicate the network connections in place, ensuring the exchange of data and control signals between the controller (PLC), operator interface (HMI), and monitoring system (PC terminal). This topology view helps visualize the system architecture and connectivity for configuration and troubleshooting of automated processes.

In wastewater treatment applications, the optimum dissolved oxygen concentration typically ranges between 4 and 6 mg/L, and maintaining this range is critical for effective aeration control and energy optimization. The PLC algorithm regulates aeration within this range by continuously adjusting the air supply based on real-time sensor feedback and process dynamics. Key parameters are monitored and analyzed to evaluate the control system's accuracy and responsiveness. Providing these quantitative assessments will enhance the scientific rigor of the study and support its claims regarding improved process efficiency and aeration energy savings.

Figure 5 shows the offline function block diagram (FBD) for the NORM-X_ SCALE-X function. This function converts the biochemical signal from any sensor output to a voltage signal, which the algorithm can handle. The circuit is used to convert the BOD sensor reading (IW64) to a desired range using the NORM_X and SCALE_X functions. First, the input value (IW64) between 0 and 27648 is printed to a percentage between 0 and 1 using NORM_X. Then, the resulting percentage (MD2) is converted to a range of 0.0-400.0 using SCALE_X, where the final result is stored in MD6 to represent the BOD value in understandable units (mg/L). In the same manner, use this function block diagram to describe other factors, such as COD and DOL, with a specific range for each.

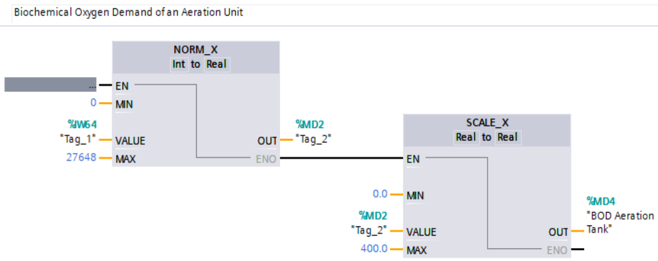


Figure 5. Offline function block diagram NORM-X – SCALE-X for BOD

The circuit in Figure 6 illustrates a logic operation using a Set-Reset (SR) function with comparators to determine the state of a digital output. The value MD14 "Tag_3," which represents a variable with a real value, is entered and compared to the constants 40.0 and 20.0. In the first comparison, if the value "Tag_3" is greater than 40.0, the Set input of the SR function is activated, making the digital output %Q0.0 "Tag_4" equal to 1 (ON). In the second comparison, if the value "Tag_3" is less than 20.0, the Reset input is activated, making Q0.0 equal to 0 (OFF). This circuit controls the ON and OFF of a process based on certain thresholds for the input values, such as turning an aerator or mixer ON when an upper limit is exceeded and turning it OFF when it falls below a lower limit.

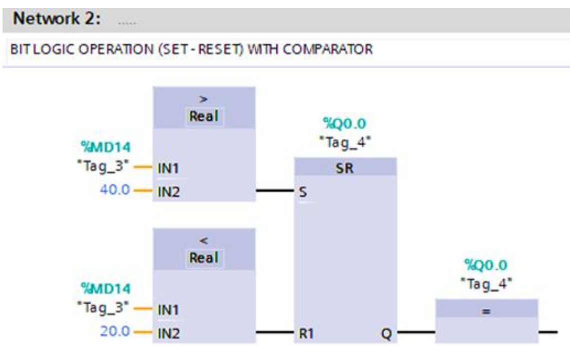
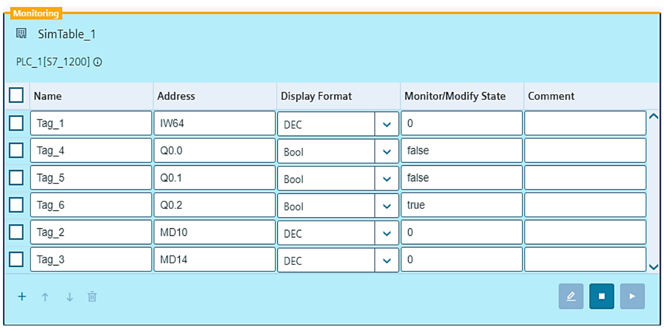


Figure 6. Off line function block diagram (set / reset) process



Monitoring

SimTable_1

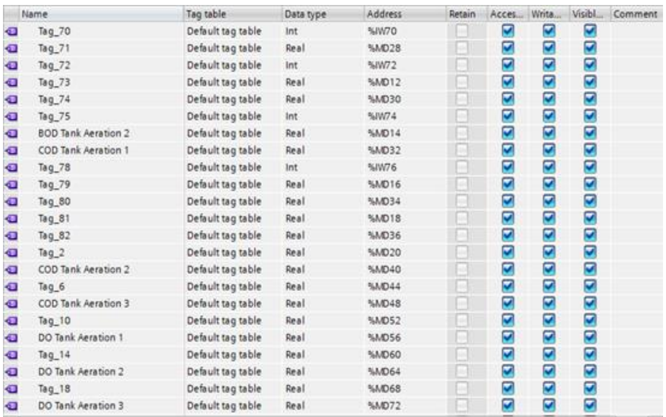
PLC_1[S7_1200]

Name	Address	Display Format	Monitor/Modify State	Comment
Tag_1	IW64	DEC	0	
Tag_4	Q0.0	Bool	false	
Tag_5	Q0.1	Bool	false	
Tag_6	Q0.2	Bool	true	
Tag_2	MD10	DEC	0	
Tag_3	MD14	DEC	0	

Figure 7. Simulation table for the input process

The monitoring table in the TIA Portal software is shown in Figure 7, which displays a set of variables used to monitor and modify the operating values of an S7-1200 PLC. The table contains columns such as Name to identify the variables and Address to identify memory locations such as "IW64" (input) and "Q0.0" (digital output). The Display Format column shows the display type, such as Decimal (DEC) or Boolean (Bool) values. The Monitor/Modify State column monitors and modifies values in real-time, with states including values such as "0" or "true/false." The table allows system analysis and troubleshooting during operation to ensure proper performance.

Table of variables (Tags) shown in Figure 8 used in PLC programming using TIA Portal. The table includes columns such as Name, which contains the variable names; Data Type (Int and Real) to specify the types of values stored; and Address, which indicates where the values are stored in memory. The Retain feature is disabled, meaning the values are not saved after a reboot. Some variables use functional labels such as "COD Tank Aeration", which helps improve clarity. Using more descriptive names and enabling the retaining feature when needed is recommended to improve system efficiency and maintainability.



Name	Tag table	Data type	Address	Retain	Acces...	Writa...	Visibl...	Comment
Tag_70	Default tag table	Int	%IW70	☐	☑	☑	☑	
Tag_71	Default tag table	Real	%MD28	☐	☑	☑	☑	
Tag_72	Default tag table	Int	%IW72	☐	☑	☑	☑	
Tag_73	Default tag table	Real	%MD12	☐	☑	☑	☑	
Tag_74	Default tag table	Real	%MD30	☐	☑	☑	☑	
Tag_75	Default tag table	Int	%IW74	☐	☑	☑	☑	
BOD Tank Aeration 2	Default tag table	Real	%MD14	☐	☑	☑	☑	
COD Tank Aeration 1	Default tag table	Real	%MD32	☐	☑	☑	☑	
Tag_78	Default tag table	Int	%IW76	☐	☑	☑	☑	
Tag_79	Default tag table	Real	%MD16	☐	☑	☑	☑	
Tag_80	Default tag table	Real	%MD34	☐	☑	☑	☑	
Tag_81	Default tag table	Real	%MD18	☐	☑	☑	☑	
Tag_82	Default tag table	Real	%MD36	☐	☑	☑	☑	
Tag_2	Default tag table	Real	%MD20	☐	☑	☑	☑	
COD Tank Aeration 2	Default tag table	Real	%MD40	☐	☑	☑	☑	
Tag_6	Default tag table	Real	%MD44	☐	☑	☑	☑	
COD Tank Aeration 3	Default tag table	Real	%MD48	☐	☑	☑	☑	
Tag_10	Default tag table	Real	%MD52	☐	☑	☑	☑	
DO Tank Aeration 1	Default tag table	Real	%MD56	☐	☑	☑	☑	
Tag_14	Default tag table	Real	%MD60	☐	☑	☑	☑	
DO Tank Aeration 2	Default tag table	Real	%MD64	☐	☑	☑	☑	
Tag_18	Default tag table	Real	%MD68	☐	☑	☑	☑	
DO Tank Aeration 3	Default tag table	Real	%MD72	☐	☑	☑	☑	

Figure 8. Database variables (Tags) for the proposed system

The SCADA system used in this research provides high-performance real-time monitoring of the aeration tank's operation, contributing to improved operational efficiency and immediate response to changes. However, the study focused on the system's functional and application aspects, as data is collected through programmable controllers (PCs) represented by digital and analog hardware and addressable signals, as described in the proposed work.

Energy consumption in bacteria ventilation systems is important as the equipment of this station has high power consumption. Therefore, using the SCADA system with PLC in such a system and programming the system with a scenario that suits the precise operation of the equipment instead of traditional methods of control without controllers and algorithms in which the operation is not studied causes energy consumption of 90 % of the proposed design.

The proposed system is a highly complex and fully integrated control and communication network specifically designed for real-world wastewater treatment operations. Unlike traditional control systems, which are typically rule-based and designed for single-process regulation, our system ensures seamless data exchange, adaptive process optimization, and multi-variable coordination across the entire treatment plant. While Fuzzy Logic Control (FLC) and Model Predictive Control (MPC) offer effective control for specific localized processes, they lack the holistic integration required for a large-scale, multi-stage wastewater treatment facility. The PLC-based control system, combined with SCADA integration, enables real-time monitoring and adaptive control, ensuring stability, efficiency, and regulatory compliance across various subsystems, from aeration and sedimentation to chemical dosing and sludge management.

6. RESULTS AND DISCUSSION

The results show that the aeration unit process in wastewater treatment significantly improves pollutant treatment efficiency and reduces energy consumption. The design relies on dynamic control of dissolved oxygen levels using advanced sensors and intelligent control systems to precisely adjust the airflow according to the actual needs of biological treatment. This approach has improved the removal efficiency of organics and reduced the residual organic load, contributing to the achievement of environmentally compliant treated water quality. In addition, improved air distribution and monitoring of biochemical signals such as BOD and COD have significantly reduced operating costs, making the design more environmentally and economically sustainable. Figure 9 shows the block diagram of the FBD function of the NORMX_SCALEX function used to convert the sensor reading output (BOD, COD, and DO) into a voltage signal the algorithm can handle. As shown, the input value is (0), and the output is (0). Figure 10 shows the online block diagram (FBD)of the NORM-X– SCALE-X function operating at 0 and 14000 input values, which converts the sensor reading output into a voltage signal that the algorithm can handle.

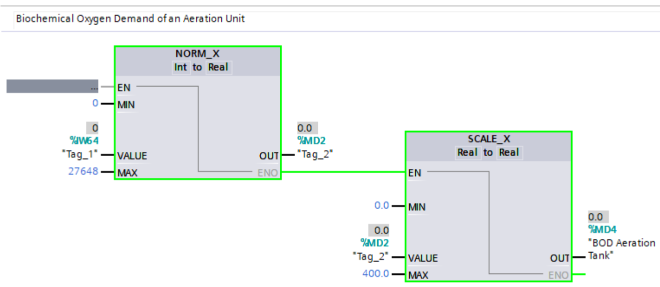


Figure 9. Online function block diagram (NORM-X – SCALE-X) for BOD with no signal

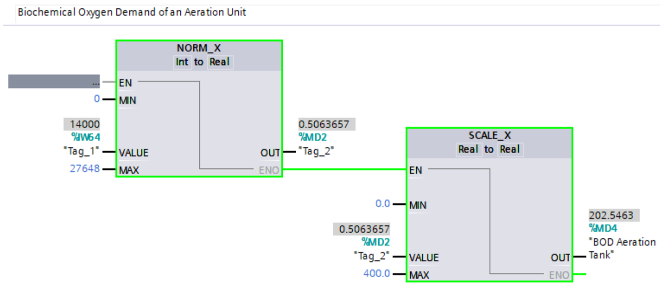


Figure 10. Online function block diagram (NORM-X – SCALE-X) bod with signal

The SCADA system interface designed for wastewater treatment, particularly for bacterial monitoring and control, is also highly advanced. Unlike legacy software platforms that lack flexibility and adaptability, our system is based on modern Siemens interface software technologies through the TIA Portal, enabling the development of sophisticated and customizable interfaces. These advanced interfaces support real-time data visualization, dynamic process control, and seamless integration with analytics. Our design offers an optimized user interface for effective operation with the capacity to continuously adapt and upgrade in the future. Unlike rigid frameworks of legacy systems, our solution offers scalability and customizability to make the interface evolve as technology improves and operational requirements demand.

System stability in the long term was ensured by making use of the latest, high-end software particularly designed to foster scalability, flexibility, and constant optimization. System resilience, efficiency, and reliability can be properly measured through analysis of short-term operating data under a simulated long-term operating setting. Proactive monitoring with the detection of performance deviation at an early point, adaptive control mechanism adjustments, and forecasted maintenance action can be provided by this practice. Apart from that, utilizing real-time analytics and automatic fault detection ensures the system is highly efficient and resilient even in changing and uncertain environmental conditions.

Figure 11 shows the ON line function block diagram (FBD) for the comparator function algorithm (Greater than / Less than) and (SET/RESET) function algorithm. The condition for this comparison operation is (If the output real value of the SCALE_X function is less than 50, then the RESET function is active). Figure 12 shows the ON line function block diagram (FBD) for the comparator function algorithm (Greater than / Less than) and (SET/RESET) function algorithm. The condition for this comparison operation is (If the output real value of the SCALE_X function is greater than 50, then the SET function is active).

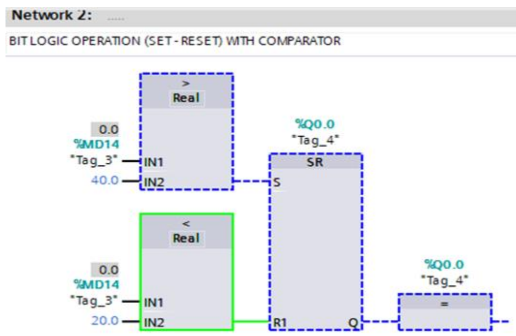


Figure 11. Online function block diagram (SR) scenario process

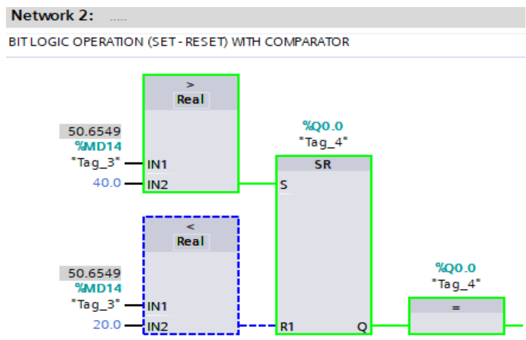


Figure 12. Online function block diagram (SR) for (14000) input

The simulation Table shown in Figure 13 represents a monitoring table in the TIA Portal software for the Siemens PLC S7-1200, which is used to monitor and manage values associated with variables or tags during PLC operation. The table contains several columns, each of which has a specific function:

Name: Specifies the tag's name used in the program to facilitate its identification during monitoring.

Address: Indicates the memory address in the PLC that stores the value or status associated with this tag. For example, IW64 refers to a digital entry in memory.

Display format: Specifies how the value is displayed, such as decimal (DEC) or logical values (Bool).

Monitor/modify state: This shows the tag's current value during monitoring and can be modified in some cases. For example, Tag_1 shows a value of 14000, and Tag_4 is a logical status with a " true " value."

Comment: This field requires user comments to document the label's functions or any additional notes.

This table allows the user to monitor the PLC's inputs, outputs, and data values, which helps to verify performance, diagnose faults, or make adjustments directly during the industrial control process. The inclusion of an emergency response system to deal with situations such as equipment failure or sudden changes in water quality lies in the addition of other treatment units that can be easily developed by implementing this system in the environmental reality in a specific location and by testing existing water rather than simulating the testing of the designed system as in our work.

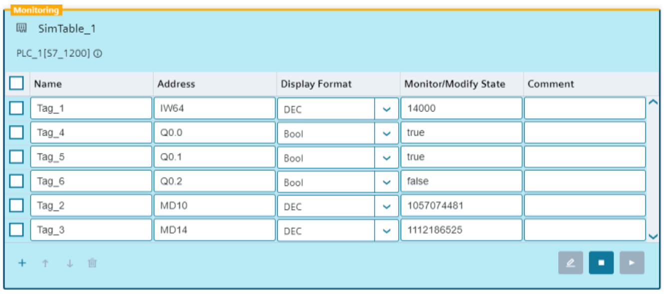


Figure 13. Simulation table for input

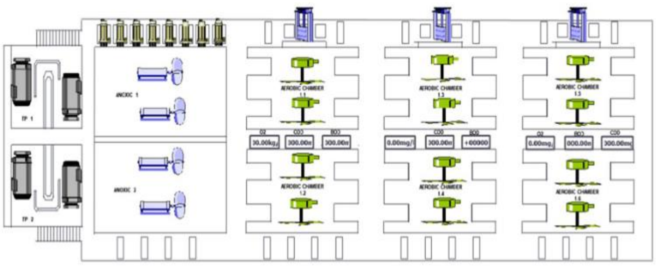


Figure 14. GUI of SCADA

Figure 14 shows the graphical user interface (GUI) - SCADA, which represents the design of an aeration within a wastewater treatment plant. The process begins with receiving tanks (Treatment Plants 1 and 2), where raw water is collected and pumped using electric pumps to anaerobic chambers. In these chambers, anaerobic bacteria decompose organic matter and remove nitrates. The water is then transferred to aerobic chambers distributed over six units, where mechanical aerators are used to increase the dissolved oxygen concentration, which supports the activity of aerobic bacteria to decompose organic matter and reduce biological oxygen demand (BOD). Chemical oxygen demand (COD) water quality and treatment parameters are monitored using specialized sensors that measure dissolved oxygen and organic matter concentration. At the same time, the process is managed through electrical control panels to ensure optimal and accurate operation.

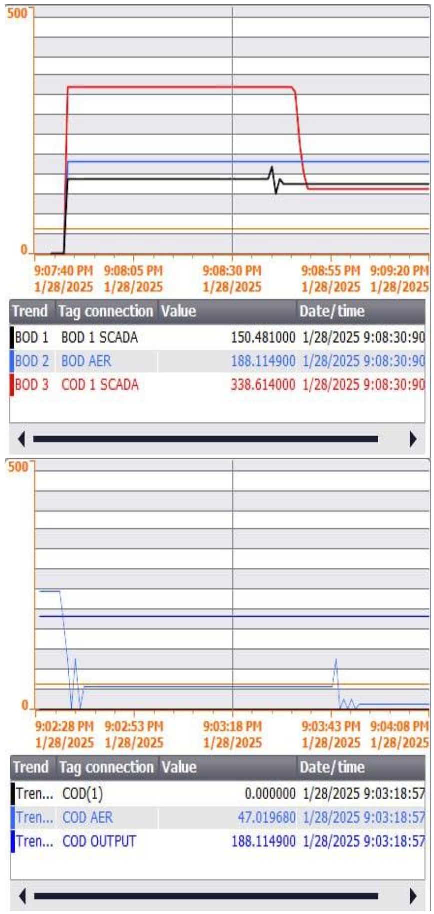


Figure 15. Sub GUI SCADA data curve

Time-lapse data of the SCADA system in Figure 15 presents variations in the values measured for several environmental variables. The BOD SCADA presents a value of 150.481000 mg/L with slight variations, while the BOD AER presents constancy at 188.114900 mg/L with no great variation. In contrast, the COD SCADA rises to 338.614000 mg/L and then suddenly drops, which could show changes in operation or environmental conditions. This behaviour characterizes the interaction within the system that, with the action of processing or abrupt discharging by certain materials, may be acting. This graph shows continuous monitoring is necessary to avoid undesirable effects and ensure process stability. It also forms the basis for corrective decisions in maintaining efficiency in the system, ensuring standards, as required, are made.

Performance data and long-term operating results are critical in assessing the reliability and stability of the S7-1200 PLC and SCADA system integration in wastewater treatment plants. Performance data includes key metrics such as response time, system availability, energy efficiency, and control accuracy. Long-term operating results include failure rates, communications robustness, adaptability to environmental and operational changes, and compliance with industry regulations. By analyzing this data in practical scenarios, the system's ability to enhance operational efficiency, reduce costs, and maintain regulatory compliance can be verified. However, this designed system is only understandable to designers and implementers. Such systems are important in real-world environments, and detailed studies as detailed as these are lacking, making their maintenance and optimization highly dependent on specialized expertise.

7. CONCLUSIONS

The design and implementation of an aeration unit in a wastewater treatment plant with PLC S7-1200 and SCADA stand for the latest technological solution to make the processes of aeration, biological process control, and the raising of the general operational performance of the plant more effective. In this regard, the present system enables automatic control that may enhance biodegradation processes of organic matter and reduce energy consumption while the system is in use. The use of PLC S7-1200 relies on the connection of probes and sensors measuring important parameters: dissolved oxygen concentration, water temperature, and biochemical signal rates. A complete GUI for remote monitoring and control is provided by the SCADA system, where an operator can monitor the performance of the systems in real-time, get warnings in case of malfunction, and make corrections manually if needed. This integration of PLC and SCADA enhances process reliability and reduces manual interventions, reducing downtimes and improving energy efficiency. This scheme is one of the applications to manage such critical infrastructures intelligently, improve environmental sustainability, and reduce operational costs in a Wastewater Treatment Plant.

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