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DATA COMMUNICATION AND SOFTWARE DEVELOPMENT FOR THE AUTOMATION OF AN INDUSTRIAL PISTON COMPRESSOR

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Keywords: Automation software; Data communication network; Piston compressor; Modbus protocol; Open platform communications (OPC) protocol; Programmable logic controller (PLC).

The work of data communication and developing software on the automation systems is related to 13 existing piston compressors located within the compressor station C144-M5 Bustuchin, Gorj, Romania. A project solution was applied to all 13 compressors and involves the communication of the parameter values of the compressors from the C144-M5 Bustuchin station to a local higher hierarchical system and a remote higher hierarchical system. The article presents the compressor automation system with a reliable architecture and a performing data communication network. The article mainly focuses on the developed software solution for the station operator panel, the compressor operator panels, and the station computer. In the second part of the article, the communication solutions for a complex data network with a higher local hierarchical system and a higher remote hierarchical system are presented from the point of view of the data server and the addresses assigned for each compressor parameter.

1. INTRODUCTION

Various factors influence the difficulty in defining a comprehensive energy policy. Compressors are crucial components in gas consumption, resulting in efforts to improve compressor efficiency.

Industrial piston compressors are pivotal in numerous applications, from manufacturing to energy production. As industrial demands grow and technology advances, efficient and reliable automation becomes paramount. This article presents significant and relevant research on parameter communication and software development, focusing on innovations that have improved the automation of industrial piston compressors [1–3].

The automation system monitors the state of the compressors in all operating modes, ensuring the start-up, regular operation, and safe shutdown of each of the thirteen compressors independently. The automation system achieves data acquisition of work and safety parameters by each programmable logic controller (PLC) and their data communication to a station computer for visualization and interpretation to ease the work of the station operator.

Monitoring the safety operation of the compressors and, in general, of the station (pressurized air, cooling water, gas emission) and taking measures to prevent undesirable and irreversible events is another function of the automation system through a custom-developed automation software having a complex data communication network as support.

Fig. 1 – Automation cabinet for a piston compressor at Bustuchin station.

The compressor automation cabinet of the C144-M5 Bustuchin station presented in Fig.1 is equipped with a network analyzer, a UPS, a network switch, relays, contactors, voltage sources, signal adapters, fuses, motor control and protection devices, a bridge with diodes, a single-phase transformer, terminals, an operator panel that interfaces with the operator and with an Emerson VersaMax programmable logic controller for safe operation of the entire station. The parameters and operation are displayed through the operator panel, programmed with custom software, as part of this work. The PLC or programmable logic controller runs a program developed as part of this work to safely monitor and control the compression process during operation.

The electrical equipment installed in the automation cabinet and the compressor's skid connects the programmable logic controller to the process. The electrical signals in the process are analog and digital inputs for the programmable logic controller. The actuator commands are on the PLC's digital output terminals in the compressor's automation cabinet. The automation cabinet also contains the power supply circuits for the various measurement lines and the actuator control.

Analog signal transducers with a 4–20 mA range are strategically positioned at key locations on the compressor skid to monitor critical parameters. These transducers transmit the gathered data to the associated automation cabinet through signal cables. The parameter values are displayed in real-time on the operator panel installed on the door of each automation cabinet. Each compressor PLC sends parameters to a station cabinet and computer through a complex Ethernet network.

Within each automation system, a protection system was programmed into the PLC, which supervises each piston compressor and operates on two levels: optical warning alarm and acoustic failure alarm. The states of each piston compressor are defined by specific software sequences within the associated programmable logic controller.

The operator can shut down a compressor voluntarily, or the logic controller can automatically do so when a protection condition for a parameter is triggered.

2. LITERATURE REVIEW

The constructive solution of the automation cabinet considers the working conditions of the compressors, the

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nature of the working gas, and the zoning related to the explosion hazard. Recent advancements in mathematical modeling and computer simulation have emerged as powerful tools for analyzing and optimizing the piston compressor process. Over the past decade, these models have significantly improved and gained better validation, enhancing their effectiveness as design tools. Looking ahead, further advancements are expected in the future. Piston compressors are crucial in various applications as they consist of essential components like the cylinder, crankshaft, connecting rod, inlet and outlet piston ports, and valves. Different compressors with specific ratings and characteristics are available to suit various needs [4–6].

Figure 2 provides a visual representation of the assembly of the piston compressor from the C144-M5 Bustuchin station.

Fig. 2 – Piston compressor at Bustuchin station.

The use of computer software for structural analysis has become crucial in modern engineering, particularly in studying piston machines' performances for cases such as a hermetically sealed reciprocating compressor using techniques such as scanning electron microscopy (SEM) and white light interferometry (WLI) [7], the clearance of a low-capacity reciprocating compressor leakage using a simulation-based model for the parametric numerical analysis [8], or the defect detection in a piston compressor unit via monitoring vibroacoustic signals [9–11].

The software development for piston compressor units has led to the research of more complex learning methods of monitoring and failure detection, using various frequently used automation programs such as MATLAB in classifying the faults using existing, pre-trained networks, reaching computation times of 570 seconds [12], while other methods are based on a multi-level fault diagnosis system, with seven different faulty states to avoid industrial failure [13].

Communication protocols are vital for efficient data exchange among automated systems and devices. They establish standardized rules for transmitting, receiving, and interpreting information in computerized environments, ensuring compatibility and interoperability among components and technologies. This seamless integration enables automation devices like sensors, actuators, controllers, and supervisory systems to collaborate effectively for complex tasks. Selecting the proper protocol is crucial for achieving smooth automation, enhancing productivity, and optimizing industrial processes in diverse sectors [14–16]. Focusing on parameter communication and software development, the study showcases novel methodologies and intelligent algorithms that have redefined the automation paradigm for industrial piston compressors. The presented contributions offer enhanced performance, safety, and operability of these vital machines in the modern industrial landscape through improved data exchange protocols and data-driven insights. The article highlights how these advancements have resulted in increased energy efficiency, reduced downtime, and extended operational lifespan, contributing significantly to the sustainability and efficiency of industrial processes [17].

3. METHODOLOGY

Data transmission within the complex communication network involved communication between 14 PLCs and 14 operator panels, of which 13 are assigned to compressors, and one is assigned to the station. On the same communication network, a station computer communicates with the 13 compressor PLCs to display all parameter values related to the 13 compressors. The parameter values are transmitted from the station computer through an OPC protocol to a remote higher hierarchical monitoring system of the beneficiary hundreds of kilometers from the location of the compressor. Also, the data of the compressors is transmitted via Modbus TCP/IP protocol by each operator panel to a second higher hierarchical system of the beneficiary, this time locally.

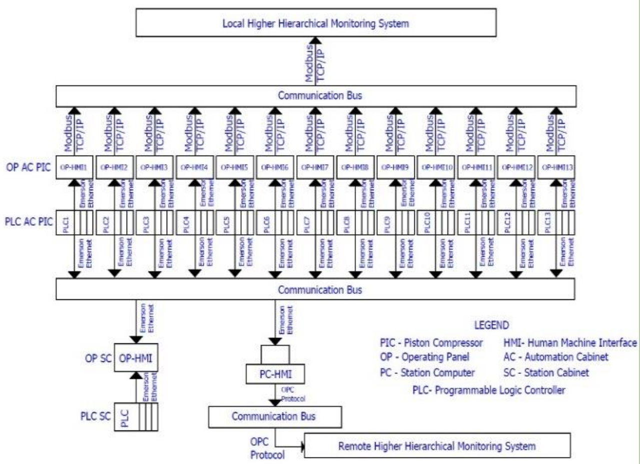

Fig. 3 – Data communication architecture.

Therefore, the data communication solution presented in Fig. 3 is unique and has a degree of novelty and originality regarding piston compressor automation.

Also, the originality of the article consists of custom-developing automation software for industrial piston compressors.

An Emerson VersaMax PLC cannot transmit data via the Modbus TCP/IP protocol. The article's originality is further enhanced by introducing a solution that uses an operating panel as an intermediary with custom-developed software to communicate with both the Emerson VersaMax controller and a higher local hierarchical system.

From a scientific point of view, the article makes contributions on an algorithm for data processing starting from transducers and up to the display of parameter values on human-machine interfaces (HMIs) represented by operator panels and the station computer.

First, the parameter values are taken from each transducer through a 4–20 mA type signal and through a designed electrical circuit they reach the PLC in the form of raw data.

The raw data range of the Emerson Versamax PLCs that comes converted from the 4–20 mA signal received from the transducers varies between 6 400 units and 32 000 units.

To be able to display the real value measured by a transducer, a raw data scaling method was created, which is part of the data processing algorithm. The scaling method used consists in the PLC execution of a universal calculation formula for each transducer. The universal formula is:

$$V_{eng} = (V_{raw} - 6\,400)\, x\, k_1 + k_2. \qquad (1)$$

The coefficients k_1 and k_2 are calculated according to the range of the transducer, which is defined according to 2 thresholds, respectively [t_1, t_2], where:

$$k_1 = \frac{t_1 + t_2}{25\,600}, \qquad (2)$$

$$k_2 = t_1. \qquad (3)$$

To transmit through the Modbus TCP/IP protocol the real and scaled value to the higher hierarchical system, another calculation formula was applied that is part of the data processing algorithm. The calculation formula applied in the software program of each PLC is:

$$V_{mbus\_r} = V_{eng}\, x\, k_3. \qquad (4)$$

K_3 is given by the number of decimals that should be transmitted to the higher hierarchical system. The V_{mbus_r} real type value will be transformed by a function available in the PLC into an integer value this being a condition to be able to be transmitted via the Modbus TCP/IP protocol.

$$V_{mbus\_r} = V_{mbus\_i}. \qquad (5)$$

Thus, an integer data composed of the V_{eng} value and its decimals will be transmitted, which will be divided into the higher hierarchical system software.

Within the data processing algorithm existing in the PLC software of each piston compressor, which performs a scientific component, a formula is integrated through which the protection of each compression unit is achieved. The formula is applied to each parameter and is defined in a universal form as follows:

$$L_{low} < P_{low} < W_{low} < V_{eng} < W_{up} < P_{up} < L_{up}. \qquad (6)$$

L_{low} and L_{up} are lower- and upper-line limits of protection for parameter's out of domain range and are usually set outside and close to the parameter's working domain. P_{low} and P_{up} are lower and upper critical limits of protection for emergency shutdown of the compressor. W_{low} and W_{up} are warning limits of visually signaling on HMI an abnormal behavior of a parameter.

Each automation cabinet features an operator panel with custom software that has been developed as part of this work, in order to meet the specific requirements of the project. Within this operator panel, screens are used to display the process parameters associated with the compressors. Therefore, the following operating panel software has been developed with ease of usage in mind, making the monitoring and command process a reliable process.

3.1. SOFTWARE DEVELOPING INTO THE STATION OPERATING PANEL

Through the main screen of the station operator panel, operators can easily acknowledge the current state of each compressor, determining whether they are actively operating or ready for operation. For a visual reference, the configuration of the main screen is illustrated in Fig. 4.

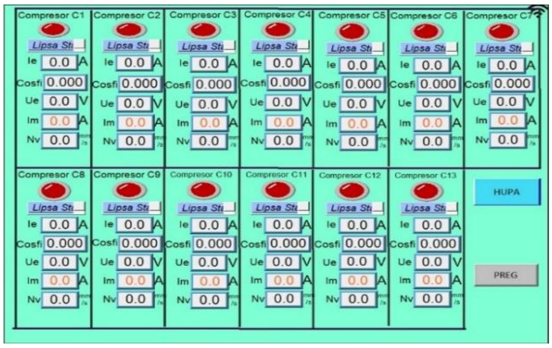

Fig. 4 – Main screen of the station operating panel.

Additionally, the operator panel allows access to a screen, which can be used from the station operating cabinet. If one or more compressors is in the Init state, operators can use the Preg button available on this screen, as shown in Fig. 5, to place up to all thirteen compressors of the station into a state of preparation for operation from one screen.

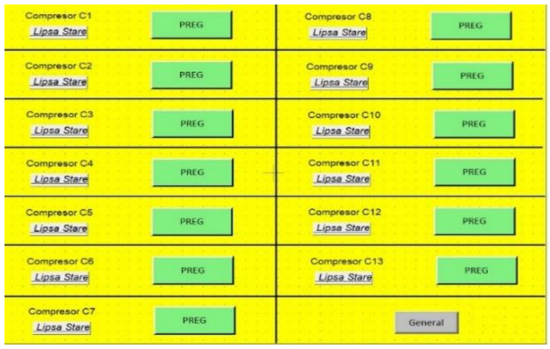

Fig. 5 – PREG screen of the station operating panel.

3.2. SOFTWARE DEVELOPING INTO THE COMPRESSOR OPERATING PANEL

The current automation cabinet operating panels are supplied by a 24 Vdc circuit featuring an integrated fuse. Upon start-up, the operator panel displays the primary screen, as depicted in Fig. 6. Upon powering the PLC, the system enters the "Init" state, a condition achieved through logic programming of the PLC. The operator panel conveniently indicates this state in the lower-left corner.

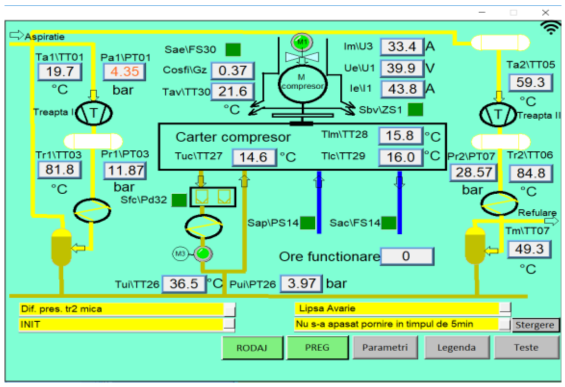

Fig. 6 – The main screen of the compressor operator panel.

On the primary screen, located at the bottom, a set of buttons exists, each having a specific programmed function. The activation of the "Rodaj" button initiates the compressor operation, bypassing certain protection sequences. The "Rodaj" sequence serves as a contingency measure for instances when a quick compressor start-up is required.

Alternatively, when the virtual button labeled "Preg" is pressed, positioned at the lower section of the main screen, the automation system transitions into the start-up state of the compressor. This action results in the display of a new state.

The main screen shows the installation's technological scheme, which includes all the process parameters located in the key points of the installation. Above the button on the main screen, several fs are intended to display messages sent by the automation system, such as warning messages, fault messages, and compressor status messages.

Upon the automation system transition into the Preg state, it becomes clear that the Init button becomes visible, whereas the Rodaj, Preg, and Test buttons vanish. To revert to the Init state, the operator must push the Init button at the bottom of the screen. Subsequently, after spending 5 minutes in the Preg state and concluding all the programmed sequences of this state, the system automatically shifts to the Ready to Start state. The operator is granted a 5-minute window to commence compressor operation through a start button. Failure to initiate the compressor within this 5-minute timeframe in the Ready to Start state results in the system's automatic return to the Init state.

The status of the automation system becomes in operation by pressing the start button near the compressor skid. Once the Func state is entered, the Stop button will appear on the screen. The operator can push this virtual button if he must stop the compressor.

The Parameters screen shown in Fig. 7 can be accessed from the operator panel at any time by pressing the corresponding virtual button. This screen displays the values of temperatures, pressures, motor and excitation currents, excitation tension, and the cos(φ) parameter. Also, value indications of digital parameters received from the field, such as water flow or airflow, are presented in a grouped screen, each in its category.

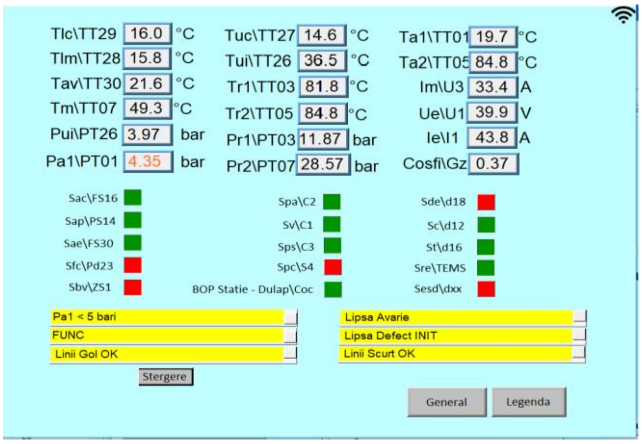

Fig. 7 – Parameter screen of the compressor operator panel.

3.3. SOFTWARE DEVELOPING INTO THE STATION COMPUTER

The compressor station computer consists of an HMI equipped with software developed according to the project requirements. The main screen is the Parameters screen, where the parameter values for each compressor and its states are presented. The screen thus developed is shown in Fig. 8.

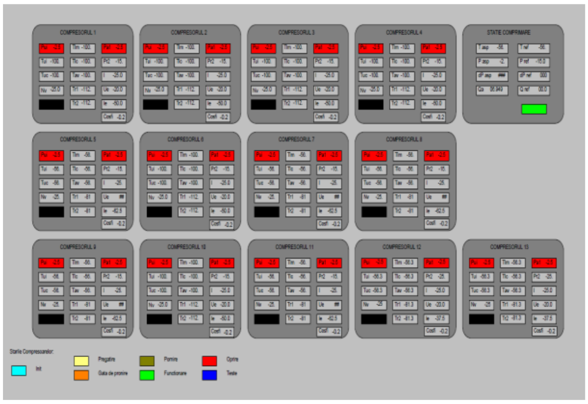

Fig. 8 – The main parameters screen for the station computer.

The technological screen presents a diagram for each compressor unit, with the process parameter values displayed. The developed scheme screen is presented in Fig. 9.

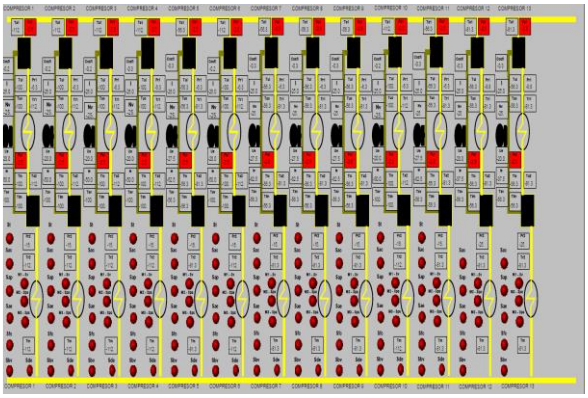

Fig. 9 – The diagram screen of the station computer.

Each compressor has a dedicated screen defined in the station computer where its parameter values can be read. Fig. 10 represents the dedicated screen of compressor 11. The rest of the dedicated compressor screens in the station computer are similar.

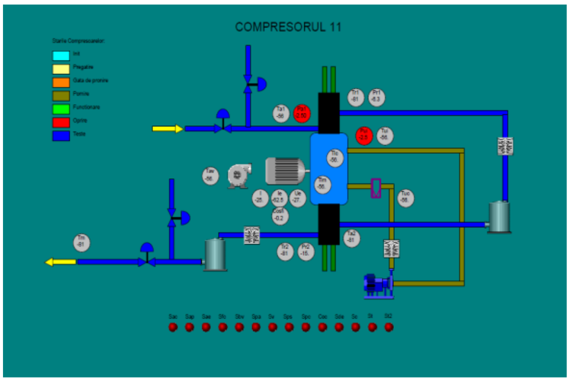

Fig. 10 – A compressor screen on the station computer.

4. RESULTS AND DISCUSSION

One of the primary objectives of this article was to address the challenge of data communication from all piston compressor automation cabinets at the Bustuchin station to two higher hierarchical systems, one local and one remote, used by the beneficiary while also ensuring the reliability of the monitoring and control process for safer operation and better fault detection for the piston compressor units.

The local hierarchical system was configured to operate in Modbus Client mode. This configuration facilitated seamless data transmission and exchange between the compressors and the higher local hierarchical system.

Successful implementation of the Modbus TCP/IP communication solution with the higher local hierarchical system requires performing a series of prerequisite tasks. The first step was achieving the list of Modbus TCP/IP registers related to the PLC addresses of each compressor. Subsequently, a Modbus TCP/IP server was configured within the automation cabinet of each compressor to perform this. The operator panel of the automation cabinet served as the intermediary equipment for installing and configuring the Modbus server.

Within the list of registers for the C1 compressor, the PLC addresses transmitted via the Modbus TCP/IP protocol from the operator panel to the higher local hierarchical system, as seen in Fig. 3, have been mapped. One address contains a parameter's real-time value.

Table 1

List model of registers for the analog addresses

MODBUS address	PLC address	Data type	Detailed description	Tag
3×1	AI00001	INT	Oil temperature in the crankcase	Tuc
3×2	AI00002	INT	Compressor bearing temperature from the electric motor	Tlm
3×3	AI00003	INT	Compressor bearing temperature opposite the electric motor	Tlc
3×4	AI00004	INT	Oil temperature entering the compressor	Tui

The operator panel transmits this address information to the higher local hierarchical system through the Modbus TCP/IP protocol. For each of the compressors (C1, C2, C3, C4, C5, C6, C7, C8, C9, C10, C11), the corresponding list of registers was initially programmed, adhering to the structure outlined in Table 1 for analog parameters and Table 2 for digital parameters.

Because the automation systems of the C12 and C13 compressors differ, the correspondence between the Modbus addresses and the PLC addresses changes compared to the rest. Considering this aspect, the correspondence in the list of registers between addresses for this compressor had to be reprogrammed.

Table 2

List model of registers for digital addresses

MODBUS address	PLC address	Data type	Detailed description	Tag
1×1	I00081	INT	Cooling water flow signal	Sac
1×2	I00082	INT	Cooling water pressure signal	Sap
1×3	I00083	INT	Air flow signaling by electric motor	Sae
1×4	I00084	INT	Oil filter clogging signal	Sfc

All fault messages are also sent to the higher hierarchical system via Modbus TCP/IP protocol through a register that, when a protection is triggered, it takes the programmed value in the list of registers. The correspondence made in the list of registers between the register of the PLC related to the cause of the shutdown of the compressor and the address under which it is transmitted via the Modbus TCP/IP protocol is presented in Table 3.

Table 3

List model of registers for the cause of shut down of a compressor

MODBUS address	PLC address	Data type	Variable value	Message
3x505	R00505	INT	0	Missing fault message
3x505	R00505	INT	1	Tuc > 70 °C
3x505	R00505	INT	2	Pui < 1,1 bar
3x505	R00505	INT	3	Tlm > 65 °C
3x505	R00505	INT	4	Tlc > 65 °C

The same method applies to a compressor's warning messages. A warning is triggered when a parameter's warning limit is exceeded. All warning limits are defined by software sequences in the PLC.

Each compressor's state to the higher local hierarchical system was also sent. This feature is also performed by transmitting a register, which takes a value programmed and mapped in the list of registers.

The possible states in which a compressor can be found are Init or the state of pause, the state of preparation for starting (PREG), and the state of ready to start (READY). The state of starting (START), the state of operation (FUNC), the state of stopping (STOP), and the state of functional tests on the execution elements (TESTS). The correspondence between the register in the PLC related to the status of a compressor and the address under which it is transmitted via the Modbus TCP/IP protocol is presented in Table 4.

Table 4

List model of registers for the state of a compressor

MODBUS address	PLC address	Data type	Variable value	Message
3×147	R00047	INT	1	INIT
3×147	R00047	INT	2	PREG
3×147	R00047	INT	3	READY
3×147	R00047	INT	4	START
3××147	R00047	INT	5	FUNC
3×147	R00047	INT	6	STOP
3×147	R00047	INT	7	TESTS

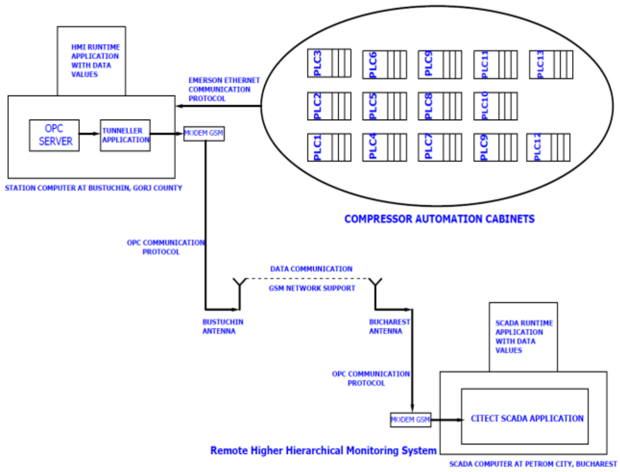

Fig. 11 – Data communication architecture of the higher remote hierarchical system.

An OPC server that runs on the station computer designs the communication system architecture of the higher remote hierarchical system. The OPC server stores all the parameter values from all 13 compressors as addresses received through the Emerson Ethernet communication protocol. Figure 11 presents a data communication architecture of the higher remote hierarchical system.

Through an implemented tunneling application on the station computer, the addresses containing values are transmitted in real-time from the OPC server through a modem that can communicate data using a GSM operator's data network as a support network.

Thus, the data arrives from Gorj County and is sent to the OMV Petrom SCADA system, which was developed on the CitectScada platform in Petrom City Bucharest.

A list of OPC registers related to the PLC addresses of each compressor was performed, the same as for the Modbus list of the higher local hierarchical system, but this time with OPC addresses from inside the OPC server.

5. **CONCLUSIONS**

The design of the communication architecture presented in the article aimed to overcome some barriers encountered by its complexity, which can cause difficulties in efficiently communicating data. Three communication protocols were used for data transmission within the same communication network, namely Emerson Ethernet, OPC, and Modbus TCP/IP, which proved to be effectively implemented because no loss of data communication with any equipment was reported during the operation of the compression station. The automation equipment that communicates in the industrial network was optimally integrated, considering there were no incompatibility problems between the equipment during the operation of the compression station. Although sophisticated, the communication system presents real-time interoperability between equipment provided by different vendors.

Using a parameter universal algorithm described in the article, starting from the scientific approach, made it possible to ensure the processing of all data received from the transducers, accurate data transmission to the higher hierarchical system, and the operation of each piston compression unit under maximum safety conditions.

Thoughtfully chosen, cost-effective solutions were analyzed and implemented, guaranteeing an optimal cost/benefit ratio. The commissioning of the communication system seamlessly integrated each compressor one by one, thanks to the meticulous planning and execution of the project.

This article presents the project’s achieved goal of establishing a reliable communication link between the COMOTI compressors and two higher hierarchical systems. The thorough selection of solutions based on cost-effectiveness and attention to detail during implementation contributed to the project's overall success.

CREDIT AUTHORSHIP CONTRIBUTION

Andrei Mitru has credited authorship contributions to all article chapters.

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