Design of the automation system for the chemical water treatment plant of the oil refinery in Santiago de Cuba

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ABSTRACT

Production processes in modern industry demand higher levels of quality and efficiency in their products. The "Hermanos Díaz" Oil Refinery Company of Santiago de Cuba, a fundamental pillar in the economic and social development of the eastern part of the country, has a chemical water treatment plant responsible for supplying processed water to the industry's boilers. The current state of this plant supports the lack of optimal physical-chemical conditions in the water it delivers and, therefore, the gradual deterioration of the boilers. This work conceives an automation solution for the dosing, precipitation, and clarification processes of the chemical water treatment plant. Control systems were designed based on instrumentation proposals, enabling reliable measurements and practical actions. In addition, an algorithm of supervision and automatic control using a programmable programmable logic controller (PLC) is presented, making the plant capable of delivering a product in optimal conditions. Images were designed for local and remote process control using a human-machine interface (HMI) panel and a supervisory control and data acquisition (SCADA) system. Finally, an automation architecture with a decentralized periphery is proposed to ensure safety and accuracy in the system's decision-making through communication protocols.

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1. INTRODUCTION

Industries demand high technology in their production flows to guarantee high efficiency and safety. The modern world is committed to initiatives minimizing manual, tedious, repetitive techniques, and advocates automated techniques that optimize production time and serve as tools to make the most of raw materials and be able to obtain products with high-quality standards. Chemical water treatment plants are facilities that timely resolve water quality needs and constitute the fundamental element that extends the useful life of industrial boilers [1], [2]. The "Hermanos Díaz" Oil Refinery Company of Santiago de Cuba is an industry belonging to the Cuba-petroleum union (CUPET) and the Ministry of Energy and Mines of Cuba. This entity aims to produce and market petroleum derivatives, emphasizing quality and care for the environment to satisfy the national market's needs and contribute to the country's sustainable development.

His company had an old technique for dosing chemicals to treat water, which did not guarantee a quality final product. Currently, this technique is not used, and automated drives that need to enable the efficiency of the plant have been implemented. The treated water that supplies the company's boilers is outside the hardness standards because the levels in the dosage of calcium hydroxide, $Ca(OH)_2$, and aluminum hydroxide $Al(OH)_3$, which constitute vital chemicals for clarifying and reducing the total hardness of the water. Furthermore, the filtering process is carried out without knowledge of its effectiveness. The incorrect water treatment process generates imports of raw materials for boiler repairs and reduces their useful life. This situation causes operational inefficiency and a lack of optimal physical-chemical conditions in the final product of the chemical water treatment plant of the "Hermanos Díaz" Oil Refinery in Santiago de Cuba. To solve this problem, an automatic control system for the physical-chemical variables that intervene in the processes of this plant is proposed [3]-[5]. The control architecture that is analyzed and proposed is based on the programming of a programmable logic controller (PLC), which will respond to the demands of the process and guarantee effective compliance with the plant's objectives.

2. METHOD

The water to be treated comes from wells near the oil refinery and is pumped by the pumping system to an elevated tank. From said tank, it descends by gravity to a precipitator tank (composed of a tank of raw or unprocessed water and another tank of clean or processed water), where the water's hardness is reduced through the treatment of lime and aluminum sulfate approximately 40-50%. The water treatment in this precipitator aims to convert the calcium and magnesium bicarbonates into insoluble neutral carbonates and transform the magnesium salts into insoluble hydroxides. Aluminum sulfate is used as a coagulant.

The precipitate resulting from the process descends to the bottom of the tank, helped by the coagulant. According to the retention time and agitation, the precipitates are kept in suspension, which will serve as a nucleus for rapidly forming new precipitates. Subsequently, the water passes to the clean water pond, and from there, the water is pumped until it reaches the anthracite filters to eliminate possible traces of lime and aluminum that have been carried along, as well as other suspended matter, obtaining the clarified water that goes to the zeolite exchangers. In these exchangers, softening is carried out by ion exchange using sodium zeolite. In contact with raw water, this resin retains calcium and magnesium ions instead of delivering sodium ions, whose salts are always soluble, so they do not cause scale. These salts accumulate in the dome of the boilers, from where they are evacuated by extraction. After passing through the exchangers, the water has the quality needed to feed the boilers, with a total hardness of up to 5 mg/l. It is then sent to the deaerator, whose function, in addition to heating the water, is to extract approximately 90-95% of the oxygen dissolved in the water. In addition, carbon dioxide and other non-condensable gases are removed before being introduced into the boilers to prevent corrosion, caustic fragility, and scale.

The addition of calcium oxide and aluminum sulfate is currently carried out without dosing. It is controlled by electrical drives that are adjusted according to the time defined by the operator. Now, these drives do not guarantee the necessary amount of each additive. Furthermore, the level control in the clean water tank has an inefficient measurement system, and the regulation valve at the inlet of the precipitator is pneumatic. On the other hand, the level of sludge generated in the raw water pond is measured with a mechanical system; all the softener valves are manual, and the filters have pressure measurement through manometers [3]-[5].

2.1. Control and measurement of lime in the hopper and its weighing on the belt scale

To control the filling process in the lime hopper, motor M1 is activated using a magnetic contactor until the level rises to a high level (3 m). Once the hopper is complete, the M1 motor will be turned off, and this state will change when it descends to the low level (0.5 m). This process will operate cyclically whenever it is in automatic mode and represents an on-off control.

After the hopper level is at a high level and the amount of water in the calcium hydroxide mixing tank exceeds the average level, the M2 motor will be turned on to drain the limescale that remains adhered to the walls of the hopper. This operation is carried out for 20 seconds, and then a soft starter is activated that allows the gradual descent of lime to the belt scale using the worm screw coupled to the M3 motor. A countercurrent technique is applied to brake this motor for a time entered by the operator on the Settings screen of the human-machine interface (HMI) panel.

The addition of water to the mixing tank is carried out through volumetric dosing. The amount of lime added will depend on this amount, a process carried out by mass dosing. To relate both types of dosages and obtain the desired mixture, it must be converted from volume units to mass units through the expression [4] implemented in the controller algorithm.

$$m = V * p \quad (1)$$

where, m is mass (kg), V is volume (m^3), and p is density (kg/m^3).

The control implemented in the PLC algorithm, Figure 1, guarantees the modification of the reference point (lime-water ratio), set by the operator on the settings screen of the HMI panel. Every 2 minutes, a sampling of the total hardness variable is carried out. Suppose it is outside the established range. In that case, the algorithm increases the mentioned ratio by 10%, which, when divided by the amount of water entered into the mixing tank, will result in a lower dosage of lime. This leads to a lower amount of salts dissolved in water, lower electrical conductivity (EC), and, therefore, a decrease in the total hardness of the processed water. Where C/H is the conversion from conductivity to total hardness, implemented in the PLC control algorithm, K represents the amount of water/lime-water ratio, CM-M2, CM-M3, and CM-M4 represent the magnetic contactors coupled to the motors M2, M3, and M4 respectively. Cm-brake is the magnetic contactor for countercurrent braking applied to the M3 motor.

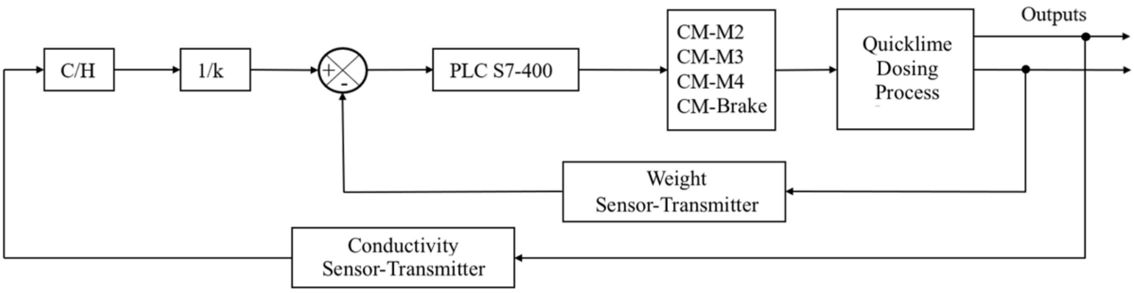

Figure 1. Ratio control for calcium oxide weighing

2.2. Control and measurement of calcium hydroxide and aluminum hydroxide levels

To control the level of calcium hydroxide, the water inlet valve to the mixing tank (VC1) is opened, and the tank is filled until reaching a high level (0.8 m). In addition, a certain amount of lime is added, thus obtaining lime dissolved in water. When the tank reaches its maximum level, the motor (M5), which has a paddle attached to mix both substances and obtain a homogeneous mixture, is turned on; this mixing will take 1 minute. After this time, the engine turns off, and the valve (VC2) opens, allowing the milk of lime to pass through to the pump (B1), which drives the mixture to the precipitator tank. The valve (VC2) and the pump (B1) are turned off when the lime milk inside the tank (T1) is below the average level (0.5 m). In maintenance operations or initial process conditions, the valve VC3 is opened to drain the lime sludge for 30 seconds; if the sludge level is less than the minimum (0.1 m), the valve (VC3) is closed.

To control the level of aluminum hydroxide, the valve (VC4) is opened, allowing water to pass through to the mixing tank until this tank reaches the maximum level (1.8 cm). Then, the valve (VC5) is opened, allowing the passage of aluminum sulfate to the mixing tank. This valve will be open depending on the opening time of VC4 and the pre-established relationship between aluminum sulfate and water. Subsequently, this valve is closed, closing the passage of aluminum sulfate, and the valve that allows the flow of compressed air (VC6) is opened, which circulates for 1 minute through a coil with small holes located inside the tank to mix both substances. After this time, valve VC6 is closed, and simultaneously, the valve (VC7) is opened, allowing the aluminum hydroxide to the pump (B2); the latter drives the aluminum hydroxide mixture to the precipitator tank. Valves VC6 and VC7 close when the mix inside the tank is below the low level (0.1 m), and pump B2 turns off 5 seconds after closing valves VC6 and VC7. The adjustment for the dosage of aluminum sulfate is made through the HMI panel, through which the relationship between aluminum sulfate and water is controlled. In addition, the process control for dosing the aluminum sulfate used in the plant has the same characteristics as the control implemented for weighing calcium oxide described in the block diagram shown in Figure 1.

2.3. Control and measurement of mud and water levels in the precipitator tank

To control the level of the lime cushion in the raw water tank, calcium hydroxide, aluminum hydroxide, and water from the wells that supply the company must be continuously added. These three substances are responsible for forming the lime cushion, and whenever the maximum level is reached, the lime sludge drain valve (VC10) must be opened for 1 minute. In the implemented algorithm, the M6 motor is electrically connected when defining the initial conditions and is turned off when the “stop” state is requested.

Water level control is done through ultrasonic level measurement in the clean water tank by opening the regulation valves VC8 and VC9. The opening time of said valves will depend on the number of boilers in operation set in the HMI. The outlet valve of the VC9 precipitator will always be open at 75% of the opening value of VC8 to achieve level stability by decanting into the clean water tank.

3. RESULTS AND DISCUSSION

To make the proposal for the instrumentation required in the process, sensors-transmitters, electromagnetic contactor, actuators, controller, input/output modules and operator panel, different selection criteria were taken into account to guarantee efficiency and quality in the process of water treatment [5]. To detect the water flows in the feed pipe to the quicklime mixing tank and in the water inlet pipe to the raw water tank, it is proposed to use flowmeters that measure and send their signal to the PLC. This same flowmeter is proposed to detect the circulation of calcium hydroxide and aluminum hydroxide from the mixing tanks. On the other hand, to control the level in the clean water tank and in the quicklime storage hopper, it is proposed to use two ultrasonic level transmitters, which will send their signal to the PLC. Capacitative level transmitters were used to display the level of the mixing tanks on the HMI panel, with high, medium, and low-level indications.

The proposed automation system also considers the measuring instruments to measure the pH value and the water temperature that guarantee that this liquid reaches all the units and systems of the process with the required parameters. The standard operating range of pH is between 9.0 and 9.7, and water temperature is between 25 and 35 °C. A manometer is proposed to measure the absolute pressure value in each filter to determine if the anthracite filters are clogged or dirty. The pressure taps are located at the inlet and outlet of each filter, and the operating value must not exceed one kgf/cm^2 so that an alarm is not activated on the HMI panel.

The total hardness in water treatment processes is measured through laboratory tests applying various methods. The replacement of the manual technique for measuring the total hardness value in the laboratory with an automated solution implies an indirect measurement of the total hardness of the water through a variable that relates to it, which may be the EC of the treated water [6]. A study carried out corroborates this statement and presents the following expression for the calculation of the total hardness of water (D_t) in mg/l from the EC in µS/cm [7]. The values used in this study of the physical-chemical characteristics of the water were obtained from the analysis carried out in some freshwater wells in Costa Rica [8]. At this moment, the “Hermanos Díaz” Oil Refinery Company of Santiago de Cuba is engaged in carrying out a detailed and specific study on the physical and chemical characteristics of the water from the wells from which it is supplied, in this way, a better adjustment of the proposed controls [5].

$$D_t = 0{,}0003 * EC^2 + 0{,}3418 * EC + 0.2710 \quad (2)$$

3.1. Field instrumentation proposal

To carry out flow measurements, the SITRANS FM MAG 5000/6000 electromagnetic flowmeter is proposed [9], and to obtain ultrasonic level measurements, the SITRANS Probe LU240 level transmitter is presented [10]. The SITRANS LC300 capacitive level transmitter is proposed to carry out level measurements in the mixing tanks due to the chemical conditions present in the process [11]. Furthermore, to measure lime cushion, the SITRANS LPS200 transmitter, which is a rotary paddle switch [12], is proposed, and to determine absolute pressure values, the SITRANS P series DS III pressure transmitter is used [13].

To measure the weight of the quicklime, the milltronics WD600 belt scale is proposed because this scale allows the transportation of the material and its weighing and also has weight sensors and transducers attached that translate the weight measurement into a current signal [14], [15]. To measure pH, the Memosens CPS11E digital sensor [16] and the Liquisys CPM253 pH/redox transmitter [17] are proposed, and to determine the conductivity value, the Indumax CLS50D digital sensor [18] and the conductivity transmitter are proposed. Liquisys CLM253 [19]. To allow the passage of water in the designed on-off control loops, electric butterfly valves are proposed, model Wafer HK60-D, which are used to control large flows of fluids at low pressure and have good hermetic seal with special coatings. on the seat [20].

The Covna brand regulation valve, globe type, TCV Series, is proposed to control the water flow at the inlet and outlet of the precipitator. This valve is designed for general-purpose applications in industry. Its modular design allows it to be easily modified using different Trim combinations since it has an inherent linear characteristic and is a double seat [21]. In addition, it has a flow coefficient (*Cv*) equal to 98 for a 10-inch line and a flow coefficient (*Kv*) equal to 14, approximate values to the results produced by the calculations carried out in our study process. The chemical water treatment plant of the "Hermanos Díaz" Oil Refinery has a maximum flow (Q_{max}) equal to 193 m^3/h, the pressure drop (ΔP) is equal to 5 kgf/cm^2, the control signal (S_c) has a range of 4 mA to 20 mA and the specific gravity of water (G_s) is equal to 1 m/s^2.

$$Kv = \frac{Q_{máx}}{S_c} = \frac{193\ m^3/h}{20\ \text{mA} - 4\ mA} = 12.06\ (l/s) \tag{3}$$

$$Cv = \frac{Q_{máx}}{\sqrt{\frac{\Delta \text{P}}{G_S}}} = \frac{193\ m^3/h}{\sqrt{\frac{5\ kgf/cm^2}{1\ m/s^2}}} = 86.16\ (m^3/h) \tag{4}$$

To perform countercurrent braking, the four-pole SIRIUS 3RT2 electromagnetic contactor [22] is proposed, and for the gradual start of the motor that moves the screw in the quicklime dosing process, it is suggested to use the SIRIUS 3RW40 soft starter from Siemens [23], which was chosen under the technical selection criteria for soft starters.

3.2. Control architecture selection, configuration, and programming

A decentralized periphery is chosen as the control architecture due to the geographical distribution of the places where measurements and actuators of the proposed control system will be located, Figure 2. This decision facilitates wiring and maintains the company's control systems standard. The ET200-M model IM 153 [24] was selected as the decentralized peripheral module for this.

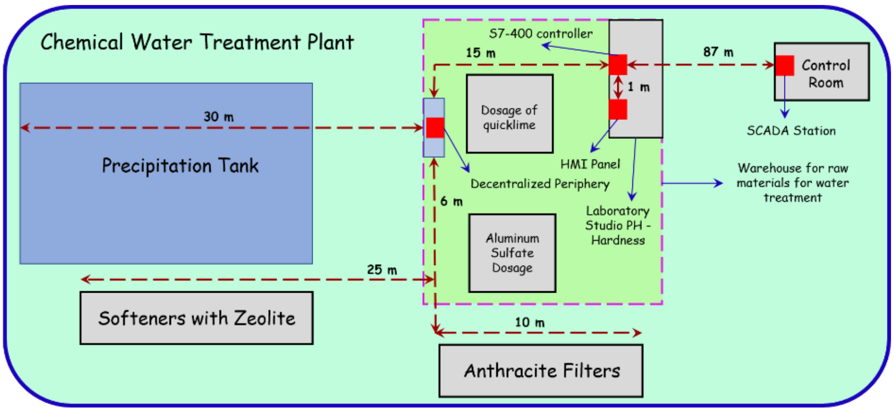

Figure 2. Geographic distribution of the proposed control system

To choose the control and data acquisition instrumentation, selection criteria, process characteristics, and the company's technical requirements were considered. For data acquisition, the distance between its location and the control system was analyzed according to the output voltage and current ranges of each measuring instrument, Figure 2. The Siemens SIMATIC S7-400 PLC, CPU 416-3 PN/DP, model 6ES7416-3ES07-0AB0 [25] is selected since it has six digital inputs for which a 16×24 VDC SM421 digital input module was used. The PLC also has 31 digital outputs, of which two SM422 digital output modules of 16×24 VDC/1.5A and one of 8x24 VDC/0.5A were used. It also has 18 analog inputs, using 3 SM431 8×14 bit analog input modules, and two analog outputs, using a 4×12 bit SM432 analog output module [26].

According to the advantages offered by using HMI panels, the most common criteria for their selection, the characteristics of the application in question, and the aspirations of the company and the Santiago refinery in general, the SIMATIC panel is selected. HMI KTP900 Basic PN, model 6AV2123-2JB03-0AX0 [27]. According to the communication interface that the selected HMI panel has, in correspondence with the interface of the selected PLC, the Profibus DP communication network [28] is established between these two devices.

To select the appropriate electrical power source, it is necessary to know the consumption of each field equipment and possible losses in the electrical circuit. The electrical connection between this equipment and the source will have a parallel distribution so that the total current consumption will equal the sum of all the currents required by said loads. For the PLC and HMI panel, the power supply with 24 V/5 A redundant architecture, SITOP PSU8200 [29], with a SITOP PSE202U [29] selectivity module [30] and a SITOP UPS1600 battery [31] with a duration of 50 minutes. The SITOP PSU100S [32] 24 V/20 A power supply, with redundant architecture, a SITOP RED 1200 selectivity module [33], and a battery similar to the one mentioned above, is selected for the ET200-M modular station measuring instruments and 24 VDC actuators. This configuration was performed in the TIA Selection Tool 2021 software, Figure 3. As a safety measure, the current consumption of the chosen CPU was added; in the event of a power failure, the AC power supply to the actuators that require it is not guaranteed.

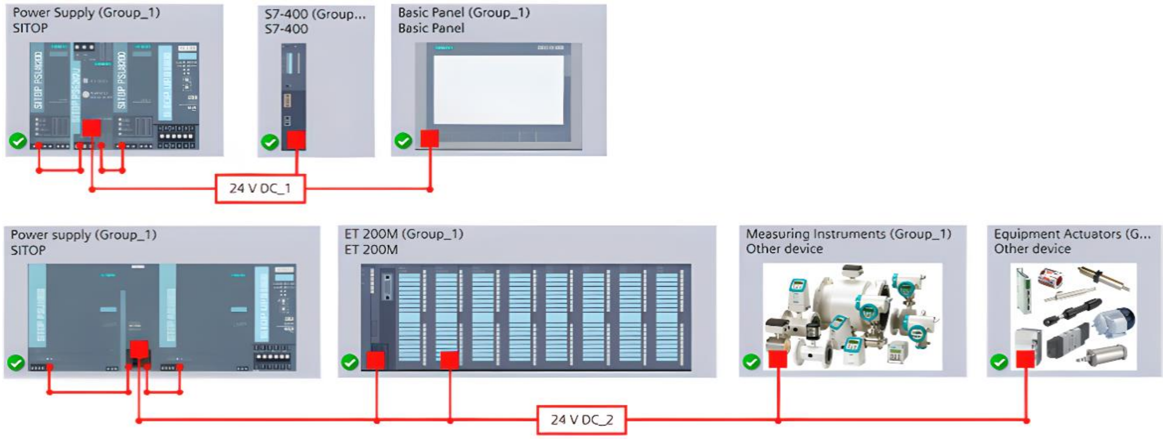

Figure 3. Electrical power distribution for the proposed control architecture

The control algorithm, configuration, and simulation of both the PLC and the HMI panel are carried out using the totally integrated automation portal (TIA) v16 development software, which includes step 7 professional for the programming and configuration of the S7 PLCs. 1500, S7-1200 and S7-300/400 and the S7-PLCSIM to simulate S7300/400. The programming logic of the selected PLC is carried out, taking into account a main organization block (OB1) where the operating system executes the routine in this block cyclically. In addition, five function blocks permanently store their input, output, and input/output parameters in instance data blocks and nine instance data blocks, all based on the more than 200 variables declared in the "Variable Table" of the PLC. All programming is carried out in Ladder language (LD), which takes into account the graphical representation of Boolean expressions, combining contacts or conditions with coils or results [34] and is structured as follows:

- OB1: in this block, all the function blocks are integrated, and with it, all the tasks to be executed by the control algorithm. If the conditions of "boot state enabled," "emergency disabled," and "mode enabled" are met, the automatic operation mode routine begins. If the emergency is activated, the "Emergency Treatment" actions will be executed. The "Manual Mode" actions will be performed if the manual operation mode is activated. The "Shutdown Treatment" will be executed if the Plant shutdown is requested.
- Treatment during shutdown and in a state of emergency: in this state, all motors and pumps are turned off, all control valves are closed, a signal is sent to open the valve VC3 and drain all lime sludge from the lime dosing mixing tank, and the valve VC3 is opened VC10 to drain all the sludge from the lime bed of the precipitator tank (both valves open for 1 minute). In an emergency, all control valves are closed, and all motors and pumps are turned off immediately.
- Automatic and manual mode: the automatic mode takes into account the tasks in each of the control loops. In manual mode, you can fully open the control valves and turn the motors and pumps on or off.

3.3. Human-machine interface panel configuration

More than 200 variables are declared in the "HMI Variables" table. Up to two administrators can be configured in the "User Administration" window. The first one has the name "Operator" and has permission to supervise all protected images of the HMI panel under the default password "OP123". The second administrator is named "Engineer" and has permission to view the same images as the operator and make any changes to the panel under the default password "ING 1234", Figure 4. In the protected "HMI Alerts" window, 12 "bit alerts" are programmed in the "Alarm" category, which corresponds to the 12 addresses, inversely, of the variables declared in the "Alarms" function block in the PLC. In the protected "Settings and Maintenance" window, only the "Engineer" can adjust the different parameters for the correct operation of the plant, including softener maintenance operations. The status change is displayed in dark green (closed/off) and light green (open/on) for all status shows that do not represent measurements, Figure 4.

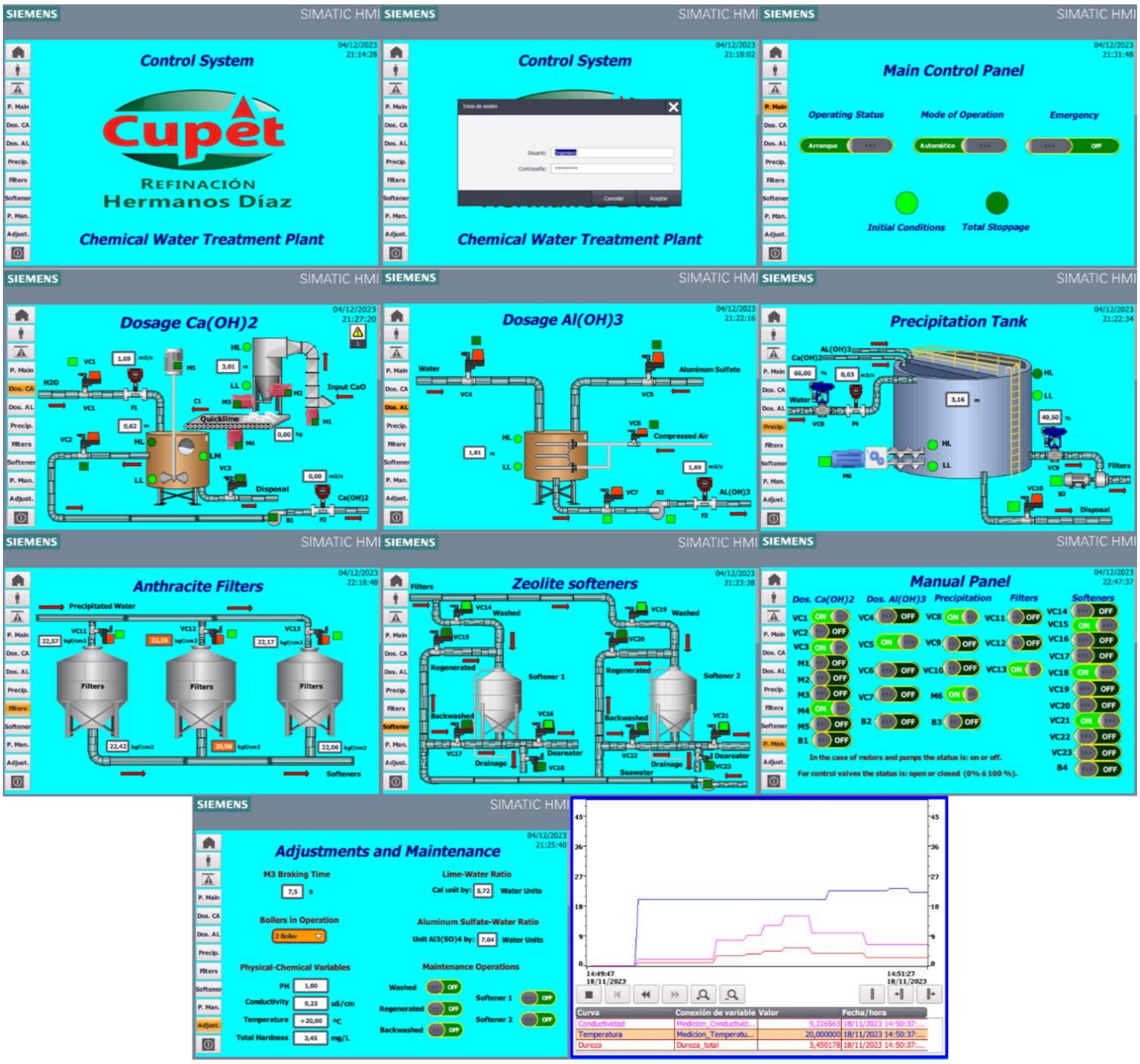

Figure 4. Images of each process described are configured in the HMI and graphic panel for quality control in the supervisory control and data acquisition (SCADA)

3.4. Supervisory control and data acquisition system configuration

SCADA is a software application designed to run on computers and monitor and control different systems and processes in real-time. It also provides all the information generated in the production process so other users can access it [35]. The supervisory system of the chemical water treatment plant of the "Hermanos Díaz" Oil Refinery was designed using the WinCC Basic software from Siemens, included in the TIA Portal v16 software. No server was used for communication because there is total compatibility between the sensors and actuators since they belong to the same manufacturer, Figure 5. Three levels of access were created to guarantee the security of the designed supervision system. The "Operator" level can only monitor the plant processes, the "Administration" level can monitor, adjust, and modify all parameters, and the "Management" level can monitor and obtain a record of the production and quality parameters for control of resources.

The screens developed in the SCADA system correspond to those designed for the HMI panel. Figure 4 shows that only a window was added for quality-production control and another window to view and store the events in the control system. These could be alarms, connections, electrical supplies, and other categories. The quality-production control window shows, through a graph, the behavior of the electrical conductivity and temperature measurements and the calculation of the total hardness of the water, offering a visual balance of the relationship between these three variables, Figure 4. In addition, this screen has counters for the raw materials used in the dosing processes. Finally, the creation of historical records was configured to evaluate the behavior of the fundamental variables of the water treatment process.

The communication established between the PLC, the HMI panel and the SCADA corresponds to an Ethernet network [36], which enables the exchange of information for the supervision and control of the process. The PLC will be configured as a master to govern the hierarchical control structure, allowing information management of the entire Plant control system. Furthermore, the PLC is connected via the Pofibus DP network to the decentralized periphery of the ET200-M modular station, Figure 5.

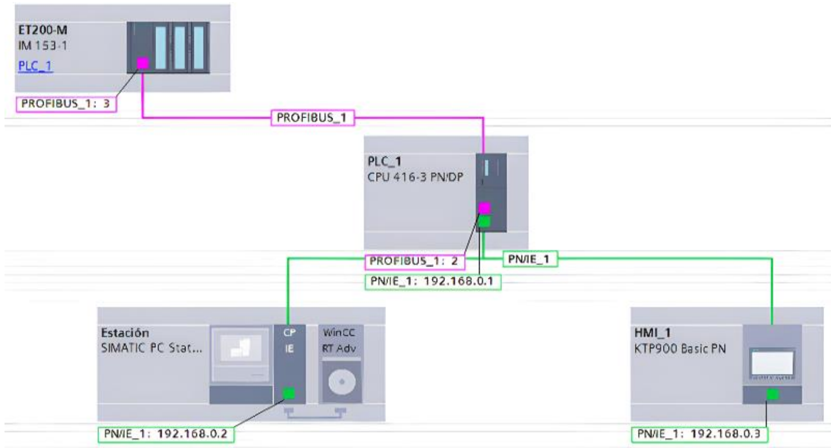

Figure 5. Industrial communication established for the proposed control architecture

4. CONCLUSION

The design of the proposed control system guarantees efficient use of the raw materials necessary for water treatment, an adequate water clarification process, and the reduction of its total hardness. The proposed control algorithm provides for automatic, manual operations, and maintenance techniques that positively and directly impact the useful life of the boilers of the "Hermanos Díaz" Oil Refinery. The proposed supervision systems guarantee the efficiency of the processes and operational activity of the Plant because the control strategies implemented are coherent and enable the operating values of the chemical water treatment plant to remain within the normal range of work. The control architecture with a decentralized periphery increases the reliability and security of the designed system, allowing the flow of information with high speed, stable power supply, and incorporation of new measurements in the process. The economic investment that the implementation of this proposal deploys can be amortized in the medium term due to savings in raw materials, electrical energy, and import substitution. This research constitutes an extraordinary contribution to the development of the "Hermanos Diaz" Oil Refinery Company of Santiago de Cuba in the interest of the transition towards Industry 4.0.

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