The National University of Science and Technology Politehnica Bucharest

Doctoral School of Electrical Engineering

STUDIES ON THE OPTIMIZATION OF AUTOMATION SYSTEMS FOR TURBOMACHINERY AND SCREW COMPRESSORS

SUMMARY

PhD student: **Ing. Cristian Valentin NECHIFOR**

PhD supervisor: **Prof.univ.Dr.-Ing. Valentin Năvrăpescu**
The National University of Science and Technology Politehnica Bucharest
Romanian Academy of Scientists

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LIST OF ABBREVIATIONS

ANN – Artificial Neural Networks

ATEX - ATmosphere EXplosible

AC - Alternating current

BDV – Blow Down Valve

CAD - Computer-Aided Design

CMOS - Complementary Metal-Oxide-Semiconductor

DA1 - Compressor Automation Cabinet

DA2 - Expander Automation Cabinet

DAQ - Data acquisition

DC - Direct Current

DF1 - Compressor Power Cabinet

DF2 - Expander Power Cabinet

ECS - Electrocompressor

EEC - Electronic Engine Controller

EMC - Electromagnetic Compatibility

ESD - Emergency ShutDown Systems

FADEC - Full Authority Digital Electronic Controller

FDI - Fault Detection and Isolation

G2P - Gas to Power

GE - General ELectric

GPIB - General Purpose Interface Bus

HMI - Human-Machine Interface

IBM - International Business Machines

IFCS - Intelligent Flight Control Systems

LCD - Liquid-crystal display

MOV - Motor Operated Valve

NASA - National Aeronautics and Space Administration

PCI - Peripheral Component Interconnect

PCMCIA - Personal Computer Memory Card International Association

PID - Proportional Integral Derivative

PLC - Programmable Logic Controller

PDA - Personal digital assistant

PNS - Digital Signal Processing

PME - Proficy Machine Edition

PXI - PCI eXtensions for Instrumentation

RTD – Resistance Temperature Detector

SDV – Shut Down Valve

SRCC - Electromagnetic Compatibility

SCR - Selective Catalytic Reduction

USAF - United States Air Force

UNIX - Uniplexed Information and computing system

USB - Universal Serial Bus

VA - Vlot Amper

VCC - Direct Current Volts

VI - Virtual Instrument

VME - VERSA-Module Euro card Bus

1. INTRODUCTION

The main objective of the thesis is to research methods for enhancing the technological level and performance of control systems for turbomachinery and compression systems produced in Romania by INCD Turbomotoare COMOTI. A significant focus is placed on improving the performance of an automatic or operator-assisted control system.

To achieve this goal, three main directions were explored and deepened: the deepening of control strategies and possibilities for improvement, innovative instrumentation research, and the study of technological advancements in data communications for applications with rotating machinery controlled by a PLC.

Each direction includes a series of research activities addressing these themes in a phased manner, both as standalone topics and interconnected ones. Significant emphasis is placed on the performance of an automatic control system used for command and control. Hardware-software ensembles that align with the research and simulation results within the project will also be prefigured.

Existing automation systems for controlling turbomachinery and gas compression systems have been identified. Different control strategies are differentiated based on their type and purpose. Turbomachinery must achieve high levels of efficiency. Criteria for efficiency enhancement and optimization in the control cycle are presented from various perspectives, including speed, temperature, pressure, vibrations, etc.

The goal is to outline a fundamental automation system for control and command, serving as a starting point for developing final intelligent control and command systems alongside the automation of installations.

2. ANALYSIS OF TURBOMACHINERY OPERATION AND CONTROL METHODS

The initial models of turbomachinery used in the aerospace industry were based on a concept of centrifugal compressors (Fig. 1. General model of a turbomotor utilizing a centrifugal compressor. Approximately 1943 in Germany [1]). The intake device, power turbine, and other components of these types of turbomachinery began to be optimized around the years 1942-1944 by the Luftwaffe in Germany, with implementation on fighter aircraft like the Messerschmitt ME 262. The inaugural flight of the Messerschmitt ME 262 took place on July 18, 1942, in Germany.

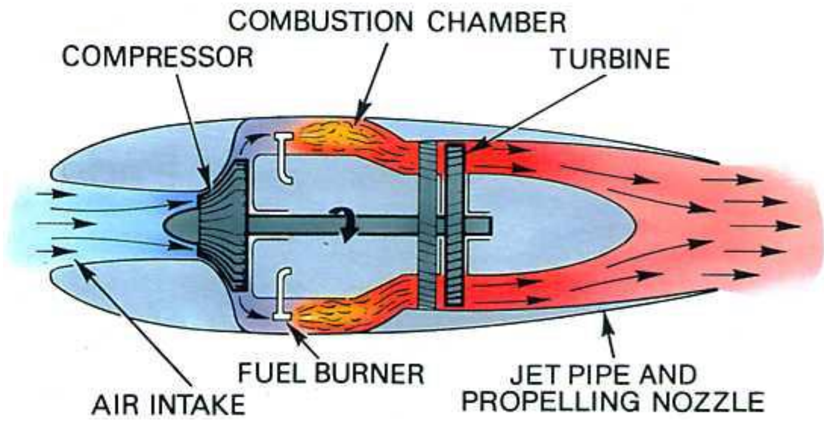


Fig. 1. General model of a turbomotor utilizing a centrifugal compressor. Approximately 1943 in Germany [1]

Today's turbomotors are reliable and trustworthy but can be expensive to operate and maintain. With the integration of available models and control algorithms, as well as the increasing intelligence in control systems, there is the prospect that engines can be operated more safely and reliably with reduced life cycle costs [2], [3].

2.1 Virtual Instrumentation

2.1.1 Virtual Instrument

According to the definition, the term "measurement instrument" refers to a "technical system for researching, observing, measuring, or controlling quantities." This definition does not make a distinction between a real instrument and a virtual one. For this reason, I have chosen to present an extended definition in this section regarding what a virtual instrument is and what it is not.

It is known that the term "virtual" arises from the fact that this type of instrument is capable of providing more information than is directly available from the physical equipment it manages. This means that a virtual instrument consists not only of physical, technical parts (equipment, measurement and control devices, etc.) but also software components.

However, some equipment, such as network analyzers or certain high-end multimeters, may include both software and physical hardware components but are not categorized as virtual instruments. This is because the concept of a virtual instrument mentioned above is not met: these instruments can only perform the tests for which they were designed to be used. Therefore, a virtual instrument is more than a system composed of physical components and programs to manage them.

2.1.2 Hardware Components

Virtual instruments combine the rapid development of software with modular and flexible hardware elements to create a user-defined measurement system. The main concept of virtual instruments is related to using computing technology to perform tests and measurements, including general-purpose hardware components and specialized software. By using different software, it allows for conducting various tests and measurements with the same system.

2.1.3 Unified virtual instruments - input/output (acquisition) boards

Data acquisition systems, as the name suggests, are primarily used for collecting information to perform measurements or analyze a phenomenon. With the advancement of technology, data acquisition has become increasingly precise, accessible across various fields, and capable of delivering reliable results. One of the most representative components is the multifunction input/output board (MIOB) [5], [6] designed to meet the requirements of virtual instrumentation systems (VIS) by offering multiple measurement modalities.

2.1.4 USB protocol and multifunction data acquisition boards with USB interface

The Universal Serial Bus (USB) communication standard [7] was introduced in 1995 to address a series of connectivity issues associated with the existing serial communication standard. The USB interface accommodates multiple devices, provides easier device installation, offers higher data transfer speeds, and simplifies wiring requirements compared to serial or parallel ports. The USB port was designed to provide a minimum required power to connected devices, eliminating the need for external power sources for devices connected to the computer through this data port.

2.1.5 Graphic programming languages

A graphical programming language is a visual programming language in which programmers do not use lines of code to describe a procedure or program. Instead, it is designed for programmers to manipulate graphical elements in a window, which can be intuitively and logically connected to create various applications.

2.1.6 Software and Hardware-in-the-Loop; VeriStand and LabVIEW - General Information

LabVIEW is a graphical programming environment developed by National Instruments [8], [9]. This language allows complex routines to be designed and programmed using block diagrams. Currently, LabVIEW is the most widely used programming environment for developing virtual instruments with applications for computers, PDAs, real-time devices, etc. LabVIEW's language uses graphical representations of component elements that resemble real-world instruments. For programming inputs, outputs, calculation elements, and program connections, graphical representations of these elements, called nodes, are used. When connected together, these nodes perform the functions of the program. LabVIEW is compatible with various operating systems such as Windows, Linux, and the Macintosh platform. Programs developed in LabVIEW are also referred to as VIs, which stands for virtual instruments. SubVIs are subroutines that can be called from other programs, making hierarchical and modular programming easy to implement in this language.

2.2 Intelligent sensors and existing monitoring technologies for turbomachinery and gas compression units

In this subsection, I have highlighted the operation and importance of both classic and innovative sensors in the operation and extended lifespan of an assembly containing a turbomachine or a bladed machine. I pointed the operating modes of conventional sensors commonly used for instrumentation of turbomachines or bladed machines, as well as current trends in the introduction of new technologies in measuring and transmitting applicable signals. The interim report highlights the advantages of approaching such instrumentation. Fiber optic transducers are of interest due to their electromagnetic immunity. Wireless transducer technology offers high data transmission speeds while contributing to material reduction. Lastly, high-performance sensors are noted for their measurement precision.

2.2.1 Presenting the current world state of instrumentation for pallet machines and compression units

Today's turbomachines are sufficiently reliable and trustworthy, but they come with high costs and can be challenging to operate and maintain. By implementing available models and specific control algorithms, along with the increasing intelligence in control and command systems, there is the potential for these engines to be operated more safely and reliably without high lifecycle costs [10],[11].

Data acquisition or the recording of information from monitoring elements is the process by which physical phenomena are converted into electrical signals by specific instruments, which are then further converted into digital signals that can be processed and stored by a PLC or computer. The data acquisition system is designed to gather data and make decisions based on it. This process can be controlled using control devices such as actuators or relays, which operate based on digital voltage or current signals.

2.2.2 Temperature monitoring

The instruments used for temperature measurement can be divided into several categories based on their operating principles. Temperature sensors commonly used for turbomachinery are primarily based on the thermoelectric effect (thermocouples) or the resistance change (thermoresistors).

Thermocouples are the most popular temperature sensors and are effective in applications with a wide range of temperatures. They are cost-effective and have a response time of a few fractions of a second. However, due to material properties and other factors, it can be challenging to achieve a measurement accuracy of less than 1°C [12].

Resistance Temperature Detectors (RTDs) are also known as resistive thermometers, and they operate based on the principle that the electrical resistance of a metal increases with temperature, a phenomenon known as thermal resistivity. Therefore, the measured temperature can be deduced by measuring the resistance of the RTD element. The relationship between the change in resistance of an RTD with temperature is called the Temperature Coefficient of Resistance (TCR) [13].

2.2.3 Pressure monitoring

Pressure measurement is a common requirement in most process control systems and is crucial for compressors, where the pressure value of the compression process must be known at all times, and maintaining a constant pressure is necessary.

Diaphragm pressure sensors are one of the three types of sensors with elastic elements, along with bellows sensors and Bourdon tube sensors. In the case of diaphragm sensors, pressure is measured at the sensor element by deforming a diaphragm. When powered with electrical energy, the diaphragm deformation is converted into an electrical output signal proportional to the measured pressure, which is then amplified and standardized.

2.2.4 Flow monitoring

The flow rate of a fluid through a closed pipe can be quantified either by measuring mass flow rate or by measuring volumetric flow rate. Of these two options, measuring mass flow rate is the most accurate because mass, unlike volume, remains constant. However, volumetric flow rate is a suitable method for quantifying substances in gaseous, liquid, or semi-liquid form with suspended particles, even though the measurement precision is lower compared to mass flow rate measurement [15].

2.2.5. Vibration Monitoring

Vibrations are commonly encountered in the operation of installations; therefore, measuring the accelerations associated with these vibrations is extremely important in industrial environments. Vibrations typically consist of harmonic linear motion. Both the oscillation frequency and displacements from the equilibrium point tend to vary quite randomly. [14].

The use of piezoelectric accelerometers is a protective measure because most common turbomachinery failures originate at the rotor level, resulting in increased rotor vibrations. Measurement is performed on three axes, in the horizontal, vertical, and axial directions, and for efficiency, the machine must accurately transmit a significant amount of rotor vibration to the bearings or casing, or more precisely to the location where the sensor is mounted.

In the articles "**Vibration Energy Harvesting Potential for Turbomachinery Applications**" [15] and „**Wireless Vibration Harvesting System For Turbine Engines”** [16] where I was one of the authors, we presented methods for harvesting energy from equipment vibrations. Energy harvesting is the process of capturing energy from vibration sources, such as rotating machinery, and converting it into electrical energy. Even though the vibration energy from a normally operating machine is low, at that time, we considered using it to power certain low-power electronic devices. The generated power depended on the inertial mass, damping factor, resonance frequency, amplitude, and frequency of the vibration source.

Both in the aerospace industry and in industrial or ground-tested turbomachinery, innovations are studied with the aim of saving and reusing the generated energy. The aspects presented in the articles can be applied to other elements that produce vibrations under normal operating conditions, such as the compression units produced by INCDT COMOTI. [16].

For the article „**Piezoelectric Harvester Performance Analysis For Vibrations Harnessing**" [17], I actively participated in testing a series of piezoelectric devices. The tests were conducted with a vibration table, driven by a sweep function generated by the impedance analyzer (SR785). This was achieved by connecting the output to a vibration shaker designed for piezoelectric sensors. The input vibrations were monitored using a precisely calibrated accelerometer mounted on the vibration table.

In test set number one, the piezoelectric device shown in Fig. 2, was mounted with screws on the vibration table platform. The results showed a peak voltage of 428.7 mV/(m/s2), which occurred at a resonance frequency of 205.25 Hz (equivalent to 4.40 V/g). In this setup, counterweights were added on the opposite side of the piezoelectric unit to amplify the vibration motion of the unit.

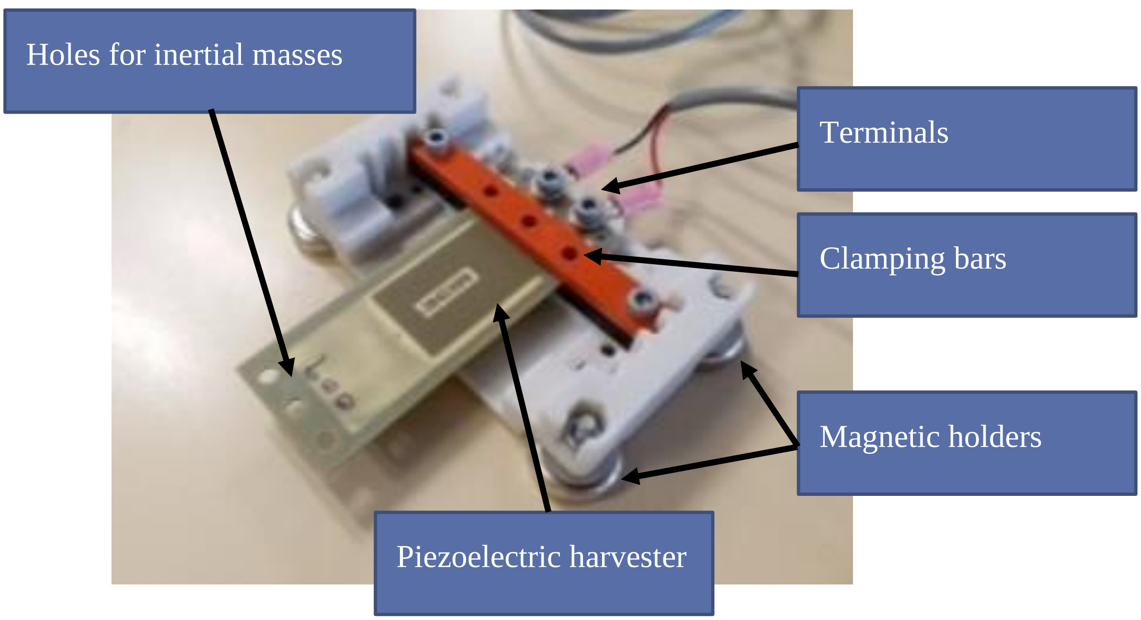


Fig. 2 – Piezoelectric harvester clamped on the testing support

For another set of tests, we conducted the trials without additional resistance by connecting the output of the piezoelectric element directly to the signal analyzer without using the vibration counter. We observed that there were still voltage drops and losses, which appeared to be due to the high input impedance of the analyzer at 1 MΩ, cable resistances, and connectors. Therefore, the transducer did not perform well without the load. A peak voltage of 358.8 mV/(m/s^2) was recorded at the resonance frequency of 203.65 Hz (3.52 V/g or ~3.17 V at 0.9 g). The measured frequency is 2.4 Hz lower than before because the electrical resistance has a damping effect. In this test setup, the counterweights were removed.

The conclusions are extensively detailed in the mentioned articles. However, it's worth noting that these piezoelectric devices capable of harvesting energy from vibrations can be integrated into any modern automation system to generate additional power. This energy can then be stored in batteries and used to power non-critical equipment sensors.

3. CREATING AN AUTOMATION SYSTEM AND USING PLCS FOR AN INDUSTRIAL GAS COMPRESSION-DECOMPRESSION (EXPANDER) ASSEMBLY

Furthermore, we have followed the steps to create a complex automation system for an assembly consisting of two compressors and a gas storage space, which, after decompression, will generate electric power. I have participated in this project alongside the team of researchers from the Electrical and Automation Installations department at INCD Turbomotoare COMOTI, both in selecting the equipment and proposing the graphical screens present in the HMI (Human-Machine Interface).

Compressed Air Energy Storage (CAES) installations are used to store electrical energy in the form of potential energy from compressed air. The heat generated during compression can be stored to improve the efficiency of the compression-expansion cycle. The solution presented consists of a 100 kW screw compressor driven by a 110 kW three-phase asynchronous motor. The compressor supplies air to vessels that store it until there is a high demand for electric power. At that moment, the compressed air is released into a 110 kW screw expander whose shaft drives a 132 kW asynchronous generator, producing electric energy and feeding it into the electrical grid. Before expansion, the air must be preheated to prevent the freezing of the expansion equipment. If the heat generated during compression is used to preheat the air before expansion, the process is adiabatic. The maximum power produced was calculated to be around 100 kW. During the commissioning tests of the air-fed expanders from a 250 kW High-Pressure Compressor (CHP), a maximum generated power of 49.7 kW was achieved, estimated to be higher when releasing the air from the tanks. Part of this project was synthesized in the article „**Compressed Air Energy Storage Installation for Renewable Energy Generation**” [18], in which I participated as an author.

In Fig. 3 the following elements are presented: 1 - Compressor automation cabinet, 2 - 110 kW electric motor of the compressor, 3 - Air compression unit, 4 - Expander automation cabinet, 5 - 132 kW motor of the expander, 6 - Expander unit, 7 - Oil pump, 8 - Oil pump, 9 - Butterfly valve, 10 - Butterfly valve, 11 - Compressed air storage unit.

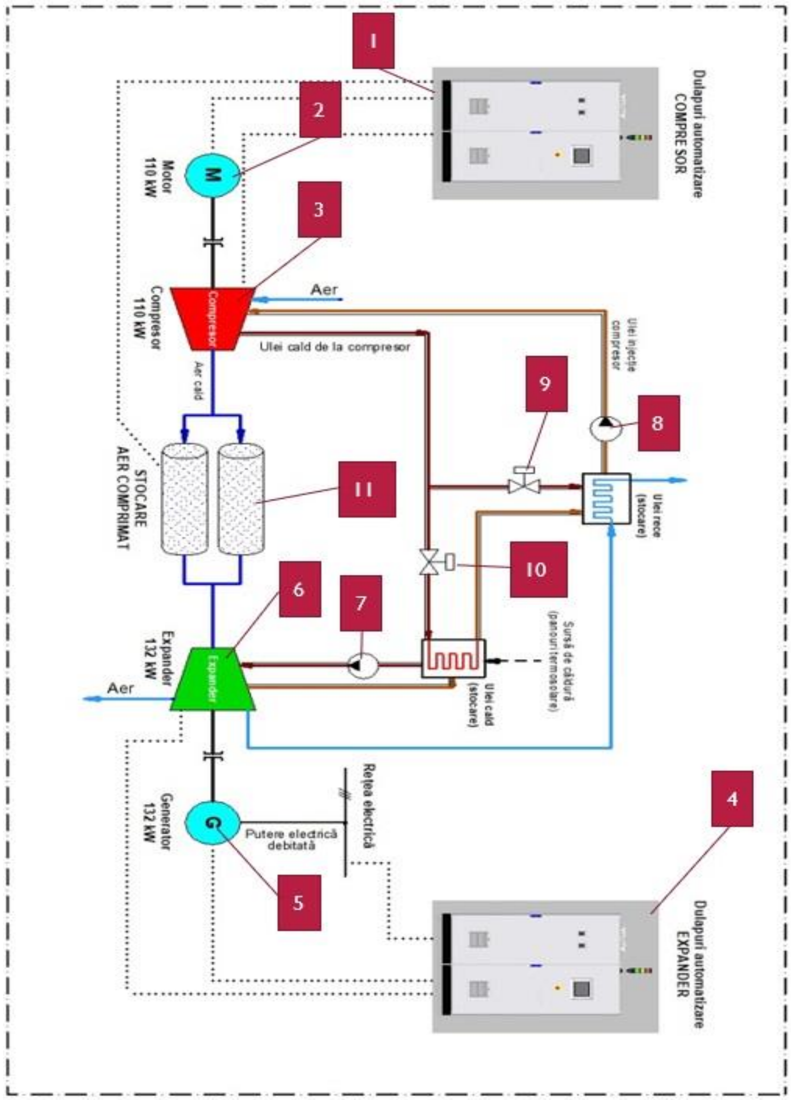


Fig. 3 - Block diagram of the ROCAES installation with process automation

The Compressed Air Energy Storage (CAES) system consists of a compressor and an expander as its main components. The compressor pumps air into a storage tank, while the expander utilizes the expansion of air to drive a generator and feed the electrical energy into the grid.

The Control and Automation System of the installation comprises four cabinets, including two automation cabinets (DA1 and DA2) and two power cabinets (DF1 and DF2). The expander cabinets have already been constructed and commissioned, and tests on the bench have confirmed the proper functioning of the automation system [18]. Fig. 3 depicts the block diagram of the ROCAES project. Both the assembly of the equipment and the performance tests presented in this work were carried out in the production hall within the INCDT COMOTI.

In the case of the compressor, the asynchronous machine will serve as the drive, operating as a motor powered from the electrical grid. The one at the expander will function as an electric generator, driven by compressed air and supplying electrical power.

The rotor accelerates, ideally approaching synchronous speed, at which the ideal torque is zero. However, in practice, the rotor reaches a rotation speed lower than that of the stator magnetic field. This difference between the speed of the stator magnetic field and the rotor is called slip. Slip is a characteristic parameter of the asynchronous machine and is equal to the ratio between the relative speed and synchronous speed.

Unlike synchronous machines, asynchronous machines offer advantages for the ROCAES system.

The values of the induced electromotive voltages in the stator phases have been adjusted to become equal to the root mean square value of the grid voltage. This is achieved by acting on the driving machine (expander) to adjust the speed by varying the amount of gas introduced. The very small frequency difference between the grid voltages and the electromotive voltages created by the generator results in a slow variation of the phase difference between the two voltage systems

The parallel connection was established when the two voltage systems were in phase. This means that the switch through which the generator connects to the grid is closed when there are no potential differences between the switch contact terminals. Closing it will not result in a current flow.

When these conditions were met, the 'synchronization' button on the PLC is activated.

The only disadvantage of the asynchronous machine is that it requires reactive power for its operation, which must be sourced from the grid or from a reactive power source (such as capacitor banks or synchronous compensators). During operation, there is a continuous, oscillating exchange of reactive power between the machine and the grid.

The generator, excited by the grid, operates in the negative slip region. This mode is achieved when the asynchronous machine connected to the grid, operating as a motor, is driven by some means above the synchronous speed. The direction of the currents is determined by the sign of the numerator for negative slip values. It is observed that the reactive power component retains its sign unchanged, while the active power component changes its sign. The same effect occurs in the stator. Regardless of the speed magnitude, the magnetization flux is created by the reactive component absorbed from the grid or from the added capacitance, and the asynchronous generator is also known as having independent excitation [19].

Starting Three-Phase Asynchronous Electric Motors

When starting three-phase asynchronous motors, a certain starting torque value must be ensured to overcome the load torque, while limiting the starting current to 4 to 7 times the rated current to avoid significant voltage fluctuations in the network and disturbance to connected consumers.

As a result, we have chosen to start the asynchronous motors using two Synergy S811+T18N3S soft starters, one for the compressor and the other for the expander. Reducing the overall system costs through the use of soft starters is possible because there is no need to adjust the speed using a frequency converter, and the installation generates power at the rated power (compressed air or electrical energy).

Considering that the installation is located outdoors, it may be exposed to atmospheric overvoltage stresses (electrical discharges). Therefore, in addition to essential grounding elements, surge protection elements can be introduced. This was not initially included in the project, but it was later suggested to be taken into account.

Reactive power can be compensated for with capacitive reactances. For this purpose, a capacitor bank (labeled C200 in Fig. 4) was provided, which will be connected to the terminals of the asynchronous machine to provide the necessary reactive power. This prevents overloading the network, and consequently, there is no need to increase the conductor cross-sections, as their sizing is done based on the active current supplied by the generator.

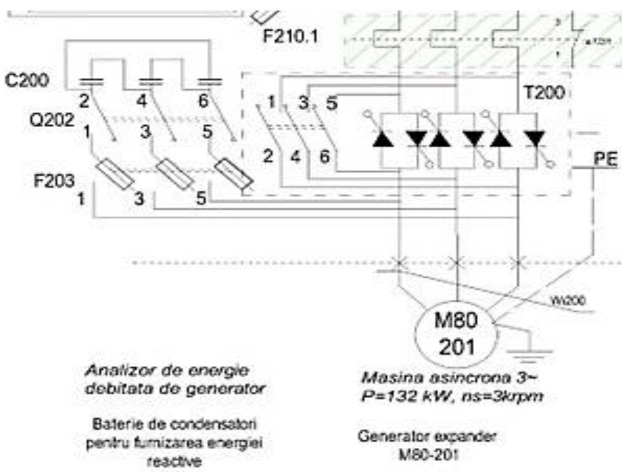


Fig. 4 – The electrical diagram of supplying the 132 kW electric machine (Expander)

Apparent power represents the total power that the generator can handle and is the square root of the sum of the squares of active power, reactive power, and distorted power. Apparent power is measured in VA (Volt Amperes), while active power is given in W (Watts).

$$S = \sqrt{P^2 + Q^2 + D^2} \qquad (2)$$

Where:

S – Apparent power; P – Active power; Q – Reactive power; D – Distorted power.

The phase active power for a balanced and symmetric three-phase network is calculated using the formula:

$$P = U_f \cdot I_f \cdot cos\varphi \qquad (3)$$

Where:

φ – the phase angle between phase currents and phase voltages.

In the figure below (Fig. 5), the phase angle φ is highlighted on the phasor diagram of voltages and currents of a balanced three-phase load connected in star.

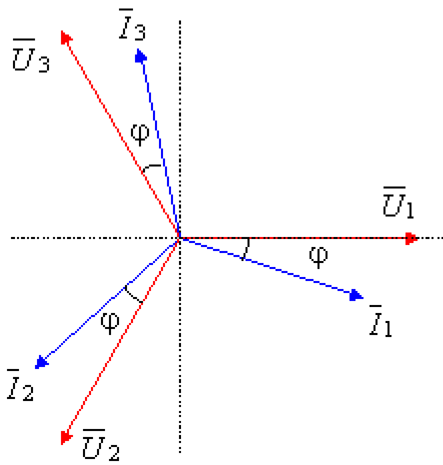


Fig. 5 - The phase angle on the phasor diagram of voltages and currents [21]

Considering that in practice the phase voltage is not measured, but the line voltage Ul=√3 Uf, and for star connection $I_f = I_l$, the following expression for the active power P in three-phase mode results[20]:

$$P = \sqrt{3} \cdot U_l \cdot I_l \cdot cos\varphi \tag{4}$$

Reactive power, denoted as Q, has the following expression per line:

$$Q = \sqrt{3} \cdot U_l \cdot I_l \cdot sin\varphi \tag{5}$$

Apparent power, denoted as S, is the total power of the three-phase asynchronous machine and has the following formula:

$$S = \sqrt{3} \cdot U_l \cdot I_l \tag{6}$$

In the case of a star connection, the currents on the transmission lines, Il (the currents between the generator and the load), are equal to the currents in the load phases, If (the current flowing through each of the load impedances) [21].

3.1 The power cabinets of the expander and compressor

For the electrical drive of the expander, the mechanical design department chose a three-phase asynchronous machine with a power of 132 kW (Fig. 6). This is the nominal mechanical power of the motor, which in our application acts as a generator. Thus, the electric machine will operate as an electric generator, driven by the expanded air in the expander and delivering electrical power to the grid. The asynchronous electric machine is of the ASU 315M-4 type and is manufactured by UMEB. The specifications of this motor can be found in the following [22].

According to Standard EN60079-14, clause 7, for rotating machines, overload protection utilizes direct temperature control (PTC thermistors or PT100 resistance temperature detectors). The ASU 315M-4 electric machine is equipped with 3 PTC thermistors in its construction for thermal protection of the rotor windings, eliminating the need for additional protective elements (thermal relays) [22].

Fig. 6 – (left) The ASU 315M 132 kW electric machine (UMEB company) / (right) The label with its characteristics

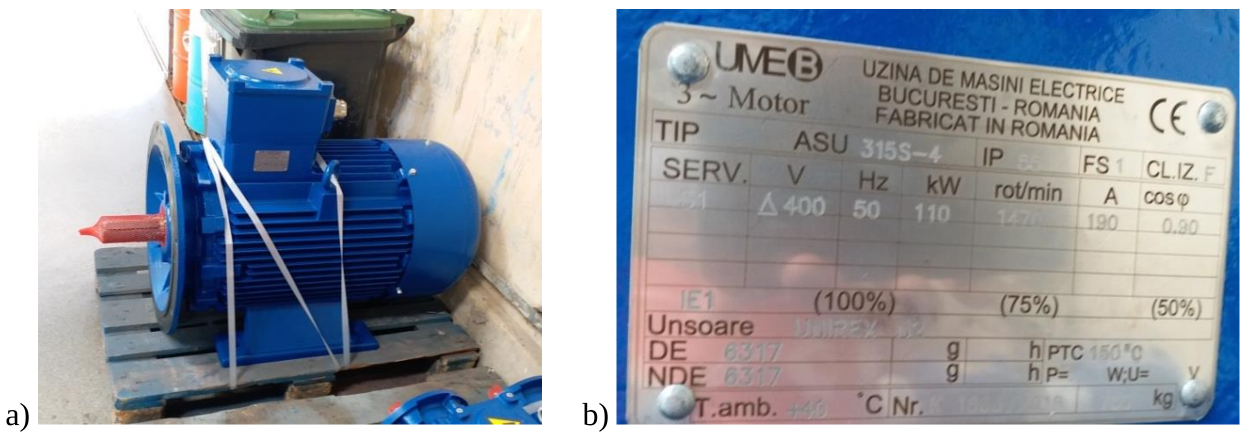


Fig. 7 – (left) The ASU 315 S 110 kW electric machine (UMEB) / (right) The label with its characteristics

For the electric drive of the compressor, a three-phase asynchronous motor with a power of 110 kW was chosen. The asynchronous electric machine is of the ASU 315S-4 type and is manufactured by UMEB. The specifications of this motor can be found in Fig. 7.

The motors meet the requirements for immunity to electromagnetic interference stipulated by the applicable regulatory documents. In the case where the motors are equipped with integrated sensors (PTC thermistors), the user must ensure a sufficient level of immunity by using shielded control cable.

3.1.1 The soft starter for starting the three-phase asynchronous generator of the expander

The expander's electric machine initially operates as an asynchronous motor and is started using a soft starter, reducing electromechanical stresses. To protect the soft starter against short circuits and overloads, ultra-fast fuse protections are used, providing efficient protection.

The soft starter operates at nominal performance between 20°C and 50°C. Above 50°C, electrical performance decreases linearly by 4% of the nominal rating per °C, up to a maximum of 60°C. This is why I proposed the use of ventilated cabinets. See Fig. 9 and Fig. 10.

The selected soft starter from the manufacturer Fairford Synergy uses semiconductor devices in the main circuit and is not designed to provide insulation at the power connection terminals. For this reason, insulation elements must be provided in the supply circuit, following the appropriate wiring and safety standards [23].

Fig. 8 – Soft starter expander Fairford SGY-305-4-01

Fig. 9 - Electric cabinet fan Eldon RFU5003R5 [24]

Fig. 10 - Ventilation grille EFA250-300R5 [25]

To cool the cabinets, a fan has been installed at the top of the control cabinet. Two ventilation grilles with included filters have been provided to circulate air and ensure the necessary airflow. The fan is of type RFU5003R5 with a capacity of 500 m3/h. The two ventilation grilles, EFA250-300R5, have dimensions of 223 x 223 mm. They come with a G3 ≥ 10 µm filter with an efficiency of 88%.

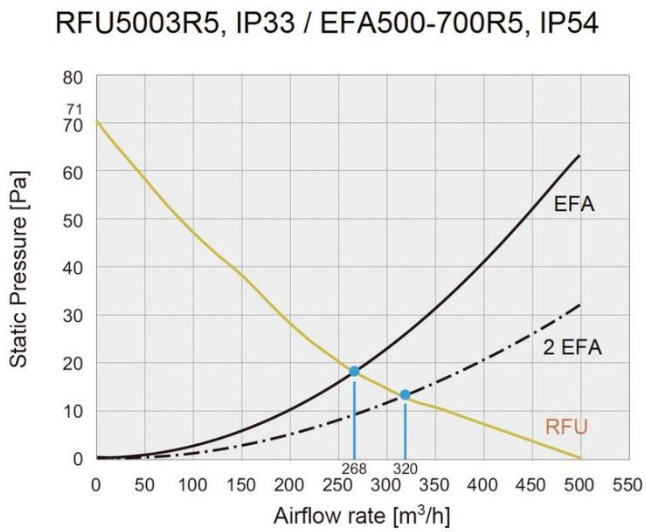


Fig. 11 – The performance of the fan with one and two EFA exhaust grilles [24]

3.1.2 The stages of execution for the expander's power cabinet

Photographs have been taken to highlight the stages of execution, from equipment placement to securing, connecting, and installing related equipment, etc.

Fig. 12 – The ongoing execution of the power cabinet from the Electrical and Automation Engineering Laboratory at COMOTI

3.1.3 Setting and describing the operating modes of the expander with the ~132 kW three-phase asynchronous motor

- The operating modes of the expander must be related to the entire ROCAES installation. The expander will only generate energy when the compressor is not active, meaning it is not pumping air into the tanks. Otherwise, it defeats the purpose of the ROCAES installation to generate electrical energy during periods when there is an energy deficit in the grid (backup for wind turbines, for photovoltaic systems, additional power to support high loads on short notice, etc.).

- The expander in operation can be in one of the following states:
- Stationary
- Start
- Loading - entering the generation mode
- Operation - supplying electrical energy according to a specific program
- Shutdown - normal or emergency.

3.1.4 Programming the soft starter

To correctly use the Fairford Sinergy SGY 305-4-01 soft starter in the ROCAES installation and start the expander motor in asynchronous motor mode, you need to make the appropriate settings. Access the Auto-Setup menu of the soft starter and select the "Compressor - Screw" option for this type of application. This choice will automatically configure the parameters to reduce mechanical shocks and limit the starting current.

3.2 The automation cabinet

In this subsection, images depicting the progress of the execution phases of automation cabinet DA2 are presented. In Fig. 13, you can observe the evolution of the automation cabinet's construction, which is configured from top to bottom across 5 levels.

Fig. 13 – Execution of the automation cabinet in progress, from the Electrical and Automation Engineering laboratory at COMOTI

3.2.1 Description of the role and operation of the PLC (Programmable Logic Controller)

Programmable Logic Controllers (PLCs) are electronic devices used for controlling machines and processes. They receive signals, process them according to the program, and control the execution elements, such as relays. Key characteristics include the number of inputs/outputs, memory capacity, and processing speed. PLCs replace relay circuits and are rugged, making them suitable for use in challenging environments [26].

3.2.2 Operation of the expander driven by the Control and Command System implemented with PLC

General Description

The main function of the Control and Command System (CCS) is to monitor the parameters of thermal, mechanical, and electrical processes during normal or transient operating conditions, regulate and control them to ensure safe operation.

The Control and Command System for the expander assembly is based on a programmable logic controller (PLC) of the VersaMax type, produced by GE Fanuc. The PLC connects to the execution elements in the installation through relays, contactors, transducers, and signal adapters.

The expander-generator assembly can be stopped both from the automation cabinet (manually or in case of emergency) and automatically whenever the operation is considered abnormal due to the exceeding of predefined operating parameter values.

3.2.3 PLC Programming for CAES Station

Due to the decision to operate the compressor and expander independently, and since these two components will not function simultaneously, it was necessary to use two separate PLCs. There is no need for communication between these two PLCs. Pressure transducers in the storage vessel will transmit information to both PLCs. When the maximum compressed air pressure in the storage vessel (26 bar) is reached, the compressor will automatically shut down. Additionally, starting the expander will only be possible when the pressure in the reservoir is sufficient to drive it.

PLC Expander Programming

The software program created in the Proficy Machine Edition (PME) software was implemented in the expander's PLC and executed without any issues during commissioning tests.

Test Screen

On the TEST screen, I have implemented a clever solution for presenting the three continuously adjustable electropneumatic valves. I chose to display them in an intuitive and easily understandable manner, providing the operator with precise control. On the TEST screen, I have included buttons that allow the opening and closing of the valves, with a clear 5% increment displayed. This way, the operator can adjust the valve positions as needed, achieving precise control.

I have included a meaningful visual element for each valve command. Next to each command, I have added a red square, indicating the current state of the equipment (activated or deactivated).

Fig. 14 – Test Screen Displayed on the Operator Panel During Operation

2.2.4 Programare PLC compresor

The software program for the compressor's PLC was developed using the Proficy Machine Edition software. It will be implemented in the PLC during the execution and commissioning phase of the cabinets. The screen in Fig. 15 displays the parameters monitored by the PLC. The status information is indicated by color (red - stopped, green - running). Additionally, the monitored parameter values are displayed.

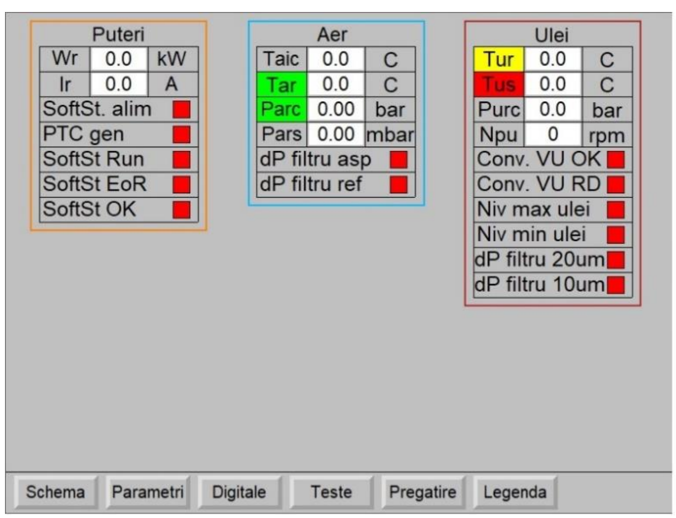
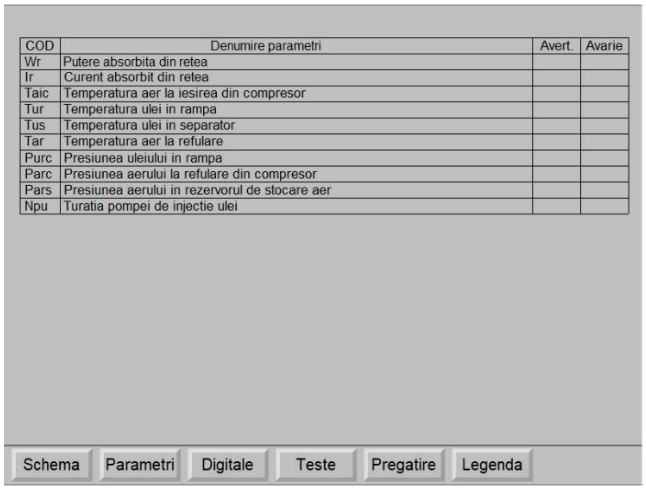


Fig. 15 – Functional parameters screen for the compressor

I tried to approach the parameter screens creatively and with attention to detail. I considered both functional aspects and aesthetics to provide a pleasant and intuitive visual experience for the operator. In an effort to ensure a comprehensive and informative experience, I proposed adding a legend screen.



COD	Denumire parametri	Avert.	Avarie
Wr	Putere absorbita din retea		
Ir	Curent absorbit din retea		
Taic	Temperatura aer la iesirea din compresor		
Tur	Temperatura ulei in rampa		
Tus	Temperatura ulei in separator		
Tar	Temperatura aer la refulare		
Purc	Presiunea uleiului in rampa		
Parc	Presiunea aerului la refulare din compresor		
Pars	Presiunea aerului in rezervorul de stocare aer		
Npu	Turatia pompei de injectie ulei		

Fig. 16 – Legend Screen

3.2.5 Expander Operation States

The operating states of the expander must be linked to the entire ROCAES installation. The expander will only generate electricity when the compressor is not active, meaning it is not pumping air into the reservoirs. Otherwise, generating electricity with the expander while simultaneously consuming electrical energy for compression is not justified.

3.3 Bench Tests with the Expander

During the tests, the expander-generator was connected to a high-pressure compressor to achieve high pressures. The machine was started using a soft starter with the intake open. It is essential to start the expander installation only when the intake is open to avoid creating a vacuum that could lead to vibrations and shocks in the equipment.

Data acquisition was performed during the tests. Operating parameters were recorded using the program developed in Proficy Machine Edition, with the computer running the software connected to the Ethernet module, enabling communication with the PLC via a data cable.

As shown in the graph in Fig. 17, the asynchronous electric machine starts in motor mode, with a maximum power consumption of 36.2 kW observed on the graph. As the vanes open and pressurized air is allowed to enter the expander, its shaft will take on the load of rotating the electric machine, which will transition into generator mode. The power generated by the electric machine in generator mode is indicated on the graph with red numbers and a negative sign.

The power supplied to the grid, Wr, is less than the generated power, Wg. The reason for this is that the generated power must also provide power for the 4 kW motor driving the oil pump, as well as the electrical consumers in the cabinet.

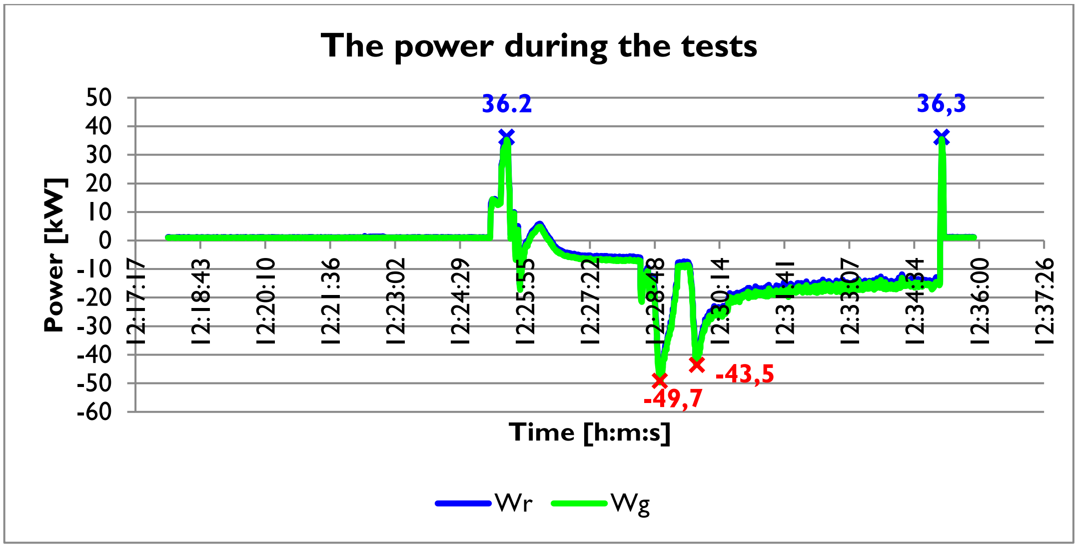


Fig. 17 – The power recorded during the operation tests

A part of this chapter has been summarized in the article "**Compressed Air Energy Storage Installation for Renewable Energy Generation**" [18], where we extensively presented the compressed air storage installation and how that compressed air can be transformed into energy.

4. CASE STUDY: OPTIMIZATION OF CONTROL FOR GAS COMPRESSION UNIT SUCTION VALVES

This stage presents how I addressed existing issues at some gas compression stations owned by INCDT COMOTI's clients. These problems involve pressure buildup in the suction line, which can lead to failed starts. I also considered the need to control a specific flow rate for the discharge of the compression unit.

I developed a position information transmission system applicable to the common valves we use, and my contribution was designing and implementing a software solution for safely starting a gas compression unit with high pressure in the suction line. I explained how information about the valve's opening position is translated from mechanical position to an analog signal in a simplified manner.

4.1 Functional configuration definition

In certain methane gas compression stations where screw compression assemblies manufactured by INCD Turbomotoare COMOTI, such as CF 128 or 180 compressor units (located in Țintea, Pișcolt, Abram), are installed, specific operational issues have been observed during the startup of the compressor assembly after prolonged periods of shutdown. During these extended shutdowns, gas accumulates in the compressor's suction system. Typically, the pressure values in the suction system reach a range of 1.5-3 bar, and the compressor assembly automatically shuts down if the suction pressure exceeds 1.5 bar.

At present, in order to facilitate the startup of the compression units, manual maneuvers are required to reduce the suction pressure in the compression unit. These maneuvers may include opening the station's basket valve and continuously purging a significant amount of gas, or partially opening the manual valve on the station's pipeline to generate pressure drop, all while initiating the compressor startup command.

We have further explored potential solutions to address this operational issue, specifically considering the use of a potentiometer or the implementation of a progressive opening controlled by the control software – our own proposals.

To secure the potentiometer and encoder, we will simultaneously pursue two construction options: one using embossed sheet metal support and the other using a support rod. Within the adapted electrical actuator, only the potentiometer or position encoder will be accommodated. The remaining analysis and decision-making devices will be mounted in a remote control and command cabinet, which can be located hundreds of meters away.

4.2 A mechanical system for determining and confirming the working position

Transducers are an essential part of any modern control device. They convert non-electrical physical quantities into an electrical signal that can be interpreted by the control system (PLC). Various types of sensors are available on the market, operating on different detection principles and used in various applications. Among these, the position transducer plays an important role in several such systems.

Position transducers with potentiometers use a resistive track with a slider attached to the object whose position needs to be determined. The movement of the object causes the slider to change its position along the resistive track, thus changing the measured resistance value between the slider's position and the end of the track. In this way, the measured resistance can be used as an indicator of the object's position. These have the following advantages: simplicity, low cost, compactness, etc.

This type of electronic component, similar to conventional resistors but with a variable value, can be used for numerous applications, but in this case, both the purpose and the method of use are special.

Using a multiturn potentiometer

A 0-5 kΩ potentiometer can be used to monitor the position of the valve, mechanically actuated by a rod connected to a gear that moves along with the butterfly valve. This solution has yielded good results. For increased precision, a gear mechanism with gears was added to amplify the movement. **(**Fig. 18**)**.

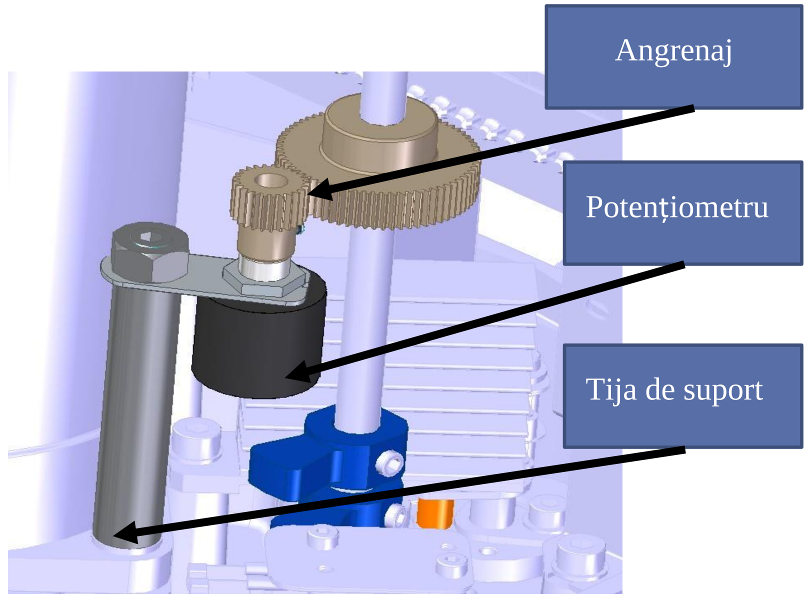


Fig. 18 — Mounting option

The gear wheels were sized by the mechanical design team, under my guidance, so that with a 90° rotation of the valve, the potentiometer would undergo a 270° rotation. This design solution is relatively simple and reliable. Furthermore, it does not require signal processing within the actuator, and the resistance value can be read remotely in the control area of the actuator.

4.3 Transmitting the position information of the valve remotely using a multiturn potentiometer

Depending on the chosen PLC, you can opt for a signal converter that converts the information received from the potentiometer, from resistance, into a 0-20 mA (milliampere) current. In the market, there are also PLCs that can directly read the resistance information, but these have a higher cost, and there's a risk of reading errors when the cable length transmitting the information from the potentiometer to the PLC exceeds 50 meters. The difference in resistance is explained by its increase with the cable length and conductor cross-section.

I further proposed that in cases where distances greater than 50 meters exist between the control cabinet and the monitored elements, busbars with conductors of at least 1 mm^2 should be used to avoid excessive voltage drop.

Defining the Functional Configuration of the Proposed System

The toothed wheels are constructed from a glass-fiber-reinforced polyamide plastic material. The key characteristics of this material include high mechanical strength, hardness, and excellent resistance to wear. Additionally, it exhibits strong resistance to mechanical stress. These components were manufactured by the mechanical design department within INCDT COMOTI, following my recommendation.

4.4 Reading the Information Provided by the Potentiometer

For reading the information, we have several options at our disposal. I presented one option that could be applied in this application.

As previously mentioned, the information provided by the rotary potentiometer reaches the control cabinet, known as the automation cabinet, as an electrical resistance (Ω). This electrical resistance needs to be transformed into information that can be read and displayed by the programmable logic controller (PLC - Programmable Logic Controller).

I used a signal converter, and this converter will transmit the signal to the PLC as a 4-20 mA signal, indicating the position from closed to open in degrees, 0-90°.

4.5 The Proposed Automation Solution

In practice, I have encountered many issues when starting ECS COMOTI compression equipment. These problems arose due to the high level of pressure in the compressor's suction, specifically, a pressure greater than 1.5 bar. In the PLC software created for the automatic and protected operation of the compression units, an alarm is implemented that will stop the compression unit if the suction pressure indicates values higher than 1.5 bar. Only safe methods have been attempted to use the compression units, ensuring safety conditions, such as delaying the suction pressure error by two or three seconds. This method allows the compression unit to take over the high suction pressure at startup.

Other methods and proposals that I have made include:

- Initiating the automated procedure to open the suction valve at the same time as starting the main motor that drives the compression unit.
- Gradually opening the valve on the suction pipe.

By carefully analyzing the operation of the compression unit and the startup sequence, I have proposed installing a second pressure transducer. This will be very useful when starting, as its role is to monitor the pressure in the main line during the stationary state of the compression unit. It will also indicate the initial position of the suction valve opening if the pressure exceeds 1.2 bar. If an adjustable valve is not installed in the suction segment, the second pressure transducer becomes unnecessary. The second pressure transducer will be named Pga1 (pre-suction pressure transducer, as shown in Fig. 19).

Definition of the solution:

With the help of a valve that has position control, which is commanded by a PLC, the pressure level in the suction pipe can be easily controlled, especially during the startup of the compression unit. The PLC can also intervene during the operation of the compression unit if the pressure transducer registers a pressure approaching the maximum allowable limit on the suction side. It will gradually start to close the butterfly valve so that the pressure at the compressor inlet (Pga2 or the compressor pressure transducer in Fig. 19) decreases.

As seen in Fig. 19, at the compressor's suction, I proposed a pressure transducer that will indicate the pressure in the main pipe supplying gas. This transducer will monitor the suction pressure at all times, even when the compressor is at rest.

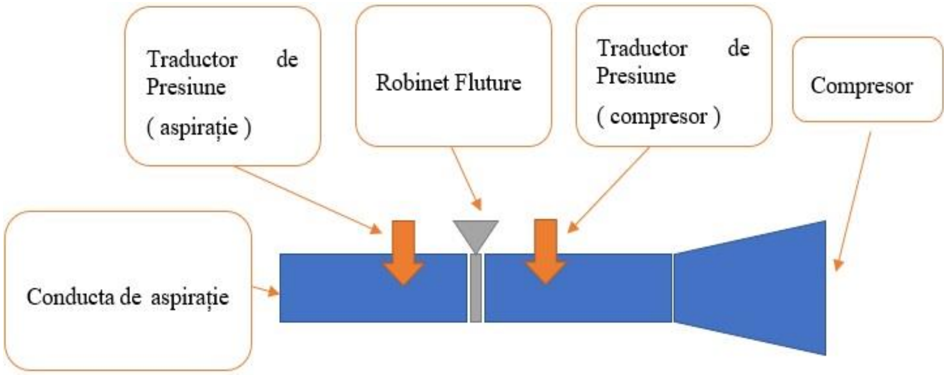


Fig. 19 — Position of the sensors on the suction line

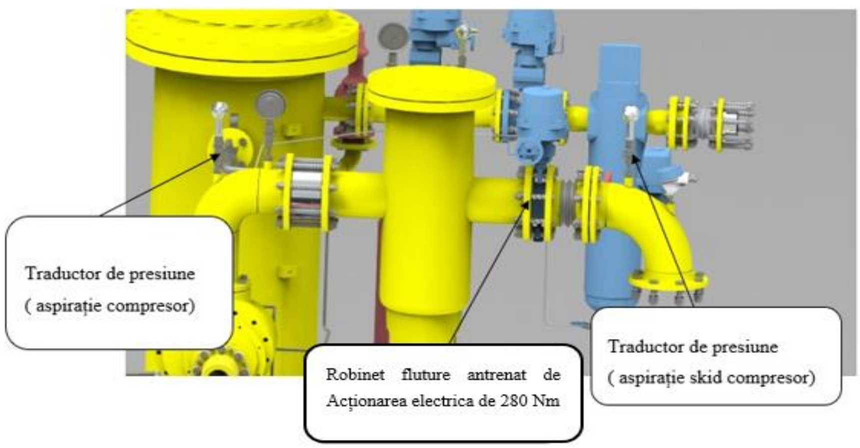


Fig. 20 — Position of the sensors on the suction line

- Compressor suction pressure transducer = Pga2;
- Suction pressure transducer Skid compressor = Pga 1;
- The actuated butterfly valve represents the valve we are controlling.

Automation Cabinet Configuration:

- the use of a programmable PLC in Ladder Diagram language in which the regulation algorithms will be implemented. In the initial specific test phase, these algorithms may be modified or adapted to optimize the valve response;
- using an Operator Panel to facilitate the interpretation of data from the PLC and to provide information to the operator. This operator panel is programmable, different screens and interfaces can be created both for the phase of specific tests and adjustments, and later for the usual exploitation phase;

- electrical protection circuits of the entire cabinet. In the technical specification development stage, a calculation of consumer power will be made;
- 24 VDC electrical power sources whose power will be sized according to consumers, with power reserve for adding additional consumers during the test phase;
- the emergency system ensures the possibility of returning the valve to a safe position in case of loss of electrical supply. It is carried out through a UPS system, designed to provide energy for the actuation of the valve;
- elements of connection, separation, marking of circuits, identification of electrical routes to facilitate troubleshooting or changes during the testing and adjustments phase;
- the electrical panel itself will be a metal cabinet dimensioned in terms of volume for the elements already defined as well as with spare space for subsequent additions. It will be equipped with passive or active ventilation elements depending on the electrical power consumed;
- the electrical connections between the Control Cabinet and the Valve in the technological installation. The electric power cables for powering the valve's electric motor will be maintained. The electric stroke end signals will also be used for final protection, and this helps to avoid exceeding the maximum allowable stroke of the valve.

Valve adjustment loop for Pga2 suction pressure values between 0.5 and 1.2 bar.

I presented next, a classic method generally used by programmers in ladder diagram language, namely using a PID controller, and then the personal solution for this problem.

In Fig. 21 shows a PID that I implemented in the software of a PLC that uses a Ladder Diagram language. It needs a prescribed value of the quantity of interest, also called a "SET POINT", which can be entered in software or set manually by the operator from the HMI (Human-Machine Interface) screen, by the process variable that is read with the help of a transducer (Pga2) and the variable controlled by the PID, that is, in the case of our application, the position of the valve.

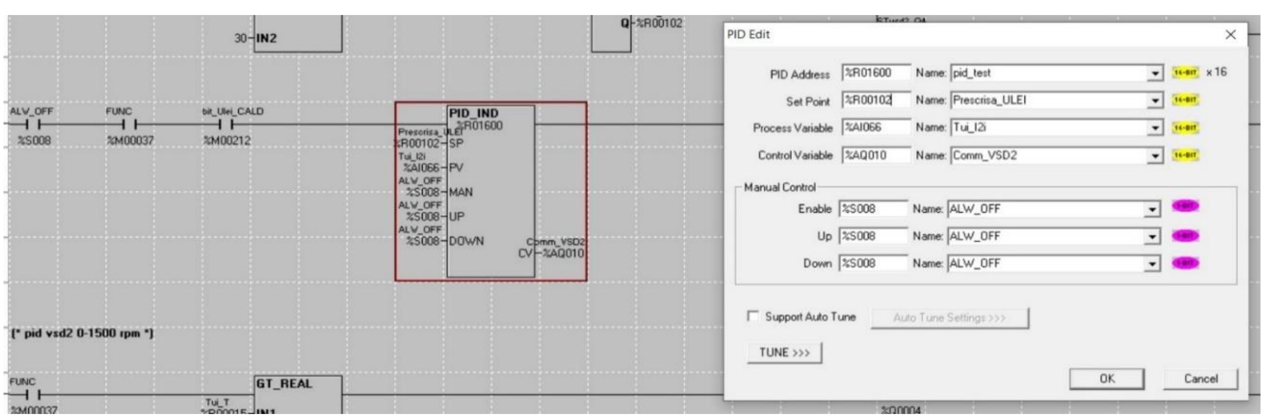


Fig. 21 — Example of PID implemented in software

4.6 Performing functional tests

The automatic system for determining and confirming the working position of a valve actuated by an electric drive, referred to as "SDV," has been installed on the suction pipe of a natural gas compression assembly produced by INCDT COMOTI. Although the assembly is designed to use natural gas as the working fluid, all tests were conducted using compressed air as the working fluid. The proposed tests can be divided into two categories based on the suction pressure. In the first part, tests were conducted at atmospheric pressure, followed by trials at higher pressures, up to 3 bar.

The electric drive is located on the suction pipe of the compression assembly. It drives a butterfly valve type DN 150 located as shown in Fig. 22. This approach was chosen because the installation of the valve is relatively simple and does not require modifications to the existing equipment of the suction pipe or the control logic of the skid.

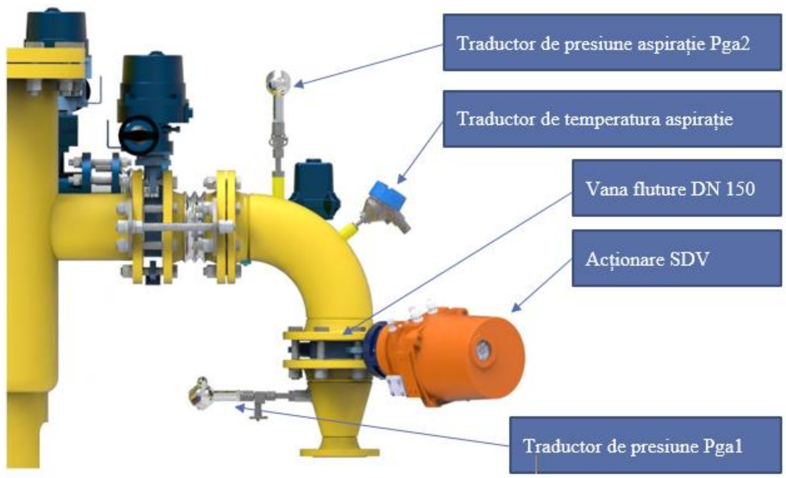


Fig. 22 - Montajul acționării pe conducta de aspirație

The main elements of the experimental installation include the compressor test stand, check valve, pressure regulator, and the compressor skid assembly. The electric motor driving the compressor in the ECS 10/10 CMT93 skid has a rated power of 55 kW. The compressor is designed to compress natural gas and will consume higher electrical power when operating with air. For this reason, an approximate calculation was made to determine the limit speed of operation during the tests.

Verification of the equipment's functionality at atmospheric pressure

The first category of functional tests was conducted at atmospheric pressure and aimed to monitor how the valve control software could respond to different variations in operating parameters of the compressor (speed, discharge pressure, etc.).

Before starting the actual tests and plotting the characteristic curves corresponding to the parameters of interest (discharge pressure, flow rate, electrical power consumption as a function of suction pressure), a test is conducted to verify the actuation.

Two sets of determinations were made: one set in which only the butterfly valve opening angle was varied, and another set in which the manual valve on the discharge line was simultaneously operated with the valve opening to maintain the pressure constant at 3.5 bar.

Fig. 24 shows a sequence of a failed start caused by the increase in suction pressure exceeding the preset limit threshold during the tests by 0.5 bar. In this case, the variation in suction pressure could not be brought and maintained by the PLC around the pre-established reference value. In Fig. 23, we can observe a successful startup sequence, where the calibrated position of the potentiometer, which is similar to the valve opening position, managed to maintain a pressure with small fluctuations.

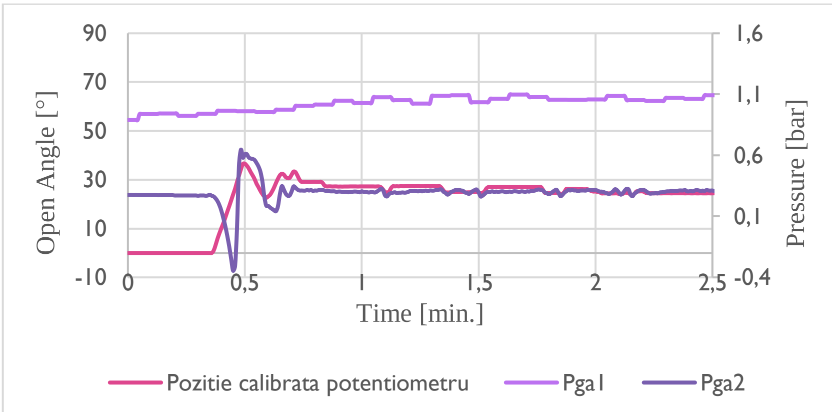


Fig. 23 — Successful start sequence

It can be observed that in the initial moments after starting, a vacuum is created in the compressor's suction. This is a regular occurrence in the startup of compressors produced by INCD Turbomotoare COMOTI. This vacuum zone can be corrected by implementing a correlation in the PLC control software between the start of the main motor of the compression unit and the opening of the valve. The command to start the motor and open the valve begins at the same time, but the valve does not actually open immediately after the relay is activated. It needs a second, perhaps even two, for its actuation to work and open at least 1 degree. In the future, it has been proposed to implement a startup sequence where the electric motor is launched after the valve switch that signals the closed position is deactivated.

The next stage in the testing involved creating a characteristic curve of suction pressure vs. valve opening angle. This curve will be used to determine a precalculated opening angle that the butterfly valve should reach when the compressor starts. The determination was made for a constant speed (n=1000 rpm), discharge pressure (Pgrs=2 bar), and suction pressure (Pga2=0.3 bar).

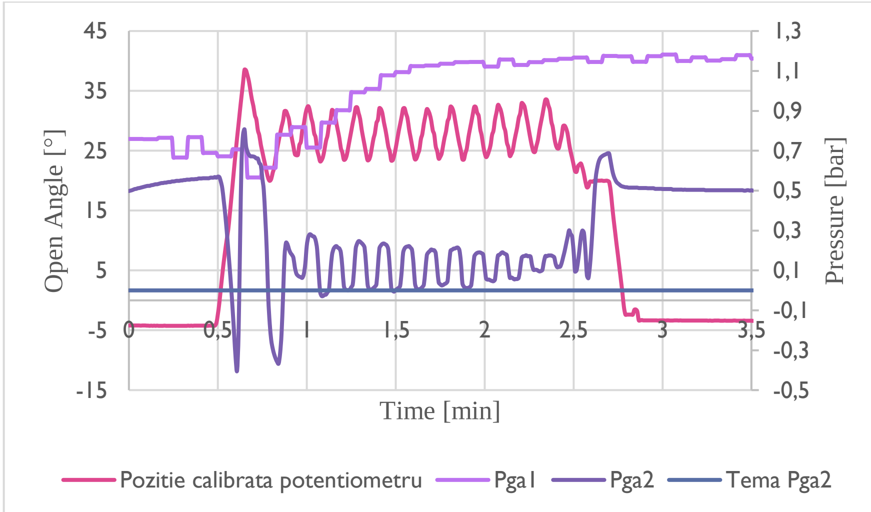


Fig. 24 — Start sequence missed

Pga1 – Pressure measurement recorded at the level of the suction pipe (see Fig. 22);

Pga2 - The pressure measurement recorded between the electric drive (valve) and the compressor (see Fig. 22).

In Fig. 24, it can be observed that the suction pressure value Pga2 could not be stabilized at the level of 0 bar, and this was due to the fact that the programmable logic controller did not have a tolerance interval of 2-3 degrees in which it would not make any decision to stabilize the pressure. There is also an increase in suction pressure, which is unlikely to occur in gas compression stations except in exceptional cases.

The pressure upstream of the valve will increase to 3 bar, which represents the upper limit of the pressure gauge mounted on the pressure regulator. The data obtained in this stage were implemented in the control software of the actuator for better operation during the compressor startup period until it reaches its nominal speed.

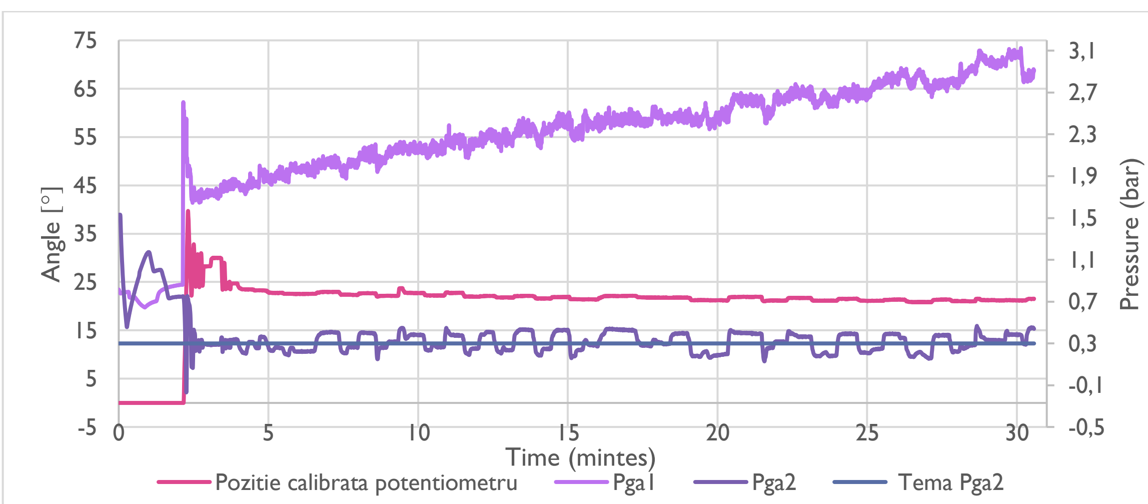


Fig. 25 — Data for determining valve operation mode

In Fig. 25, it is very clear that the valve receives frequent commands for closing or opening for very small variations in pressure Pga2. However, the results are satisfactory, and I will attempt to correct those small variations, as I will present in the next chapter.

Presentation of the functionality and utility of the functional model with a positioner, controlled through a control and command cabinet

In most operational skids, automatic operation is implemented in a speed control loop of the electric motor based on the suction pressure recorded at the inlet of the compression skid (Pga). The speed variation range is between 1200-1500 rpm, and the suction pressure range is configurable within the interval [-0.15÷1] bar.

The functional tests conducted using the experimental installation described above used compressed air as the working fluid, which led to the need to modify the suction pressure adjustment range to [-0.5÷0.5] bar, limited by the nominal power of the electric motor.

The solution has proven to work well in maintaining a constant suction pressure within a range of gas pressures supplied between 0.5 and 1.2 bar. When this value is exceeded, the process's evolution is faster than the actuator's ability to make corrections. The oscillations illustrated in Fig. 26 are characteristic of an "on/off" control mode. It can be observed that the stabilization duration increases proportionally with the set pressure from the regulator.

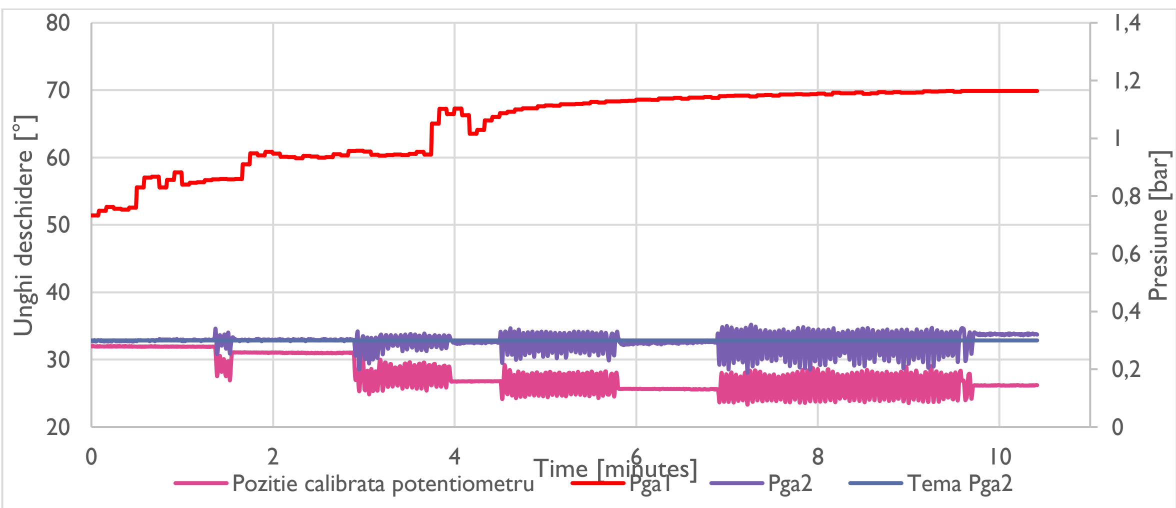


Fig. 26 — Loop suction pressure adjustment

The electric actuation controlled by the PLC demonstrated its utility during the tests performed both at startup and during operation. The butterfly valve can be adjusted by imposing the pressure setpoint that the control logic attempts to maintain. When the compression unit starts, using as input data the level of pressure in the suction pipe and the opening angle measured either by a potentiometer or a digital encoder, the control software selects a limited opening angle.

The rotary potentiometer provides information in the form of a variable resistance proportional to the angular position of the valve. This information reaches the control panel where it needs to be transformed into a quantity that can be read and displayed by the programmable logic controller (PLC). In case the information requires conversion to voltage (0..10 V) or current (0..20 mA), an analog signal converter will be used.

The tests also aimed to verify the functionality of implementing the potentiometer to indicate the valve position, and it was found to be a very good solution.

One of the personal observations I made following the operational tests was that it will be necessary to replace normal coil relays with solid-state relays, as the very frequent switching frequency can lead to premature wear of the coil contact used in the normal mode.

4.7 My personal solution to reduce valve position oscillations

Using the equation of a straight line implemented in the PLC software, a simple control loop can be created for a device that operates in response to a value recorded by a transducer, in our case, a pressure transducer.

I have implemented a register in the Ladder Diagram software that can be controlled (control_SDV), and a parameter recorded by a transducer, in this case, Pga2. For valve control, I considered a range between 20 degrees and 90 degrees, and for the pressure value of interest, Pga2, I considered the interval between 0.5 and 1.2 bar.

The application of the control loop will be carried out according to the logic presented below and in the software lines from Fig. 28 and Fig. 29. The explanation of each line is provided in the work.

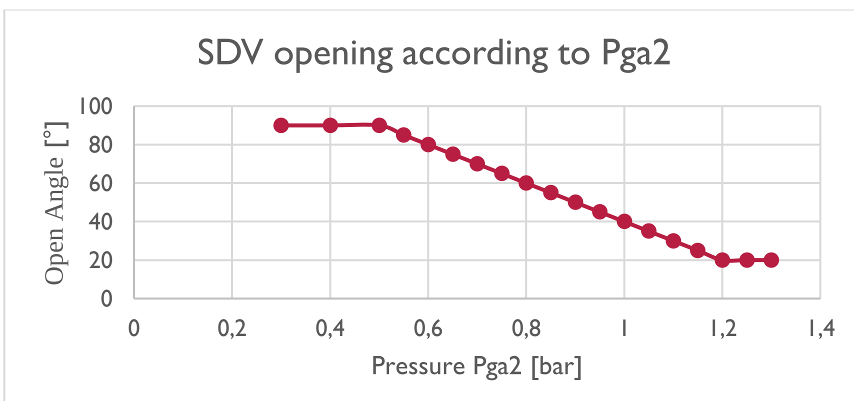


Fig. 27 - The line that defines the control loop for valve opening based on Pga2

I have successfully used this method of control, using the linear equation, for controlling the motor that operates the oil cooler fan in the compressor. In this case, the reference is provided by a single sensor indicating the oil temperature at the outlet of the radiator.

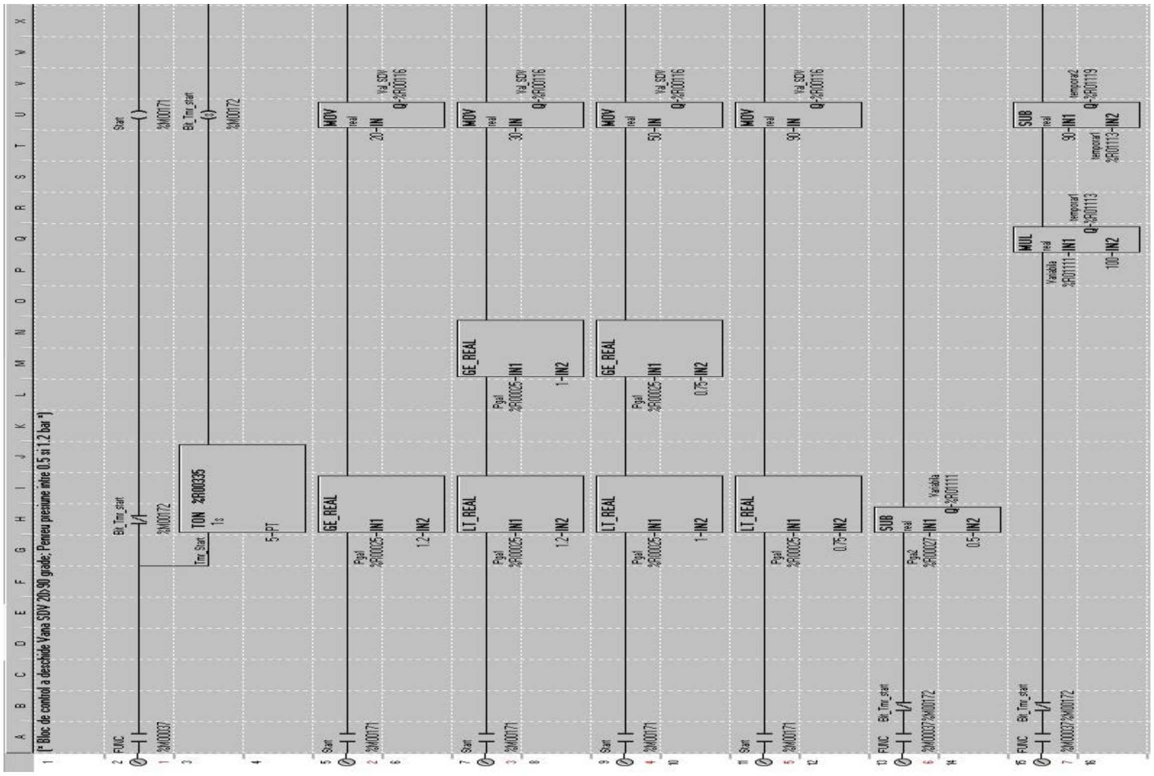


Fig. 28 – The introduction of the straight-line equation into the software and controlling the valve using it - 1

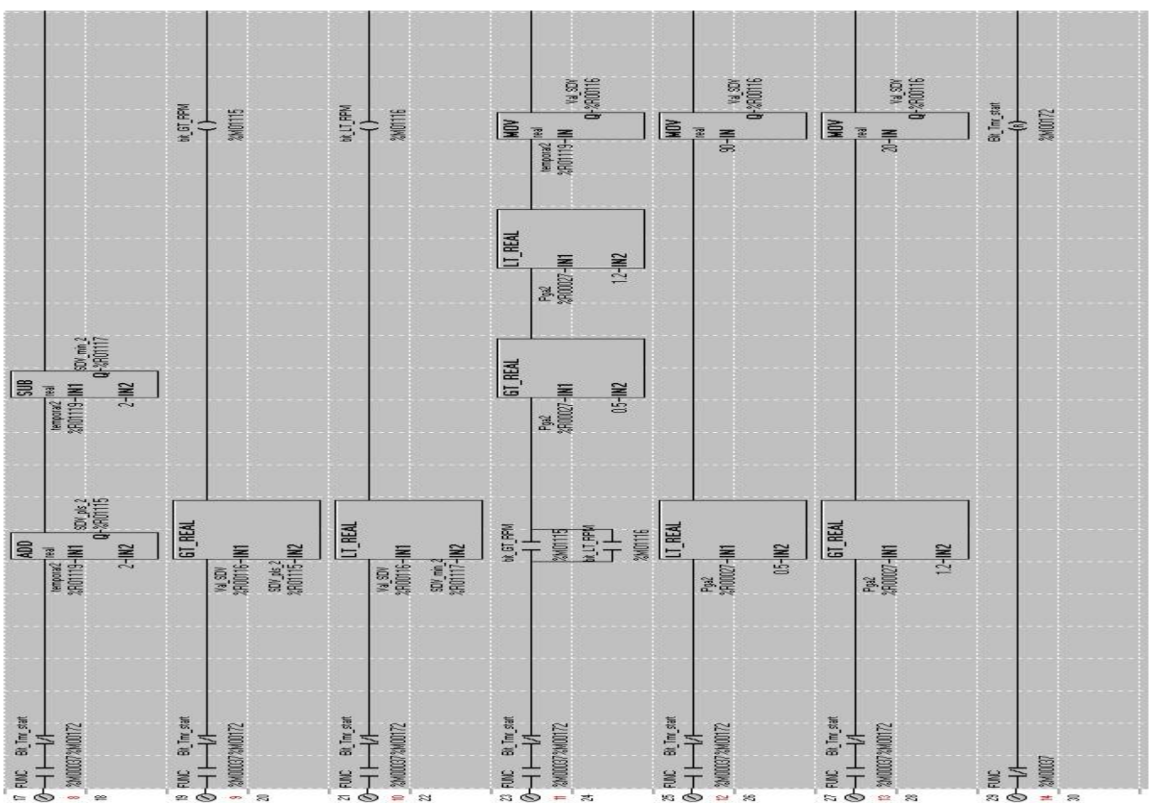


Fig. 29 – The introduction of the straight-line equation into the software and controlling the valve using it - 2

A summary of this chapter was presented in the article "Optimizing the Electronic Control of Suction Valves for Gas Compression Units" [27], where I served as the primary author. Another article that formed the basis of research regarding valves was "Electronic improvements made for industrial valve" [28]. For this article, I studied the aspects of the classic valve construction and the use of standard products to enhance its characteristics concerning user interface, valve status during operation, and control interface with classic standardized communication protocols like EtherCAT®, ProfiBUS®.

The concept of implementing this control loop addresses issues arising from high suction pressure during the startup and operation of compression units. It provides the compression unit operator with the ability to configure specific control loops through the HMI based on their preferences.

If using a valve without precise position indication is considered, the entire process can be simplified, as I will explain in the next section.

5. ECS START UP UNDER HIGH PRESSURE CONDITIONS WITHOUT HARDWARE INTERVENTION

The valves generally used by INCD Turbomotoare COMOTI have a protection rating of at least IP 67, which means protection against dust particles and waterproofing for submersion in liquid up to 1 meter deep for a duration of 30 minutes. Inside these valves, there are electrical components classified in the ATEX Group IIB with a temperature class of T4 for heating (maximum 135°C). The electrical actuation marking of the valve will be: Ex II 2G d IIB T4, as specified in the article "Electrically actuated valves for gas compression installations located in potentially explosive atmospheres" [29].

During my doctoral studies, I researched the development of an ATEX-certified control and command cabinet for use in hazardous areas. These units are essential for placement near compression units or in potentially explosive areas. They must adhere to strict ATEX safety standards, which include precise requirements for construction, protection methods, testing, and certification. The main purpose is to minimize the risk of sparks or overvoltages that can cause fires. Such devices significantly contribute to safety in hazardous environments.

Due to the current ATEX regulations, it is prohibited to add or remove elements from inside equipment that holds an "Ex" certification. This leads to the necessity of recertifying the equipment. For this reason, I considered a second solution for starting compression units when there is high pressure in the suction pipe.

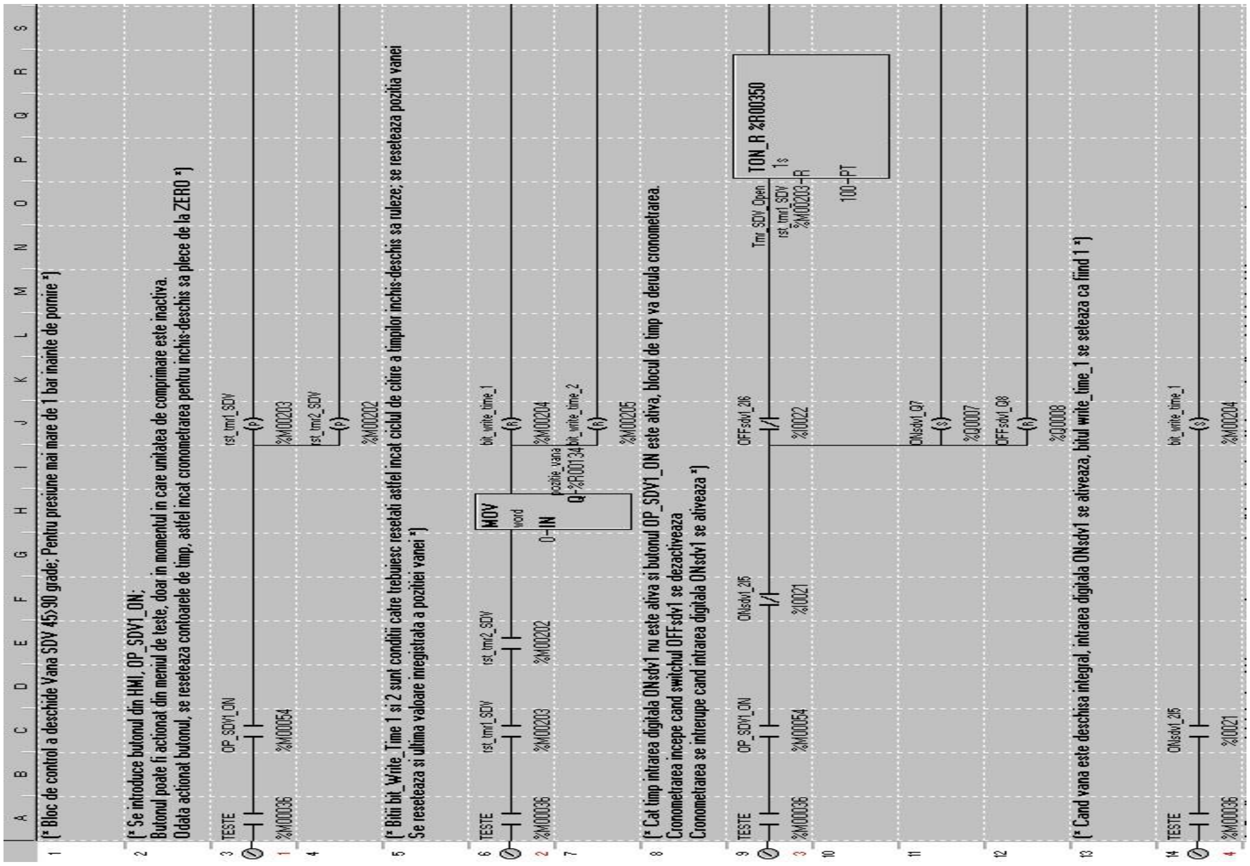


Fig. 30 – Page 3: Software for Starting the Compressor under High Pressure Conditions

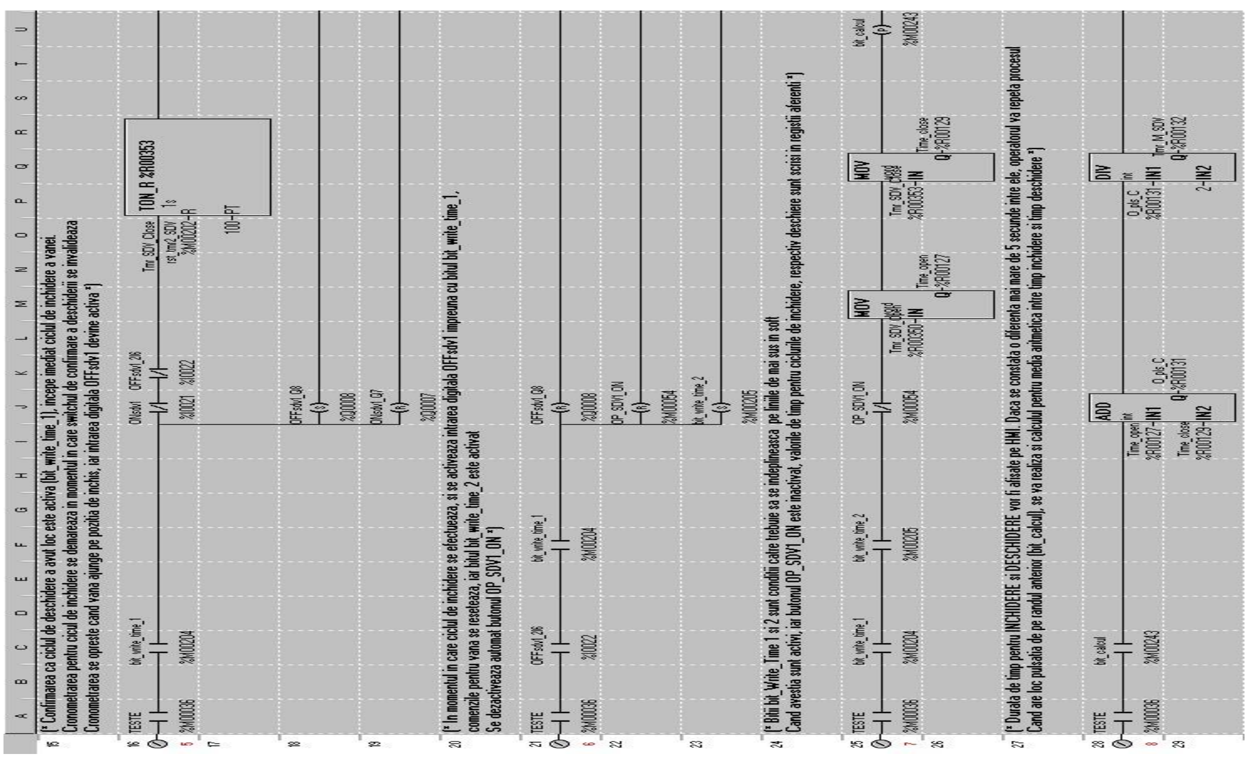


Fig. 31 – Page 2: Software for Starting the Compressor under High Pressure Conditions

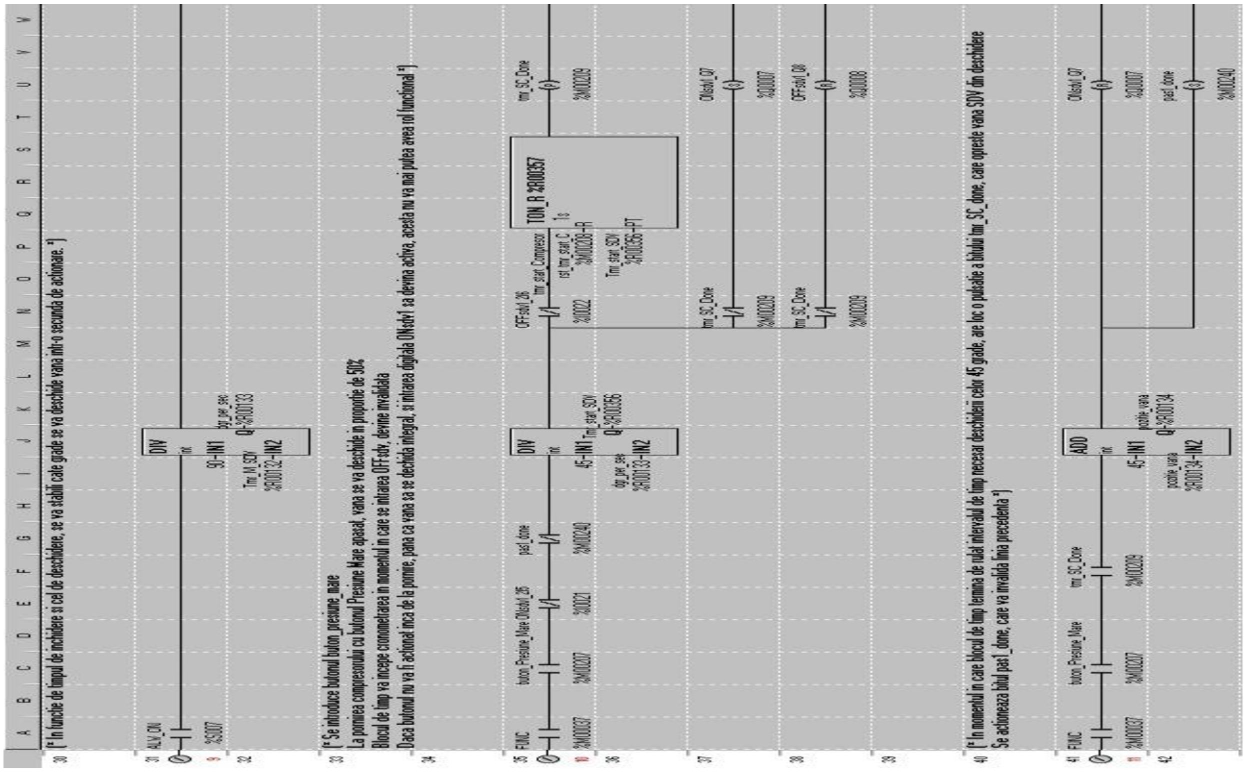


Fig. 32 – Page 3: Software for Starting the Compressor under High Pressure Conditions

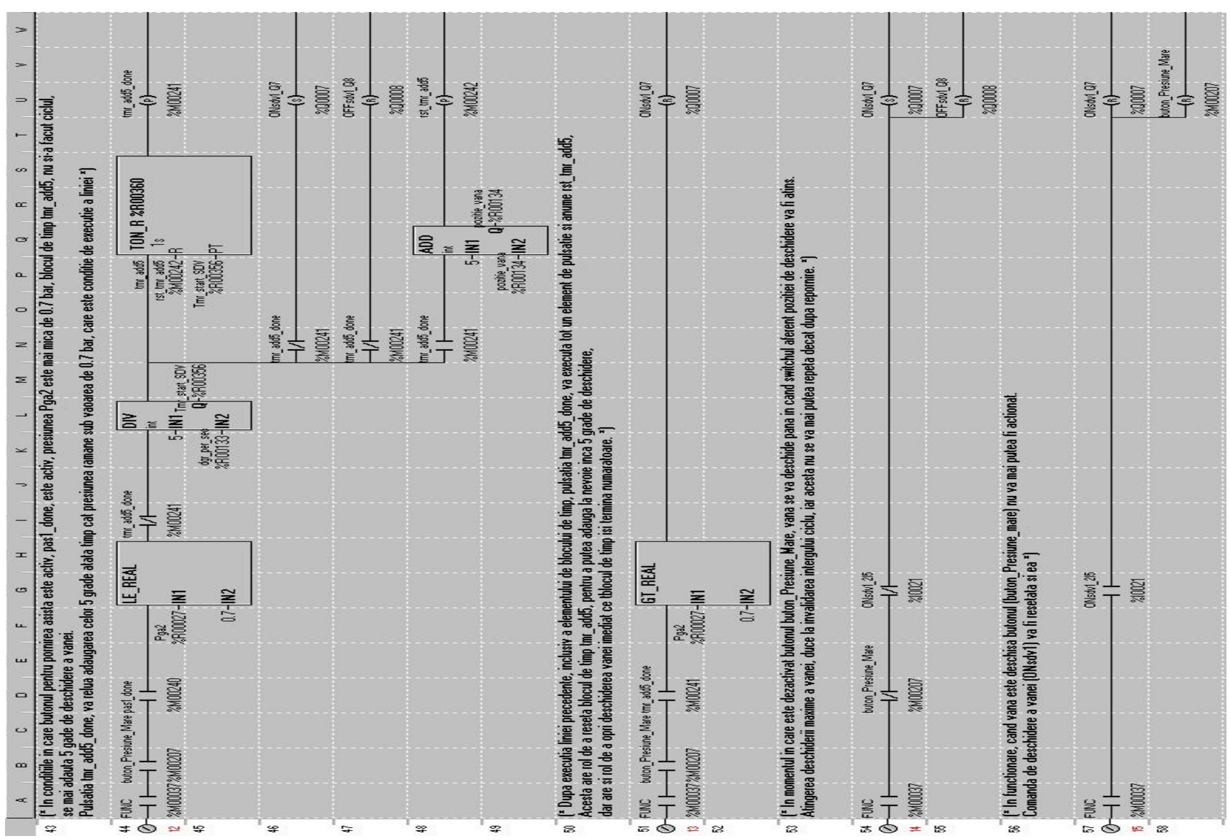


Fig. 33 – Page 4: Software for Starting the Compressor under High Pressure Conditions

I proposed an initial valve opening at 45 degrees, representing half of the total opening, which was tested in the Functional Testing phase (PIF). This value can be adjusted through software or on the HMI screen, with a limit of 20 degrees to avoid prolonged vacuum conditions at the suction and ensure compressor safety.

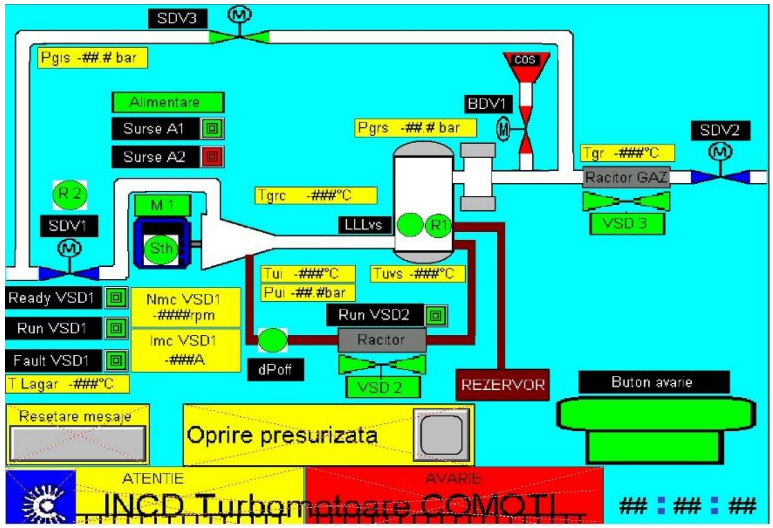


Fig. 34 – HMI screen in operation mode (FUNC) of the compression unit

The button for high-pressure startup only appears on the initial "INIT" screen. After pressing the startup button, the HMI will display the screen shown in Fig. 34. On this screen, you will notice the presence of both the stop and high-pressure stop buttons. This screen belongs to the operating state (FUNC) of the compressor.

With the software I have developed and presented above, it is possible to safely start any compression unit produced by INCD Turbomotoare COMOTI, without the need for any modifications to the existing automation cabinets at the beneficiaries' end.

Certainly, there can be many additional ideas to complement those presented in this chapter. I have focused on creating a software configuration that aligns with specific current needs. These solutions are intended to be of use to beneficiaries in the oil and gas industry in the future without incurring significant intervention costs on the machines currently in operation.

6. CONCLUSIONS AND OWN CONTRIBUTIONS

The purpose of this doctoral thesis was to develop automation systems for screw compressors in Romania, with a case study on the screw compressors produced by INCDT COMOTI. Emphasis was placed on the construction of control and power cabinets, valve control, and possible applications in other industries.

The importance of automation systems for screw compressors was highlighted, as they optimize the performance and efficiency of these devices. Valve control contributes to regulating gas flow, improving efficiency, and reducing environmental impact.

The research underscores the need for ongoing development of automation systems for screw compressors and valve control in the gas industry for efficiency and sustainability.

6.1 Own Contributions

The doctoral thesis aimed to make contributions regarding the command and control of screw compression assemblies, produced in Romania to INCDT COMOTI.

I will now briefly present the original contributions made in this thesis:

- I conducted an analysis to determine how signals are recorded by transducers and subsequently transmitted to a PLC or control unit to provide operators with information and enable the creation of efficient and dynamic control and automation systems. This involved studying the current state and trends in the instrumentation technology of compression units. (Chapter 2).
- I presented a method for harvesting energy from equipment vibrations. Energy harvesting is the process of capturing energy from vibration sources, such as rotating machinery, and converting it into electrical energy. (Chapter 2.4.5).
- I explained how I participated in a project aimed at creating a gas compression-decompression assembly (expander) with a team of researchers from the Electrical and Automation Systems section at INCD Turbomotoare COMOTI. This included the selection of equipment and the proposal of user-friendly graphical interfaces in HMI for easy operator use. (Chapter 3).
- I described the steps involved in creating control and power cabinets for screw compression units produced by INCDT COMOTI.
- I developed a system for transmitting position information applicable to standard valves used in gas compression assemblies, designing and implementing control solutions from both hardware and software perspectives. (Chapter 4).
- I explained how position information from a valve's mechanical position is translated into an analog signal in a simplified manner, the potential issues that can arise during information transmission, and the calculations to consider when dealing with such a device. (Chapter 4).
- I explored solutions for addressing operational issues that arise when the suction pressure of a compressor exceeds the design limits (Chapter 4.1).
- I successfully transformed a standard valve with open-close relay control into a valve with position indication, representing a significant upgrade (Chapter 4.2).
- I recommended using gear wheels to read the resistance transmitted by a potentiometer, converting it into position information (Chapter 4.3).
- I proposed the installation of a pressure transducer to monitor pressure in the main gas supply pipeline for a compression unit, even when the compressor is idle, to estimate the need for controlled starts of the compression units (Chapter 4.5).
- I conducted a series of experimental tests that demonstrated the successful implementation of the position information transmission solution using a

potentiometer and gear wheel. However, some issues related to valve calibration arose (Chapter 4.6).

- With the help of Ladder Diagram software used for controlling a compression unit, I created a control loop for valves installed on units produced by INCDT COMOTI by implementing a linear equation. This control method was also successfully applied to control the motor driving the compressor oil cooling fan. (Chapter 4.7).
- I proposed a second solution for starting compression units when there is high pressure in the suction line, taking into account ATEX regulations that prohibit adding or removing elements inside an "Ex"-certified equipment, which would require recertification (Chapter 5).
- I suggested various startup methods for compression units with high suction line pressure (Chapter 5).
- With the control method I developed and presented in the thesis, safe startups of any compression unit can be achieved without requiring modifications to existing control cabinets at client sites (Chapter 5).

6.2 Prospects for Further Development

The results obtained open up new avenues for research and development, such as the more efficient use of screw compressors in expander mode or advancements in valve control. Their impact is reflected in energy efficiency. I am confident that these conclusions will continue to be leveraged in future research and development efforts in the oil & gas industry.

I acknowledge that there are still challenges and opportunities for expanding research in this direction, and our work aligns with a broader context of developing efficient and sustainable technological solutions in the gas industry. Here are some additional ideas for future developments that could be considered:

- Advanced Signal Collection and Transmission: Further exploration of advanced methods for collecting and transmitting signals from measurement instruments to the control and command unit. Consideration can be given to using wireless data transmission technologies for more efficient and rapid communication. Additionally, implementing monitoring and control systems at the IoT (Internet of Things) level could be a promising avenue.
- Enhanced HMI Functionality: Developing new functionalities and features for the HMI graphical interface to ensure the most intuitive and efficient user experience for operators. This might include options for interface customization, interactive alarms and notifications, as well as tools for data analysis and reporting based on the collected data.
- Exploration of Alternative Position Information Transmission: Continued exploration of alternative technologies and methods for transmitting position information, such as non-contact position sensors or digital communication technologies. Assessing the performance of these alternative solutions and

integrating them into the specific context of valve control applications could be beneficial.

- Advanced Control Strategies: Building upon the valve control method and the developed control system, new control strategies can be investigated and implemented to improve the performance and efficiency of compression units. Advanced control algorithms and optimization techniques could be explored to achieve more precise and reliable system operation.
- Real-World Testing and Validation: Conducting tests and experiments to validate the proposed solutions and assess the system's performance under real-world conditions. Collecting and analyzing experimental data can help validate the theory and demonstrate the effectiveness and benefits of the proposed solutions.

These future developments could further enhance the efficiency, reliability, and sustainability of automation systems in the gas industry, contributing to the ongoing improvement of gas compression technologies and their applications.

6.3 List of original works

Adrian Stoicescu, Marius Deaconu, Romeo Dorin Hritcu, **Cristian Valentin Nechifor**, Valeriu Alexandru Vilag; „Vibration Energy Harvesting Potential for Turbomachinery Applications” INCAS BULLETIN, Volume 10, Issue 1, pp. 135-148, pp. 2247-4528, ISSN 2066-8201. Jan-March 2018. DOI: 10.13111/2066-8201.2018.10.1.13

Cristian Valentin NECHIFOR, Adrian STOICESCU, Romeo Dorin HRIȚCU. „Wireless Vibration Harvesting System For Turbine Engines” Scientific Journal TURBO, pp. 34-39, ISSN: 2559-608X, June 2018. http://www.comoti.ro/docs/jurnal/TURBO%20Vol%20V_No%201_2018.pdf .

Claudia BORZEA, Daniel COMEAGĂ, Adrian STOICESCU, **Cristian NECHIFOR**. "Piezoelectric Harvester Performance Analysis For Vibrations Harnessing", U.P.B. Scientific Bulletin, Series C Electrical Engineering and Computer Science, vol. 81, iss. 3, pp. 237-248, 2019, ISSN 2286-3540. https://www.scientificbulletin.upb.ro/rev_docs_arhiva/full7e5_563283.pdf

Claudia Borzea, Iulian Vlăducă, Dan Ionescu, Valentin Petrescu, Filip Niculescu, **Cristian Nechifor**, Gabriel Vătăşelu, Mihai Hanek. "Compressed Air Energy Storage Installation for Renewable Energy Generation", E3S Web of Conferences, Vol. 112 (2019): 02010. DOI:10.1051/e3sconf/201911202010.

Cristian Nechifor, Valentin Năvrăpescu, Sorin Tomescu, Claudia Săvescu, Mihaela Roman, Rareș Conțiu, Adrian Stoicescu, „Optimizing the Electronic Control of Suction Valves for Gas Compression Units”, Revue Roumaine des Sciences Techniques - Série Électrotechnique et Énergétique, vol. 68, no. 2, pp. 182-187, 2023. https://journal.iem.pub.ro/rrst-ee/article/view/508. ISSN 0035-4066, IF 0.670.

C. Nicolescu, B. Vărăticeanu, A. Stoicescu, **C. Nechifor**, "Electronic improvements made for industrial valve", EEA - Electrotehnica, Electronica, Automatica, Received: 30 June 2020, Vol. 68(3), iulie-septembrie 2020, pp. 5-12. DOI: https://doi.org/10.46904/eea.20.68.3.1108001

Cristian Nechifor, Claudia Borzea, Iulian Vlăducă,Ion Mălăel, Filip Niculescu. „Electrically actuated valves for gas compression installations located in potentiallyexplosive atmospheres", 2020

Cristian Nechifor, Claudia Borzea, Adrian Stoicescu, Daniel Lale, Mirela Vasile, "Modular automation cabinet for proactive monitoring in ATEX Zone 2"; MATEC Web of Conferences, vol. 354, p. 00044, 2022. DOI: 10.1051/matecconf/202235400044 (10th Edition of the International Symposium on Occupational Health and Safety – SESAM 2021, 18 October 2021)

Claudia Săvescu, Valentin Petrescu, Iulian Vlăducă, Daniel Comeagă**, Cristian Nechifor**, Filip Niculescu Theoretical and Experimental Analysis of a Twin-Screw Compressor as Potential Source for Vibration Energy Harvesting Revue Roumaine des Sciences Techniques - Série Électrotechnique et Énergétique, vol. 68, no. ??, pp. ???-???, 2023. Link. ISSN 0035-4066, IF 0.670. *Trimis spre recenzare.*

6.4 List of works outside the research area of the doctoral thesis

- Valentin Petrescu, Claudia Săvescu, Teodor Stănescu, **Cristian Nechifor**, Mirela Vasile, Sorin Tomescu, Experimental analyses of twin-screw compressors' energetic efficiency depending on the volume ratio 11th International Conference on Thermal Equipment, Renewable Energy and Rural Development (TE-RE-RD 2023), Bucharest, 08-10 June 2023. DOI: ???????. Trimis spre recenzare.
- Daniel Lale, Claudia Borzea, Sorina Gogoneață, **Cristian Nechifor**, Mirela Vasile, Filip Niculescu, Monitoring System with Microcontroller for Passengers in Public Transportation Means Scientific Journal TURBO, vol. VIII, no. 2, pp. 4-11 (2021), ISSN 2559-608X. http://www.comoti.ro/docs/jurnal/Journal%20TURBO%20Vol%20VIII%20No%202%202021.pdf
- Iulian Vlăducă, Claudia Irina Borzea, Mirela Letiția Vasile, George Iulian Bălan, Adrian Săvescu, Andrei Mitru, Dragoș Filip Niculescu, **Cristian Valentin Nechifor**, Teodor Stănescu, Petre Gabriel Badea, Daniel Ușeriu, Răzvan Ciobanu, Automation Control System for Naval Propulsion Retrofitting 2021 International Conference on Applied and Theoretical Electricity (ICATE), Craiova, 27-29 May 2021. DOI: 10.1109/ICATE49685.2021.9465065
- Filip Niculescu, Mirela Vasile, Adrian Stoicescu, **Cristian Nechifor**, Comparative analysis between gas turbine and electric combined propulsion EV2019 - Electrical Vehicle International Conference & Show, Bucharest, October 3-4, 2019, DOI: https://doi.org/10.1109/EV.2019.8893015
- Adrian Stoicescu, Răzvan Ciobanu, Alexandra Taranu, **Cristian Nechifor**, Filip Niculescu, Hardware in the loop test platform concept for adaptive turbine engine controller Scientific Journal TURBO, vol. VI, no. 2, pp. 6-11, 2019, ISSN 2559-608X.
- Constantin Vilcu, Claudia Borzea, Andrei Mitru, Marian Draghici, Filip Niculescu, **Cristian Nechifor**, Mirela-Letitia Vasile „Power correlation of driving motor for turbo blower with industrial process requirements„ Scientific Journal TURBO, vol. V, no. 2, pp. 4-10, ISSN 2559-608X, Dec. 2018. http://www.comoti.ro/docs/jurnal/Scientific%20Journal%20Turbo%20Vol%20V%20No%202.pdf
- Razvan Ciobanu, Adrian Stoicescu, **Cristian Nechifor**, Alexandra Taranu, Self-Learning Control System Concept for APU Test Cells MATEC Web of

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