NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY

POLITEHNICA BUCHAREST

DOCTORAL SCHOOL OF ELECTRICAL ENGINEERING

PHD THESIS SUMMARY

CONTRIBUTIONS ON THE AUTOMATION OF ELECTRICAL INSTALLATIONS OF TEST BENCHES FOR NAVAL PROPULSION

Author:

Eng. PhD Student. Mirela-Letiţia VASILE

Scientific guide:

Prof. PhD. Ing. Valentin NĂVRĂPESCU

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Acronyms and symbols

LMDN	**N**aval **D**iesel **Engine L**aboratory
CPU	**C**entral **P**rocessing **U**nit
I/O	**I**nput/**O**utput
LCD	**L**iquid **C**rystal **D**isplay
LED	**L**ight **E**mitting **D**iode
PC	**P**ersonal **C**omputer
UPS	**U**ninterruptible **P**ower **S**upply
LCP	**L**ocal **C**ontrol **P**anel
PLC	**P**rogrammable **L**ogic **C**ontroller
DCS	**D**istributed **C**ontrol **S**ystem
SCADA	**S**upervisory **C**ontrol **a**nd **D**ata **A**cquisition
HMI	**H**uman **M**achine **I**nterface
ITT	**I**nter **T**urbine **T**emperature
JB	**J**unction **B**ox
TPC	**T**ouch **P**anel **C**omputer
OP	**O**perator **P**anel
NH	High pressure compressor speed
NL	Low pressure compressor speed
NTP	Power turbine speed
IP	Propulsion installation
SAE	**S**ociety of **A**utomotive **E**ngineers

INTRODUCTION

1. The objectives of the doctoral thesis

The main purpose of the doctoral thesis is to contribute to the development and optimization of the automation processes of the electrical installations of the test benches for naval propulsion, in order to improve their efficiency, safety and performance. This research will help to better understand these automation systems, to use them more clearly and precisely, to improve the efficiency of the processes, to understand and interpret other similar systems, to faster processing methods and to verify the installations by checking some parameters; the control and command of these systems helps to reduce fuel consumption, reliability and efficiency.

CHAPTER 1

RESEARCH AND DEVELOPMENT OF A COMMAND AND CONTROL SYSTEM SOLUTION FOR A LABORATORY BENCH FOR NAVAL DIESEL ENGINES

1.1. **The objectives of the naval diesel engine laboratory team**

This naval diesel engine laboratory aims to develop the skills of operating and maintaining the propulsion system. Here, students learn the components of the propulsion system, learn more about the construction of four-stroke internal combustion engines, learn how to correctly monitor the operating parameters of the marine diesel engine, the operating parameters of the speed reduction gearbox and the operating parameters of the hydraulic brake. Among the laboratory works they perform also exercises in successive loading of the marine diesel engine and the interpretation of its behaviour, but also the practical determination of the indicated average pressure and the combustion pressure of the engines in operation.

1.2. **Description of the propulsion installation**

The propulsion system is a complex system for students. The drive unit is a Volvo Penta d16H diesel engine, with fuel injection, driven by a pneumatic starter. The propulsion system assembly includes a fuel tank, lubrication system, oil cooler, oil filters, control and shut-off valves, measuring and protection equipment.

The propulsion system assembly is equipped with a control and monitoring system for automatic control of work processes and continuous monitoring of functional parameters. The control system ensures the start-up of the propulsion system, monitoring of working parameters and adaptation of operation to changes in input and output parameters within the prescribed limits, protection and shutdown of operation to prevent damage.

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1.3. **The components of the propulsion installation**

The propulsion equipment is developed based on a Volvo Penta naval engine with functional characteristics capable of ensuring the imposed technological parameters.

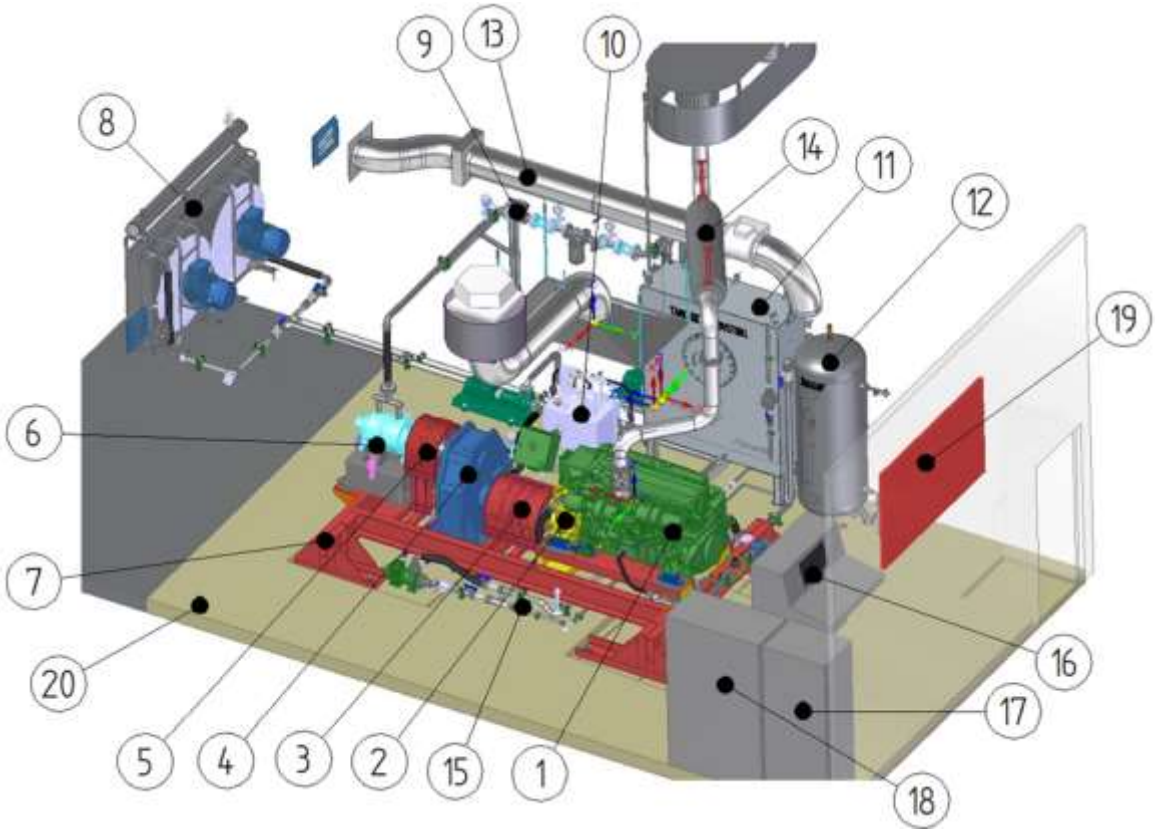


Fig. 1.1. Naval diesel engine laboratory.

The components of the propulsion system are shown in Fig. 1.1: Volvo Penta thermal engine (1), Reverse gearbox(2), Cardan shaft (3), Multiplier (4), Elastic coupling (5), Hydraulic brake (6), Frame assembly (7), Heat exchanger (8), Hydraulic brake circuit assembly (9), Multiplier lubrication circuit assembly (10), Fuel supply system assembly (11), Compressed air system assembly (12), Ventilation system assembly (13), Exhaust system assembly (14), Engine cooling system assembly (15), Control panel (16), Automation cabinet (17), Power cabinet (18), Repeater screen panel (19), Room assembly, Pail assembly (20)

1.4 Design of the propulsion assembly command and control system

The design of the command and control system of the entire propulsion assembly was created based on the list of parameters and taking into account the starting and operating conditions of the entire assembly.

The automation system performs the starting, operation and shutdown of the diesel engine within the LMDN bench. It ensures the acquisition of parameters in transient mode and in operation at the regime, saving data for visualization and processing. The automation system provides the necessary commands for testing and safe shutdown, allowing the tests to be carried out.

The automation system components are illustrated in fig.1.2.

I contributed to the development of the block diagram of the Volvo Penta D16 engine automation control system, which helped to identify and define the main components of the system, establish connections between equipment and provide a general view of the equipment. This diagram helped to develop detailed electrical diagrams, taking into account the dimensions of the electrical components, so that they comply with the technical characteristics and the available space. The block diagram allowed for a clear understanding of the overall system architecture and an efficient implementation in the booth.

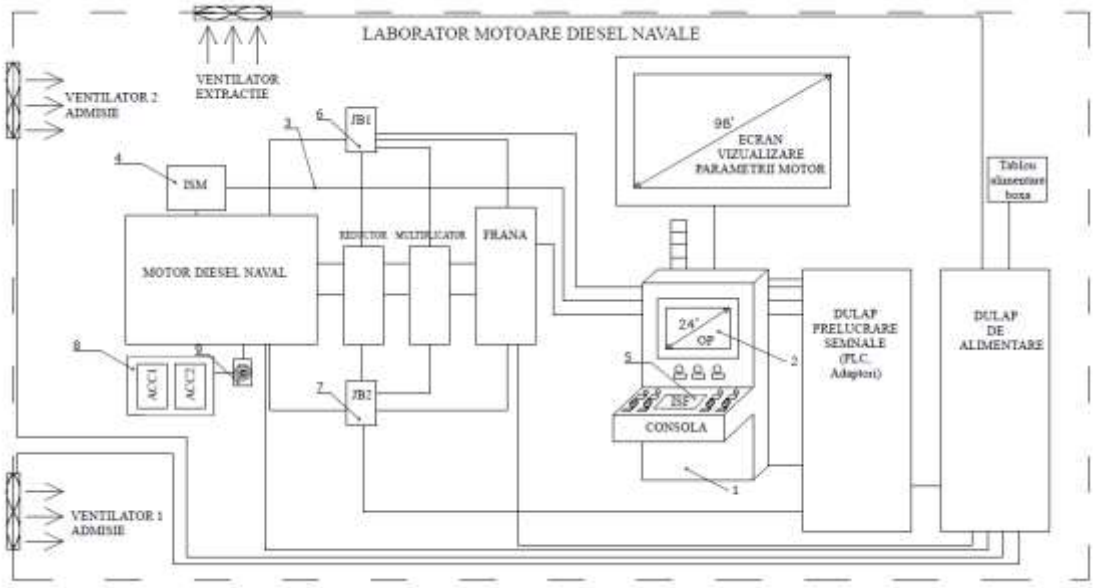


Fig. 1.2. Block diagram of the Volvo Penta D16 engine automation control system.

1. Console;
2. OP –Operator Panel;
3. Connection cables;
4. ISM – Engine monitoring system;
5. ISF – Brake monitoring system;
6. JB1 – Analog signal junction box;
7. JB2 – Digital signal junction box;
8. Engine starting batteries;
9. Engine starting contact.

1.4.1 Electrical components of the propulsion installation

I contributed to the design of detailed electrical diagrams, the choice of electrical equipment based on technical characteristics, the preparation of the required electrical materials and equipment, the purchase of materials and equipment and the execution and connection of electrical components.

1.4.1.1 Automation cabinet (DA)

The display of parameters and operation is carried out through the operator panel, produced by Emerson Automation Solutions, also programmed in COMOTI's own design. The programmable automatic interface - process, is realized by the electrical equipment located on the propulsion installation.

The electrical cabinet also contains the corresponding power supply circuits for both the various measurement lines and for the control of the execution elements. The list of parameters and the electrical diagrams are part of the execution documentation of the Automation Cabinet and describe its composition.



Fig. 1.3. Automation cabinet (DA).

1.4.1.2 Power cabinet (DF)

It includes three converters for the water-brake cooling fan motor, the main brake water pump and the secondary brake water pump and other electrical circuit protection equipment.



Fig. 1.4. Power cabinet (DF).

1.4.1.3 Control console (CC)



Fig. 1.5. – Control console.

The console includes the operator panel on which the user interface is located, the diesel engine control lever (MC), the engine operator panel, the brake operator panel, as well as other control and signalling equipment.

1.4.1.4 Sensors and transducers

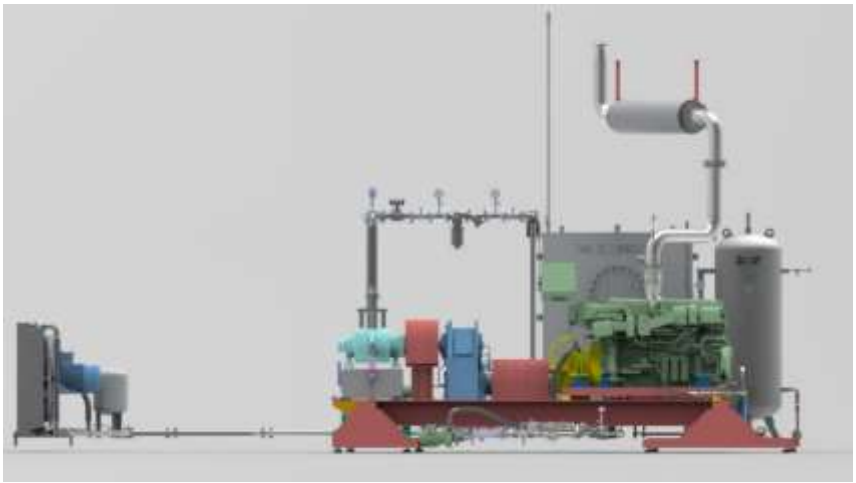


Fig. 1.6. – Propulsion system assembly (side view).

The transducers (of temperature, pressure, level and flow) are positioned on the entire propulsion system, at various points so that they take over the important parameters of the system.

1.4.1.5 Wiring and junction boxes

The wiring and junction boxes are positioned on the propulsion assembly (see figure 1.7).

The junction boxes have the following role:

- • JB1 connects analog signals;
- • JB2 connects digital signals;
- • JBM connects signals between the engine and the monitoring panel.



Fig. 1.7. – Junction boxes.

1.4.2. The acquisition of input/output parameters

After analysing the requirements and the experience accumulated through the design and execution of several types of test benches by INCDT COMOTI, we established analogue and digital input and output parameters, which ensure the optimal operation of the installation, and based on them we chose the equipment for monitoring and controlling the diesel engine, in order to satisfy all the imposed requirements.

For the PLC, we chose the configuration based on the VersaMax structure produced by Emerson, which has proven its reliability in other projects based on it. The price / reliability ratio is the best compared to other configurations based on other types of processors. We chose the input-output modules so as to cover the number and types of analogue and digital signals required for the project.

The solution for the automation and command-control installation of the LMDN bench, a result of the research, is notable for:

- optimized layout of the transducers, junction boxes and local control cabinet in the test room;
- modern local control via touchscreen operator panel;
- three-position signal lamp for quick visualization,
- remote monitoring of parameters with saving of essential operating data.

1.4.2.1. Input/output parameters of the system

The input/output parameters of the system are represented by temperatures, pressures and other important parameters in the installation. Regardless of the operating sequence, the integrity of the measurement lines is checked. The measurement line that is out of order will be signalled by a message in the lower left of the operator panel.

1.5. Testing of the components of the command and control systems of the Marine diesel engine laboratory bench

1.5.1. Introduction

The propulsion installation is developed based on a Volvo Penta engine with functional characteristics capable of ensuring the imposed technological parameters and consists of the following main test elements:

• The propulsion system mounted on the chassis assembly:

- Volvo Penta/ D16 MH piston diesel engine (600HP/1800 rpm);
- D-I.I./ DMT280H reducer-inverter gearbox (i=2.06);
- INCDT Comoti/ CHP220 multiplier (i=3.06) – necessary to increase the speed and decrease the engine torque at the input shaft in the hydraulic brake;
- Horiba DT900-2 bidirectional hydraulic brake – necessary to ensure the resistive torque (simulation of the propulsion propeller on board the ship);

• Automation, control and monitoring system of the LMDN bench;

• Auxiliary and service installations of the LMDN bench.

This program was developed specifically for testing the propulsion installation of the LMDN bench and is applicable only to testing this type of propulsion installation. Figure 1.8 shows a part of the dedicated software program developed in Proficy Machine Edition 10.4, based on which the PLC controls the operating sequences of the bench.

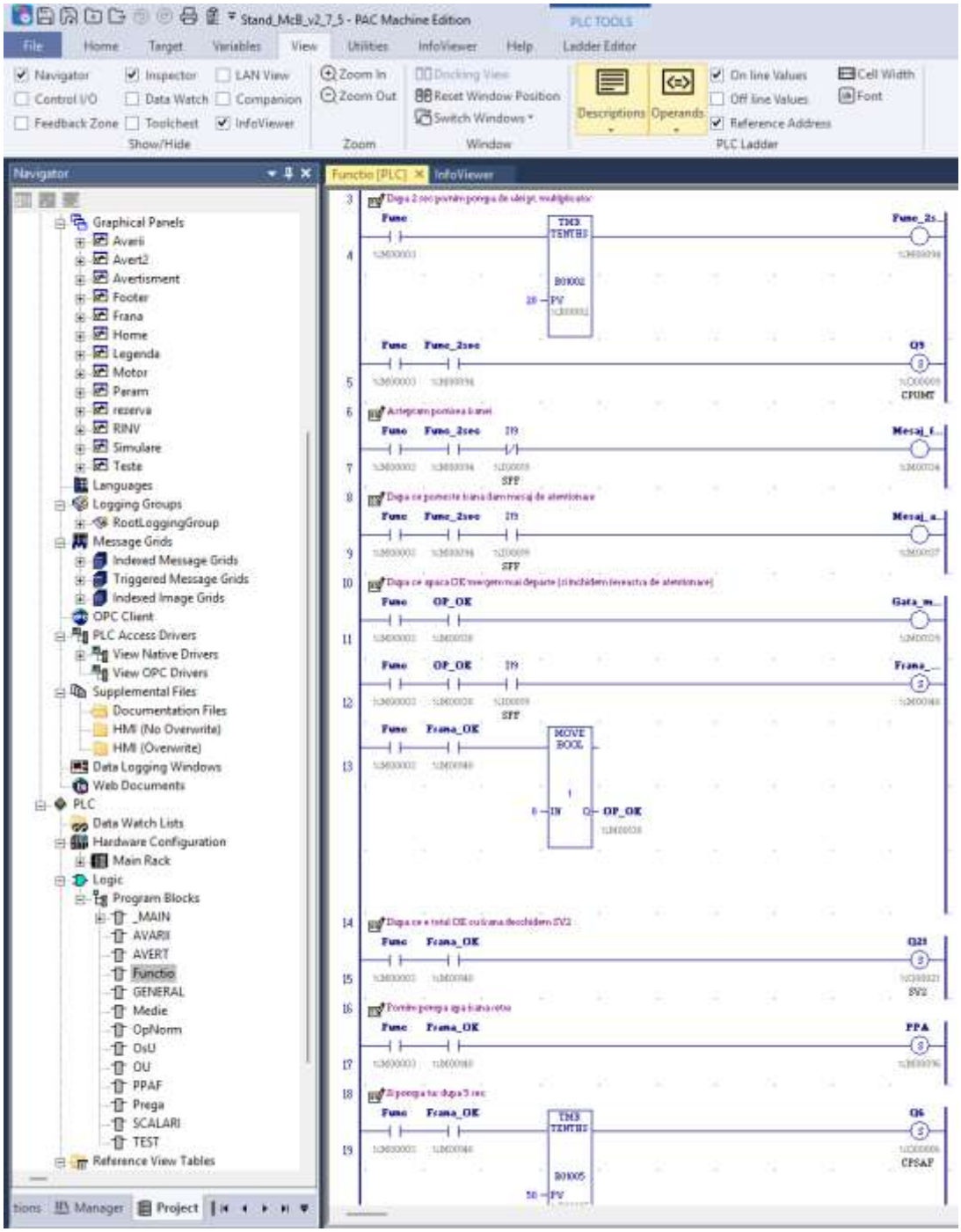


Fig. 1.8. – Sequences from the software program.

1.5.2. Technical conditions for testing marine diesel engine laboratory bench

Fig. 1.9 shows a part of the software implemented in the PLC, programmed in Proficy Machine Edition, representing the normal operating sequence of the test bench. The structure reflects the logical flow, respecting the order of operations and dependencies within the control process. The custom programmed software supports data acquisition, data processing, analysis and observation of the system operating parameters.

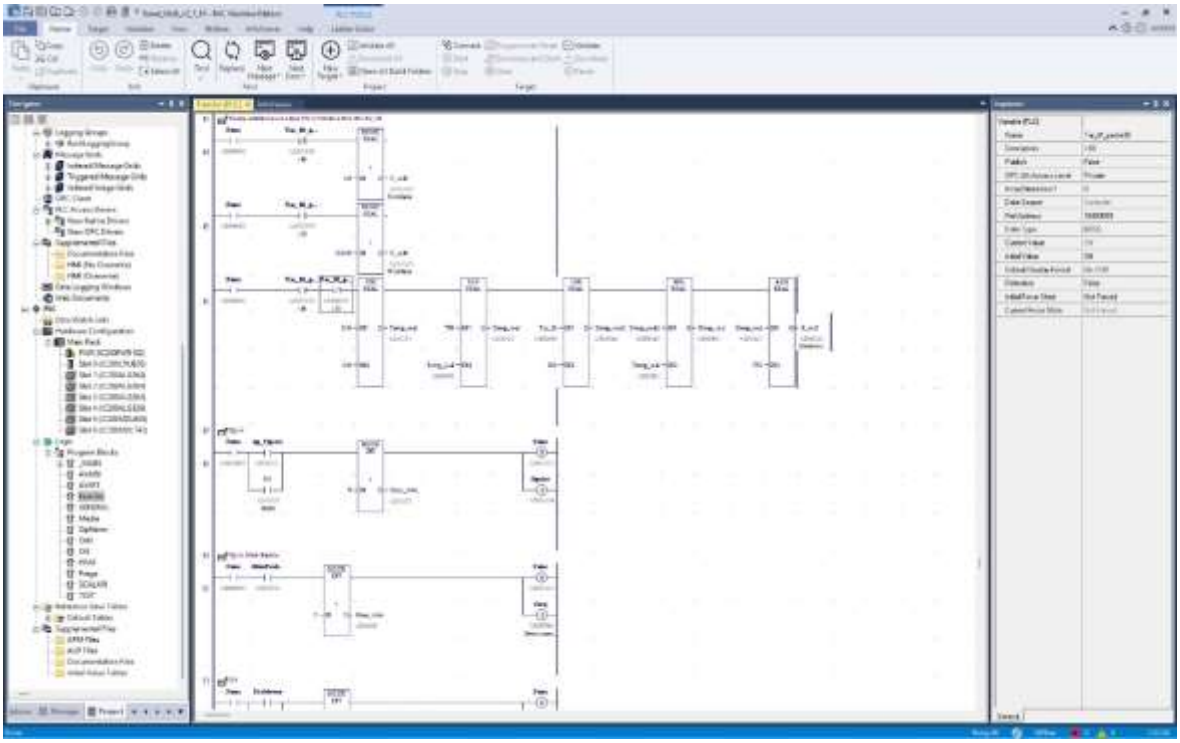


Fig. 1.9. – Graphical representation implemented in software.

1.5.3. Preparation of installations for start-up of the propulsion group

The preparation of the installations for the running of the LMDN bench includes three stages:

- installation and preparation of the propulsion installation equipment/systems;
- testing and adjustment of the systems/installations;
- verification of the control systems of the LMDN bench.

1.5.4. IP testing of the LMDN bench

IP testing is basically performed by the automation system, which performs the following main functions:

- starting, ensuring the operation and safe shutdown of the propulsion plant;
- command and control of the propulsion plant in Simulation mode;
- viewing all parameters on the operator panel;
- signalling of failures and protection;
- changing the limits for certain parameters;
- displaying and memorizing the cause of the shutdown;
- monitoring parameters, etc.

From the point of view of the automation system, the operation of the propulsion installation is of sequential type, having the following defined states (fig. 1.10):

INIT	Initial state (idle, start-up can be initiated)
TESTE	Manual tests (installations can be tested)
FUNCTIONARE	Operation (start-up, idling, operation under load)
OPRIRE NORMALĂ	NORMAL Stop sequence

OPRIRE DE URGENTA EMERGENCY Stop sequence

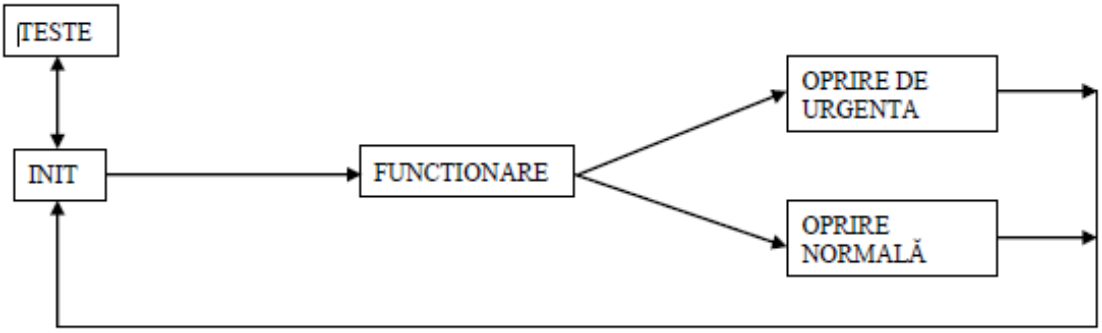


Fig. 1.10. – Operating states of the propulsion installation.

When the operator panel (OP) is powered on and the software is running normally, several screens can be displayed that are accessed via the buttons at the bottom of the PRINCIPAL screen - represented in fig. 1.11 in the form of an intuitive drawing, I have created a simplified diagram in which all the main equipment of the bench appear, in which the monitored parameters and the technological scheme of the propulsion installation are presented. In this screen, I have implemented buttons for all other screens.

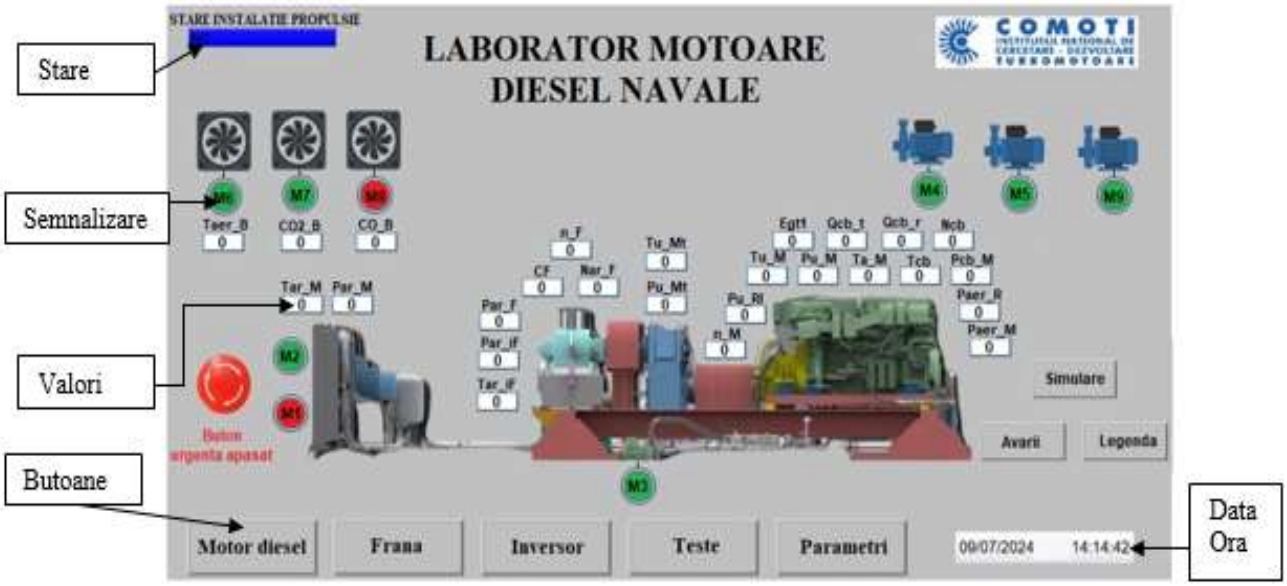


Fig. 1.11. – PRINCIPAL screen

The propulsion system is started and stopped automatically by commands given from the Operator Panel (OP) in the Machinery Control Station (PCM). After the engine has started and warmed up, the commands and the operating mode adjustment can be made from the Operator Panel and the adjustment lever in the Machinery Control Station (PCM) console.

The choice of the operating mode of the propulsion system is made by prescribing the parameters of the dynamometer/hydraulic brake that simulates the characteristics of the ship's propeller, resulting in the engine torque and power developed depending on the speed regime.

During the operation of the equipment, the PLC monitors the essential parameters of each equipment in the bench. If a fault is detected, the PLC will automatically activate the semi-emergency stop sequence (ESD02) and emergency stop (ESD01) of the bench and will display an error message on the screen.

1.6 Contributions regarding the optimization of the command and control system

1.6.1. Optimization of the application monitoring screens

I have modified and optimized the screens so that they are easy to use and intuitive. As can be seen in fig. 1.16 we have reduced the number of buttons that, when pressed, switch to another screen of the application. In the new MAIN screen we have grouped the parameters to be easier to view depending on the working fluid/gas mixture or depending on each equipment that makes up the propulsion system.

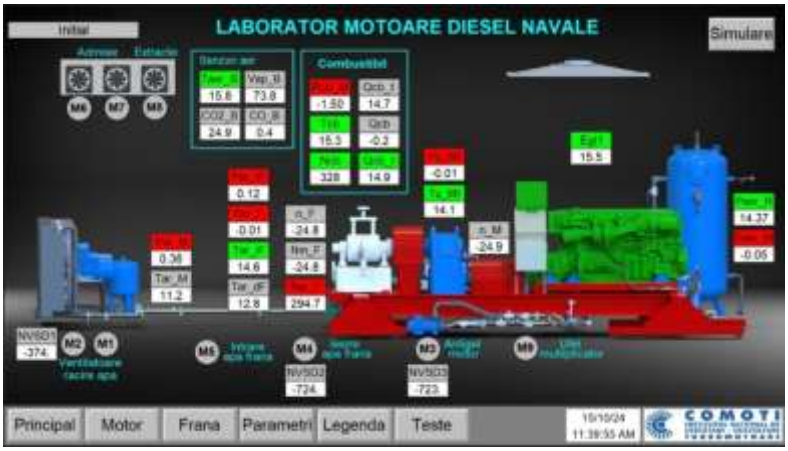


Fig. 1.16. – The new PRINCIPAL screen

As can be seen from figure 1.17, I have integrated the motor screen and the reducer-inverter screen into one. From the two screens we have obtained a much more colourful and attractive one by optimizing the application. Through this transformation we have reduced the number of parameters monitored in the case of the motor from 11 to 9, in the case of the reducer-inverter there is no parameter to monitor.

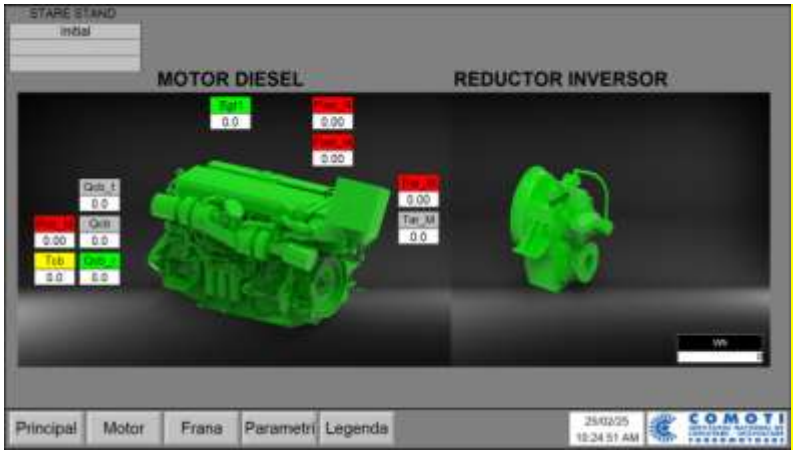


Fig. 1.17. – Motor and Reductor inverter gearbox screen

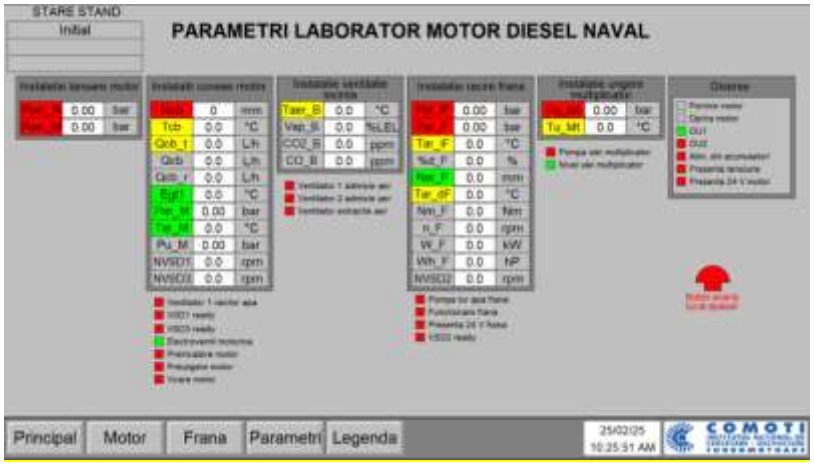


Fig. 1.18. –PARAMETRI screen

All propulsion system parameters can be viewed in a single screen – PARAMETERS (fig.1.18).

1.6.2. Engine communication with the PLC

The integration of the Volvo Penta D16 engine control unit (ECU) with the automation system's panel computer was achieved using the SAE J1939(CAN) and MODBUS TCP/IP communication protocols. The panel computer used for the automation system, manufactured by Emerson, does not support the SAE J1939 protocol, using the MODBUS TCP/IP communication protocol, so I look for an adapter module with which I could realize the communication between PLC and the engine control unit.

This higher-level SAE J1939 protocol is a standard adopted by Volvo Penta for the communication of the engine control unit with other computing devices.
The structure of a J1939 message is:

- PGN (Parameter Group Number) – identifies the data type;
- Source Address (SA) – address of the device sending the message;
- Data – transmitted content (e.g. speed, temperature).

Below is the structure of the message used in the case of reading the speed parameter from the address provided by the engine ECU:

Table 1.3. The structure of the speed message:

NR. CRT	PGN	DESCRIERE	DATE UTILE
1	61444	TURAȚIE	RPM%

The architecture of the communication system (see figure 1.19.) consists of: panel PC, Can-Modbus TCP/IP adapter and engine controller.

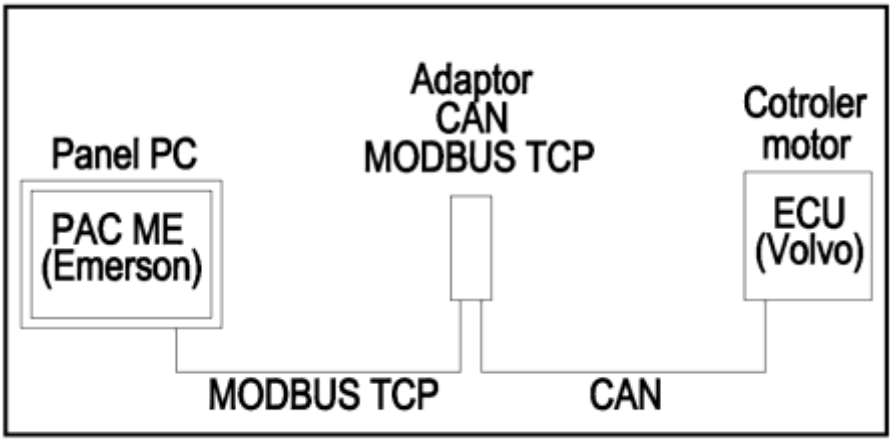


Fig. 1.19. – Communication system architecture.

Gate 5118 industrial gateways (fig.1.20) support the SAE J1939 protocol, which is based on the CAN bus (Controller Area Network). SAE J1939 is used to implement communication and diagnostics of vehicle components, diesel engine generators and compression engines.



Fig. 1.20. MGate 5118 MOXA controller [2].

The communication between the on-board computer and the ECU proceeded without problems. After making the connections and powering the equipment, we obtained, by raising the engine at different speeds, the data that can be found in table 1.4.

Table 1.4. Values read via the CAN open interface in the case of speed

N	x	0	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800
Mbus	y	255	4863	5631	6655	7167	8191	8959	9727	10495	11519	12031	13055	13823	14335

Where N represents the speed in rpm, displayed on the diesel engine monitoring screen, and Mbus the values provided by the communication adapter for each speed level.

Graphically representing these values, the figure is obtained 1.21.

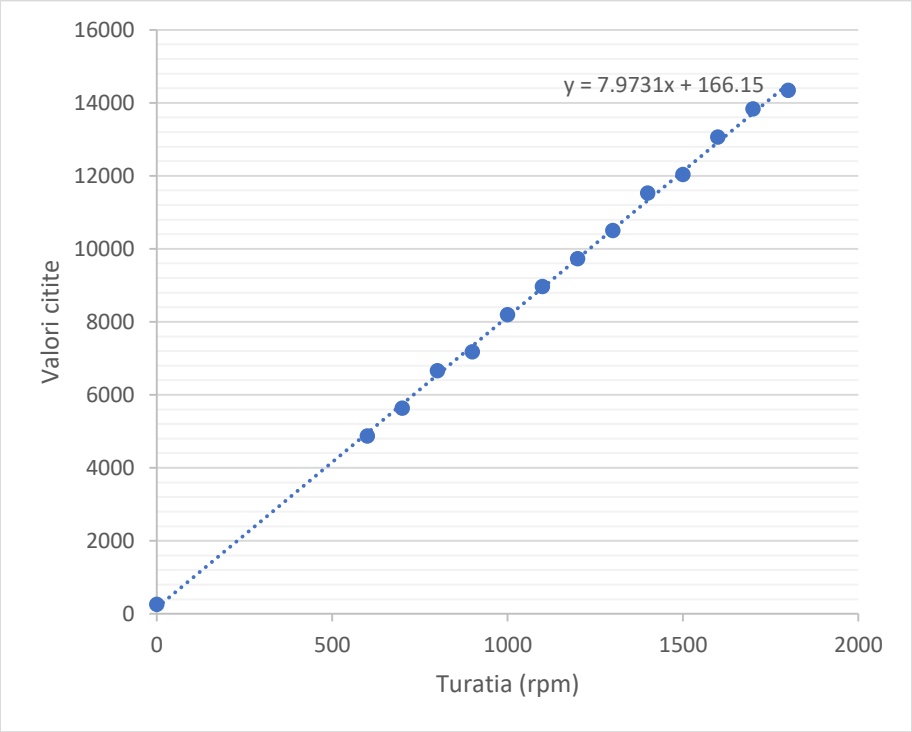


Fig. 1.21. Engine speed graph

The equation of the line obtained by interpolating the points is:

$$y = 7.9731x + 166.15 \qquad (1)$$

1.7. Analysis of the experimental results obtained in the LMDN bench

1.7.1. Testing and verification of engine performance

Based on the data recorded during the functional tests, the parameters filled in the tables with basic engine performances and IP performances for the engine speed range 600-1860 rpm.

To test and verify the engine performances, I conducted tests with the engine for 3 days. From the recorded data, I extracted certain parameters that contribute to the engine performances, and I used other parameters in formulas to verify other performance characteristics.

Table 1.5. Basic engine performance:

No.	Test/activity name	Requirements	Conclusions/ Experimental data	Supporting documents	Obs.
0	1	2	3	4	10
1.	Checking engine performance characteristics				
1.1	Engine nominal power	400 - 600 kW	441 kW (600 CP)	Recorded parameters table	*
1.2	Specific fuel consumption - at maximum torque	Max. 215 g/kWh - 100% load	217,5 – 199,2 g/kWh	Recorded parameters table	*
1.3	Overload running	Min. 10 % - 15 min. / 12 h	15 min. / 12 h	Recorded parameters table	*

1.7.2. Comparison of the experimental results

The parameters of the engine, brake and other components of the propulsion system are recorded in order to analyse its behaviour during the tests.

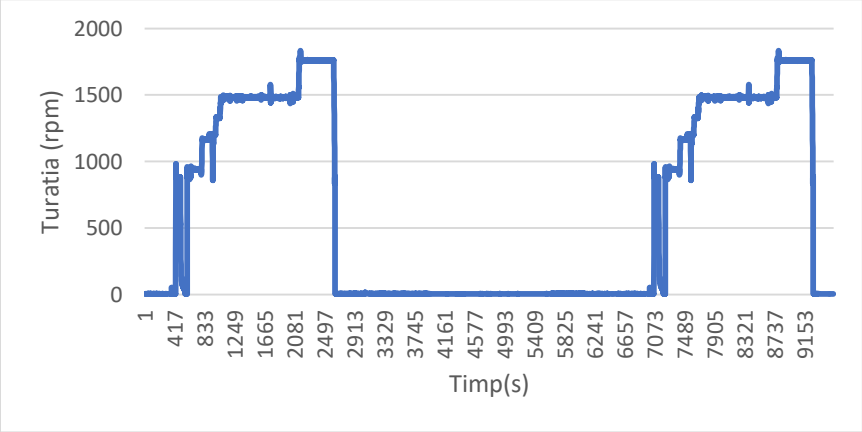


Fig. 1.23. Brake speed evolution

From the evolution of the brake speed, shown in Fig.1.23, it can be seen that in the chosen time interval, two starts were made with the motor-reducer-brake assembly, for each start the regime varying between zero and the speed of 1800 rpm. Analysing the way in

which the brake responds to the two successive starts, it can be seen that the system brakes efficiently when stopping and that there are no delays or oscillations in the braking process.

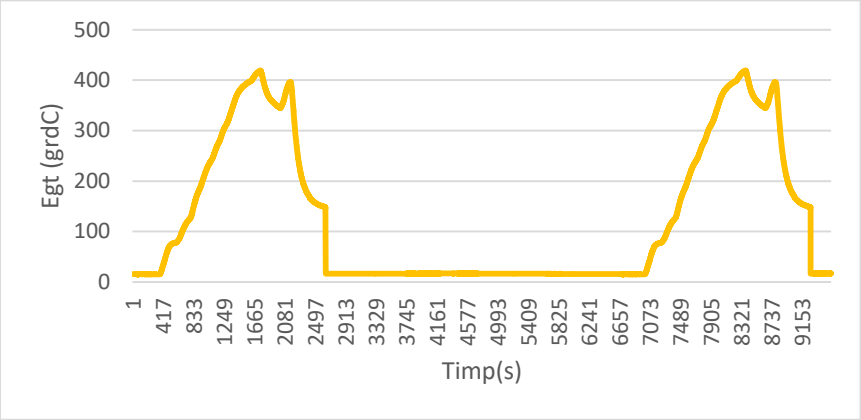


Fig. 1.24. Gas exhaust temperature evolution

The maximum exhaust gas temperature, measured on the gas outlet section connected between the engine and the outside of the test bench, reached a maximum value of 419.4°C, which corresponds to normal engine operation at the tested regime.

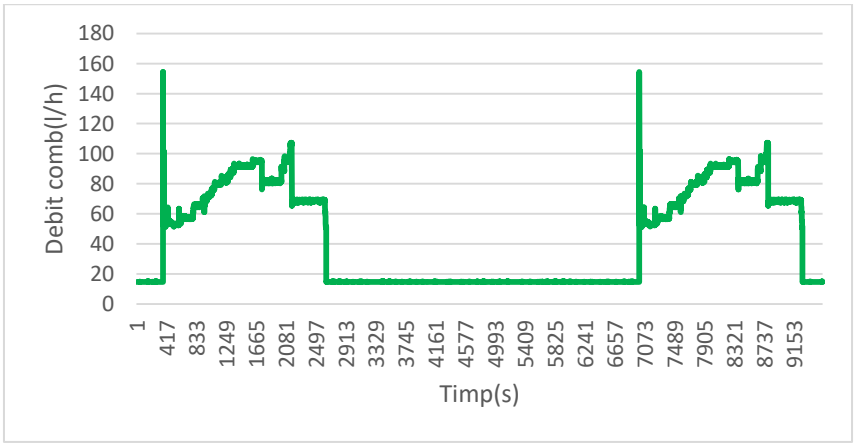


Fig. 1.25. Fuel flow rate evolution

Fuel flow rate is controlled by the engine's electronic control unit (ECU) and varies with operating conditions, with a peak at engine start. The evolution of exhaust gas temperature and fuel flow rate is very important in helping to diagnose performance, efficiency and faults.

CHAPTER 2

CONTRIBUTIONS TO MODERNIZATION AND IMPROVEMENT OF AUTOMATION OF A TEST BENCH FOR TESTING NAVAL PROPULSION WITH ST40M GAS

2.1. Description of the ST40M gas turbine

The ST40M is a gas turbine widely used in marine applications. It is manufactured by Pratt & Whitney Canada and is derived from the PW150A aircraft engine.

2.2. Configuration of the test bench for testing naval propulsion based on the ST40M gas turbine

This bench has the necessary equipment to test a propulsion used on civil or military ships within the Romanian Navy. The main equipment used in the tests are:

- Starter, electric or pneumatic;
- Fuel tank;
- Air tank;
- Lubrication system;
- Air intake;
- Exhaust gas exhaust;
- Dynamometers, for turbo engine loading;
- Control and data acquisition system (SCADA) [3].

2.3. Dynamometers and auxiliary electrical installations

The dynamometers are of the Froude type in which the mechanical energy developed by the gas turbine under test is converted into heat by the friction inside cavities of pressurized water. These two dynamometers can operate both separately and in tandem, developing a total power of 5200 HP sufficient for the maximum loading of the 4000 kW naval gas turbine. For surveillance, the test cell has implemented a closed circuit video system consisting of several mobile and fixed video cameras.



Fig. 2.1. Froude Dynamometers – Gas turbine bench.

The auxiliary electrical equipment necessary for the operation of the dynamometers, designed and manufactured within INCDT Comoti, are the electrical box for the lubrication pumps and the control cabinet together with the pumps necessary for the cooling water installation.

2.3.1. Electric box for brake lubrication pumps

This electrical box has the role of starting the 3 oil pumps required for each brake in an order imposed by the brake manufacturer. It is provided with control and protection elements for each oil pump, as well as with a general protection.



Fig. 2.2. Electrical box for the lubrication pumps – dynamometers.

The implemented electrical scheme allows both local control of starting/stopping the pumps and remote control via the digital outputs of a programmable logic controller.

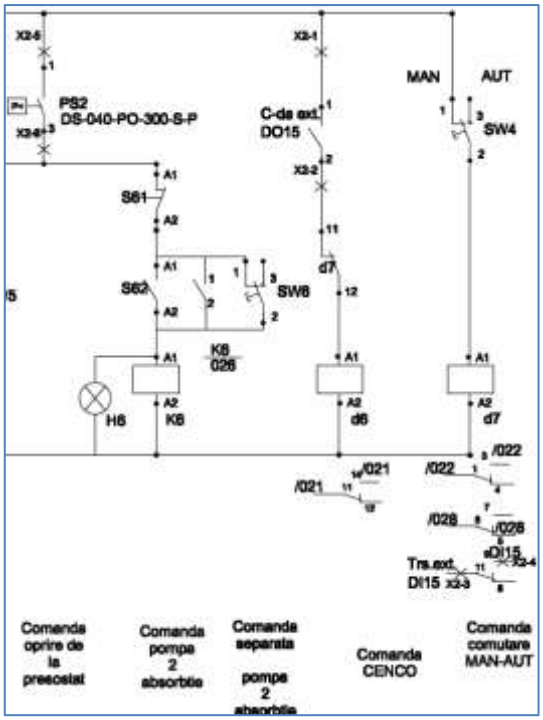


Fig. 2.3. Manual - Automatic brake lubrication pump control switching diagram.

2.3.2. Automation of the electrical installation of a water cooling pump for brakes

The brake water supply system has the role of supplying the water needed by the brakes to achieve the resistant torque of the gas turbine during the tests on the bench. The brakes have an inlet valve and an outlet valve through which the water passes and depending on their position, resistance is generated to the rotation of the brake shaft. After passing through the brakes, the water heats up proportionally to the energy taken from the gas turbine and must be cooled by gravity in a cooling tower.



Fig. 2.4. Brake water pump control cabinet

The cabinet allows the control of the pumps and fans of the water cooling tower from a Manual - Automatic switch, either from the buttons on the cabinet door, or automatically

through the application programmed in the PLC. The brake water pump control cabinet controls the 3 pumps that must supply water at a certain pressure at the entrance to the two dynamometers, the recirculation pumps and the brake oil cooling pump. The water flow rate varies with the power developed by the dynamometers, but the pressure must remain constant.

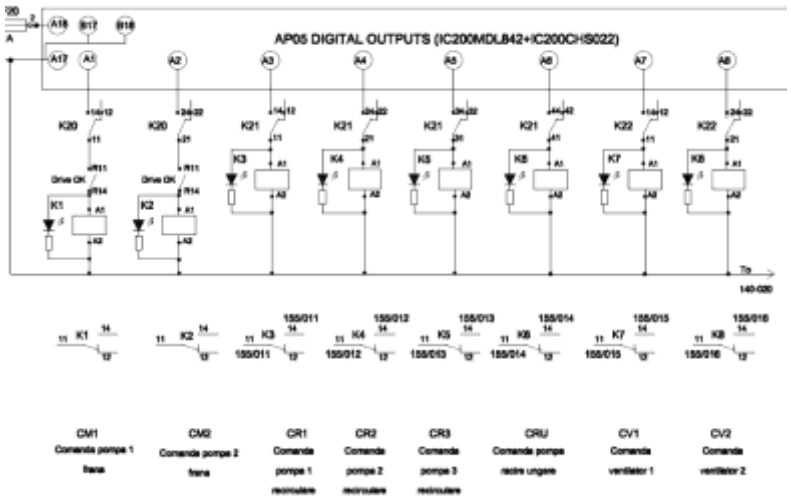


Fig. 2.5. Brake water pump digital controls.

2.4. Data acquisition equipment – gas turbine bench

The acquisition, data processing and control equipment available at the naval gas turbine test bench is represented by several systems, each with its well-established role. These are:

- Gas turbine command and control system;
- Auxiliary parameters acquisition console;
- Cenco acquisition system.

2.4.1. Gas turbine command and control system control

The block diagram of the turb command and control system is shown in the figure 2.6.

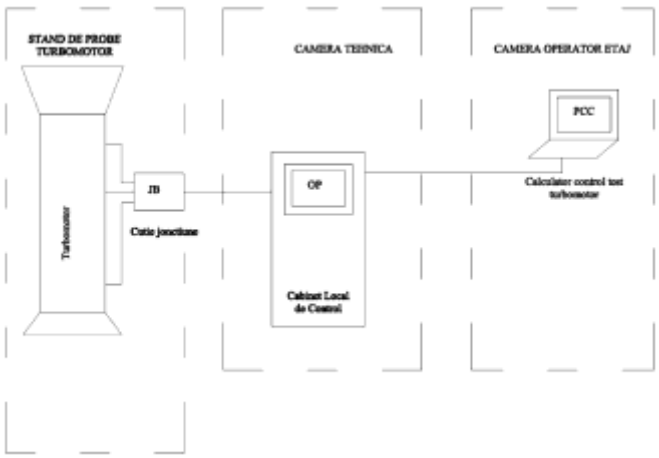


Fig. 2.6. ST40M gas turbine acquisition and control system on bench - block diagram.

2.4.2. Auxiliary parameters acquisition console

The auxiliary parameters acquisition console has the role of taking over, adapting, displaying and loading into the CENCO system of the bench parameters that refer to the rest of the bench installations, apart from the gas turbine and the two dynamometers.



Fig. 2.7. Auxiliary parameters acquisition console of the bench

The acquired parameters are temperatures and pressures of the exhaust gas pipe, temperatures and pressures of the air intake manifold, vibrations of the transmission shaft or reducers used by the tested naval propulsion.

2.4.3. Cenco acquisition system

The acquisition and control system provided by CENCO for the naval gas turbine bench is an integrated system for acquisition, processing and operation of the parameters of the bench installations, such as the fuel installation.

The system works with a proprietary Cyres programming environment. It allows the creation of multiuser applications using graphical objects to access the data and engine models in the database (fig.2.8).

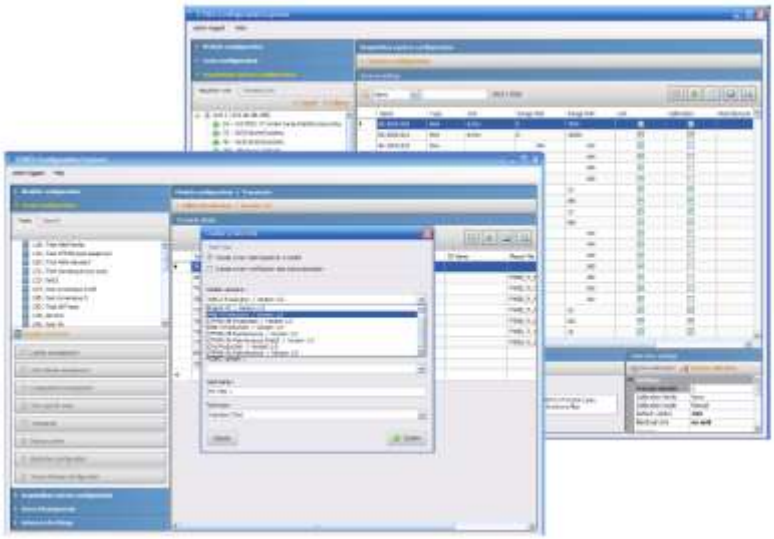


Fig. 2.8. CENCO application screens

The Cyres programming environment allows the creation of the following configurations saved in the server database:

- Models: creation/modification/saving of engine configurations;
- Tests: creation/modification/saving of test configurations;
- Acquisition: modification/saving of acquisition parameters;
- Users: creation/modification/saving of users with access to Cyres.

In the case of the test configuration, in the experimental cell for shaft-powered gas turbines, the GPN NPRM-ST40M propulsion group, in the Starboard Cruise technical configuration, will be connected to the 2 HS2600 dynamometers, mounted in tandem.

2.4.3.1.Instrumentation of the auxiliary installations

The instrumentation of the auxiliary installations is established based on the technical diagram of the installation. Depending on the electro-mechanical and hydro-mechanical equipment, such as pumps, stop valves in the installation and the aggregate (motor, reducer, multiplier, starter) that the installation serves, the types of parameters and commands that require instrumentation are established and an analysis of the technical solutions for the execution and installation of the measuring probes and sensors is developed.

2.4.3.2.Data acquisition logic for auxiliary installations

The acquisition of data for the command and control of auxiliary installations in order to ensure the operation of the GPN NPRM-ST40M Starboard Cruise propulsion group for its testing in the shaft power gas turbine cell involves the acquisition of data of the next type:

- Digital Output (DO);
- Digital Input (DI);
- Analog Output (AO);
- Analog Input (AI).

2.4.3.3.Program logic with command and control of auxiliary installations

The command and control program of the auxiliary installations is executed in the CYRES 8.2 program, which is the software component of the data acquisition, command and control system (DACS). As previously mentioned, for the command and control of the auxiliary installations the CYRES 8.2 program communicates with the mobile acquisition cabinet MAC and the fixed acquisition console PLC, for the acquisition of parameters and for sending the command signal to the electro-mechanical and hydro-mechanical equipment of the auxiliary installations.

The command and control program of the auxiliary installations in the CYRES 8.2 software involves:

- execution of a model in which the parameters and commands that are instrumented are entered, shown in Fig.2.9;
- execution of an interface with the operator for the operation of the commands either manually or automatically and for the display of the measured values of the parameters, shown in Fig.2.10;

- execution of a logic program through which various logical sequences of command, control, warnings and protections are executed.

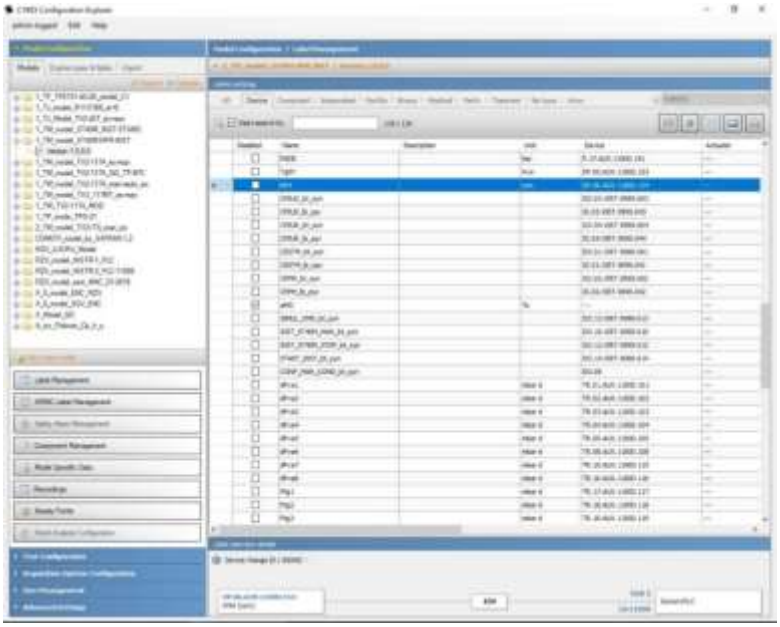


Fig. 2.9. The model in the Cyres software with parameters and commands



Fig. 2.10. Operator interface

2.5. Power and torque calculation – Gas turbine bench

The equations used in determining torque and power are those used in calculating the torque and power of a gas turbine, customized for the ST40M.

1. **Calculation of corrected speeds:**

$$NHC = \text{NH} \times \sqrt{\frac{288}{T_1+273}}[rpm]$$

(2.1)

$$NLC = \text{NL} \times \sqrt{\frac{288}{T_1+273}}[rpm]$$

(2.2)

2. **Calculation of the temperature between the turbines in Kelvin degrees and in Celsius degrees ITTk şi ITTc:**

$$ITT_k = RT_{ITT} \times (T_1 + 273)[°K]$$

(2.3)

$$ITT_c = ITT_k - 273\ [°C]$$

(2.4)

3. **Calculation of air flow Ga:**

- $G_a = \frac{P_0}{1032.5} \times \sqrt{\frac{288}{T_1+273}} \times G_{ac}[\text{kg/s}]$

  (2.7)

- $P_0 = P_1 + PDA/10[bar]$

  (2.8)

4. **Calculation of corrected fuel flow Gc :**

$$\boldsymbol{G_c = \frac{P_0}{1032.5} \times \sqrt{\frac{288}{T_1+273}} \times G_{cc}}[\text{kg/s}]$$

(2.12)

5. **Calculation of parameters Gaca and ALFA :**

$$G_{aca} = 0.9935 \times RG_g \times G_a[\text{kg/s}]$$

(2.15)

$$ALFA = \frac{G_{aca}}{14.5 \times G_c}$$

(2.16)

6. **Calculation of enthalpies H :**

$$HITT_g = 0.6889 + 0.2354\ \times\ ITT_k + 3.21 \times 10^{-5} \times {ITT_k}^2[\text{kcal/kg}]$$

(2.20)

$$HITT_a = 4.089 + 0.2181 \times ITT_k + 2.765 \times 10^{-5} \times {ITT_k}^2 [\text{kcal/kg}]$$
(2.21)

$$HITT_{am} = \frac{15.5 \times HITT_g + 14.5 \times (ALFA - 1) \times HITT_a}{1 + 14.5 \times ALFA} [\text{kcal/kg}]$$
(2.22)

$$HT6M_g = 0.6889 + 0.2354 \times (\text{T6M} + 273) + 3.21 \times 10^{-5} \times (T6M + 273)^2$$
[kcal/kg]
(2.23)

$$HT6M_a = 4.089 + 0.2181 \times (\text{T6M} + 273) + 2.765 \times 10^{-5} \times (\text{T6M} + 273)^2 [\text{kcal/kg}]$$
(2.24)

$$HT6M_{am} = \frac{15.5 \times HT6M_g + 14.5 \times (ALFA - 1) \times HT6M_a}{1 + 14.5 \times ALFA} [\text{kcal/kg}]$$
(2.25)

7. Calculation of power and torque :

$$G_g = G_{aca} + G_c [\text{kg/s}]$$
(2.26)

$$WTP_c = 4.185 \times 1.03 \times G_g \times (HITT_{am} - HT6M_{am}) [\text{kW}] [1]$$
(2.27)

$$MTP_c = 9549.6 \times WTP_c / NTP [\text{Nm}]$$
(2.28)

Implementing formulas in the monitoring and control program

The values obtained by calculation are displayed in the gas turbine hot start screen. I have modified this screen to simultaneously display the calculated torque MTPc and the calculated power WTPc in the lower left corner, simultaneously with the measured torque Cuplu and the measured power Pkw displayed at the top of the screen (figure 2.11).

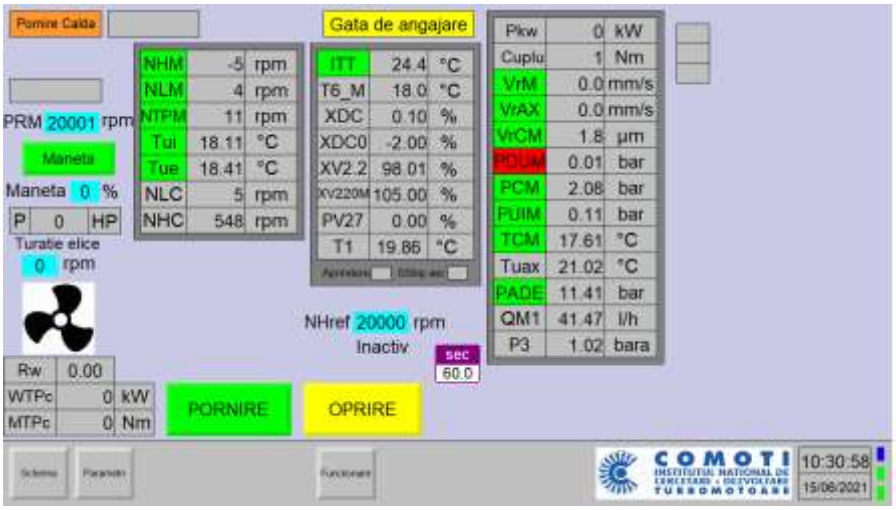


Fig. 2.11. The final „**Pornire caldă**" screen

Besides the two calculated parameters, the ratio between the calculated power and the measured power, Rw, is displayed. I recorded this data in the data file of each bench test.

$$Rw = \frac{WTP_c}{WTP} \tag{2.29}$$

The implementation of the equations in the software application of the command and control panel was done in Proficy Machine Edition in the form of a SXWM subroutine. An example of the implementation of the equations using the software components of the mentioned programming environment is shown in the figure 2.12.

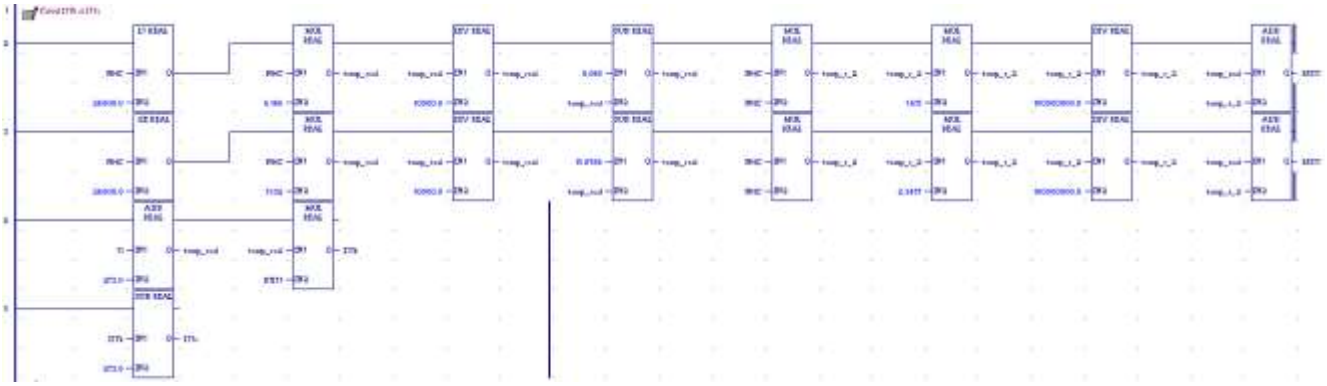


Fig. 2.12. Subroutine SXWM –ITTk and ITTc calculation

CHAPTER 3

CONTRIBUTIONS TO THE AUTOMATION OF ELECTRICAL INSTALLATIONS FOR BENCHES OF MECHANICAL ASSEMBLY FOR NAVAL PROPULSION

3.1. **Automation of the electrical installation for the AI inverter gearbox test bench**

The inverter gearbox test bench was created to test this equipment at speed and torque regimes defined by the manufacturer, before being installed on the ship (fig.3.1).

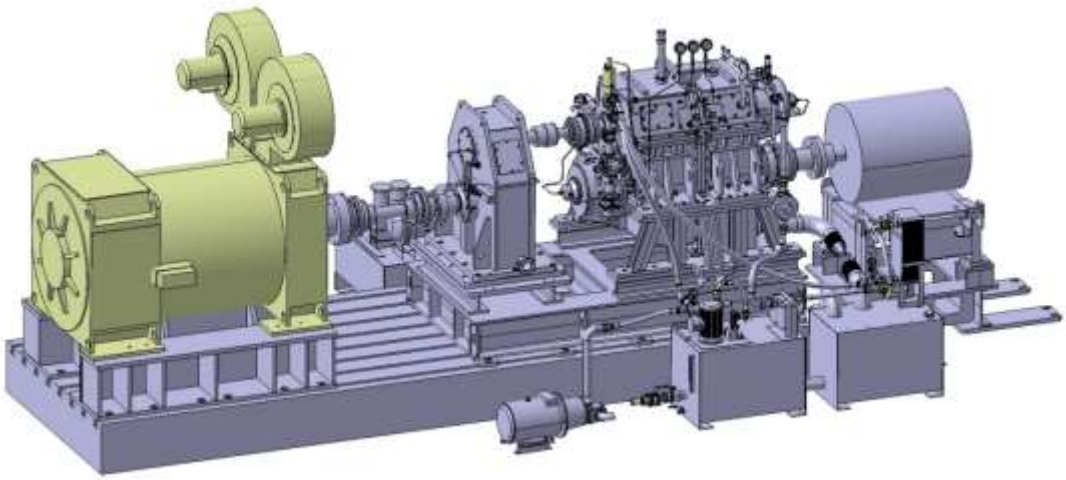


Fig. 3.1. Reductor-inverter gearbox test bench

The inverter bench is composed of a DC motor with a maximum speed of 1200 rpm, a power of 1.3MW, driven by a converter. The motor drives a multiplier with a ratio of 5.77, and the obtained speed is transmitted further to the tested reductor gearbox. The load acting on the gearbox is simulated by means of an asynchronous generator.

The block diagram of the testing process is presented in figure 3.2

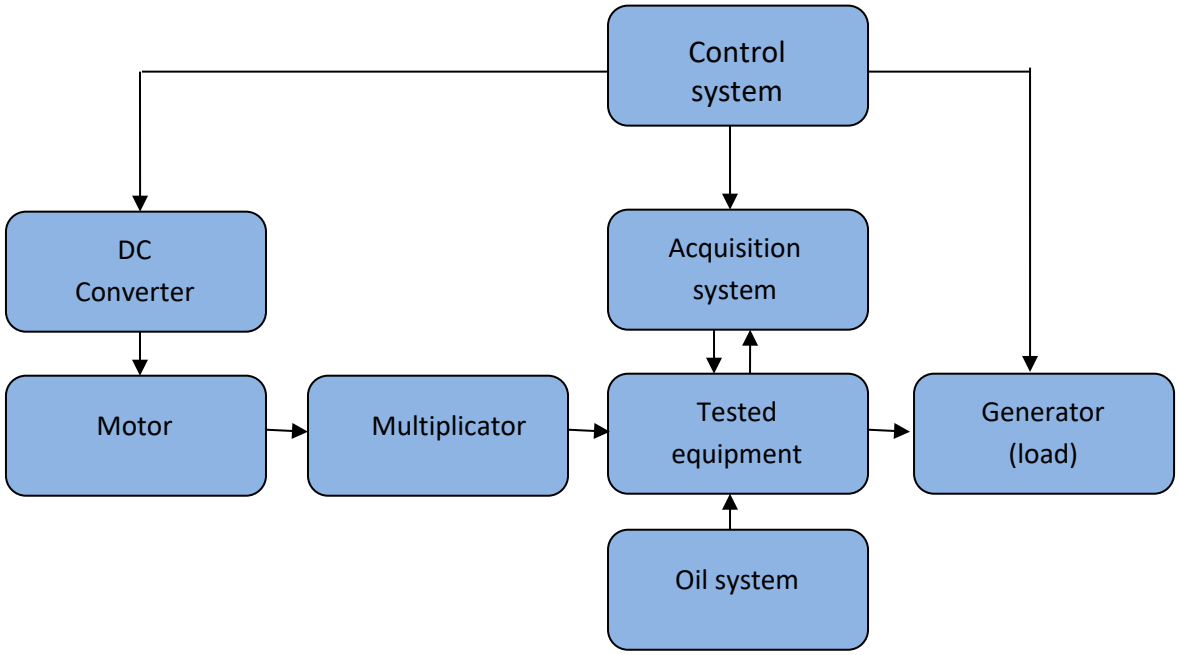


Fig. 3.2. Reductor-inverter gearbox test bench block diagram

3.1.1. Tested equipment

The tested equipment is the main objective for the realization of the bench. It is represented by a reversing reducer that must fulfil all the operating tests in various regimes and must be mechanically functional at the end of the tests (no various defects such as: cracks, shaft seizure, turbine blade breakage, etc.)

On this bench, mechanical gears can be tested in various combinations, in a speed range of up to 1200 rpm and at a load of up to 400kW. On the bench (fig.3.4), instead of the reversing reducer, a reducer used in aeronautical applications was tested. The rest of the bench composition remained the same.



Fig. 3.4. The bench ready for test.

The test data is recorded and processed continuously for instant information or for subsequent analysis of the behaviour of the tested gear. The tested equipment is intended in particular for testing the reducers that will be mounted on ships equipped with ST40M turbines.

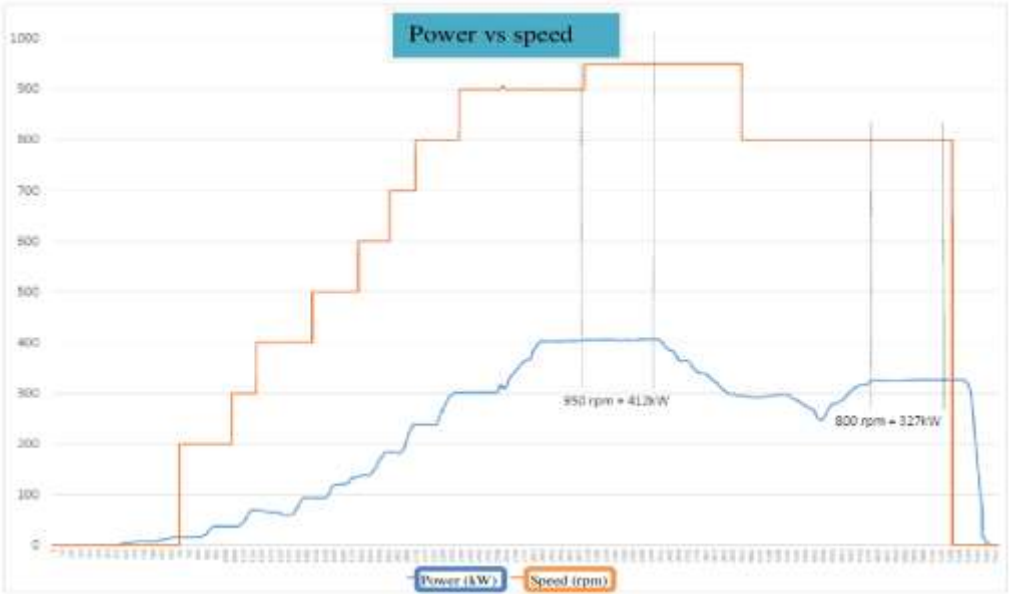


Fig. 3.5. Graph of speed and power developed during gearbox testing on the bench[4].

From the data analysis, the graph (fig.3.5), it can be concluded that the load of the reducer increases with the increase in the driving speed of the main engine. Also, a decrease in the generator power at a constant speed can be observed, which was determined by a decrease in the generator excitation current.

The graph in figure 3.5 and the conclusions resulting from testing the reducer on the bench were published in the paper "Test Bench for Naval Propulsion Gearbox", with M.L.Vasile, F.Niculescu, D. Lale as authors, presented at the Advanced Structures, Materials and Electrical Systems ASMES conference from 09-12 May 2024, held in Tulcea, Romania

3.1.2. Functional description of automation software

At the test bench for the AI reductor, we developed on the automation software for a PLC that controls the process and a software for a PC HMI that has the role of monitoring the process.

The PLC software contains 7 routines in which all the software sequences necessary for the proper functioning of the bench are programmed. The 7 routines are found in figure 3.6 and are the following:

- ✓ MAIN;
- ✓ SCALARE;
- ✓ INIT;
- ✓ FUNCTIONARE;
- ✓ OPRIRE;
- ✓ AVARII;
- ✓ TESTE.

In the main routine MAIN, of the PLC software, the other routines are executed.

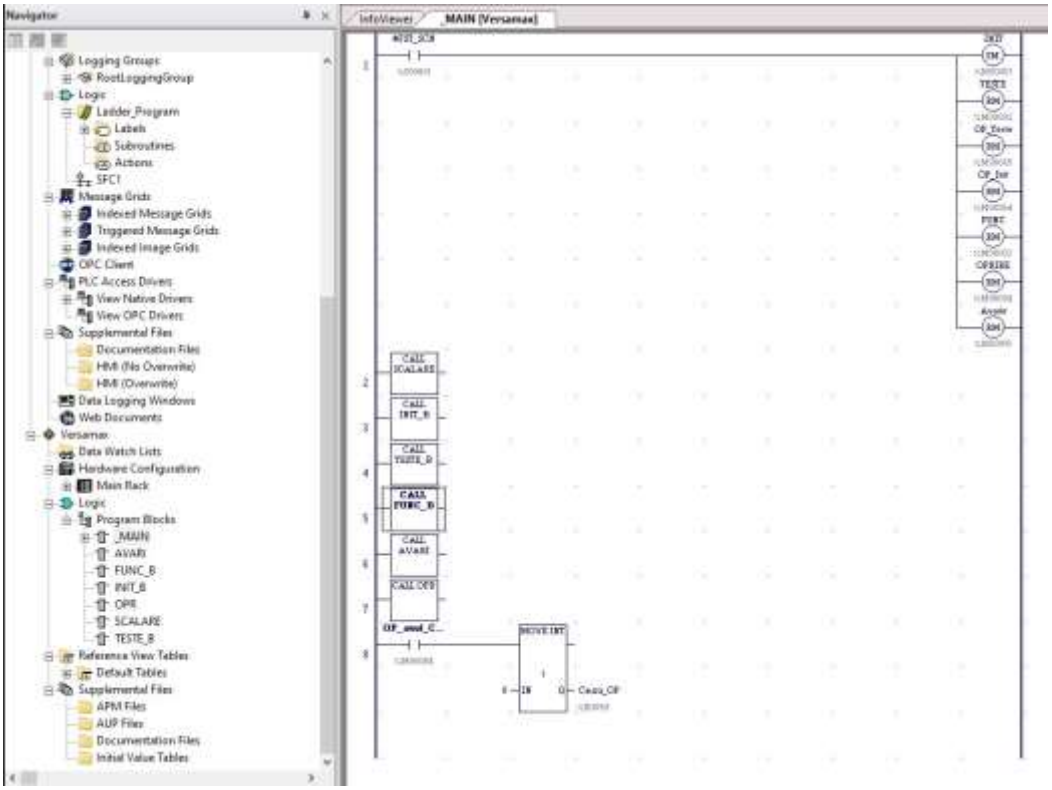


Fig. 3.6. The 7 routines

The sequence in which the bench is stationary is called INIT. In the INIT sequence, the return to 0 of all the execution elements of the bench is commanded, as well as of the prescribed main engine speed, main engine excitation current and generator excitation current.

he SCALARE sequence contains all the analogue input parameters of the bench having individual scaling formulas. At the end of applying these individual scaling formulas, an individual address is obtained for each bench parameter that expresses the real-time value of the respective parameter.

In fig.3.9, is shown the existing Schema screen within the tracking software installed on the HMI PC that I designed and realized is shown..

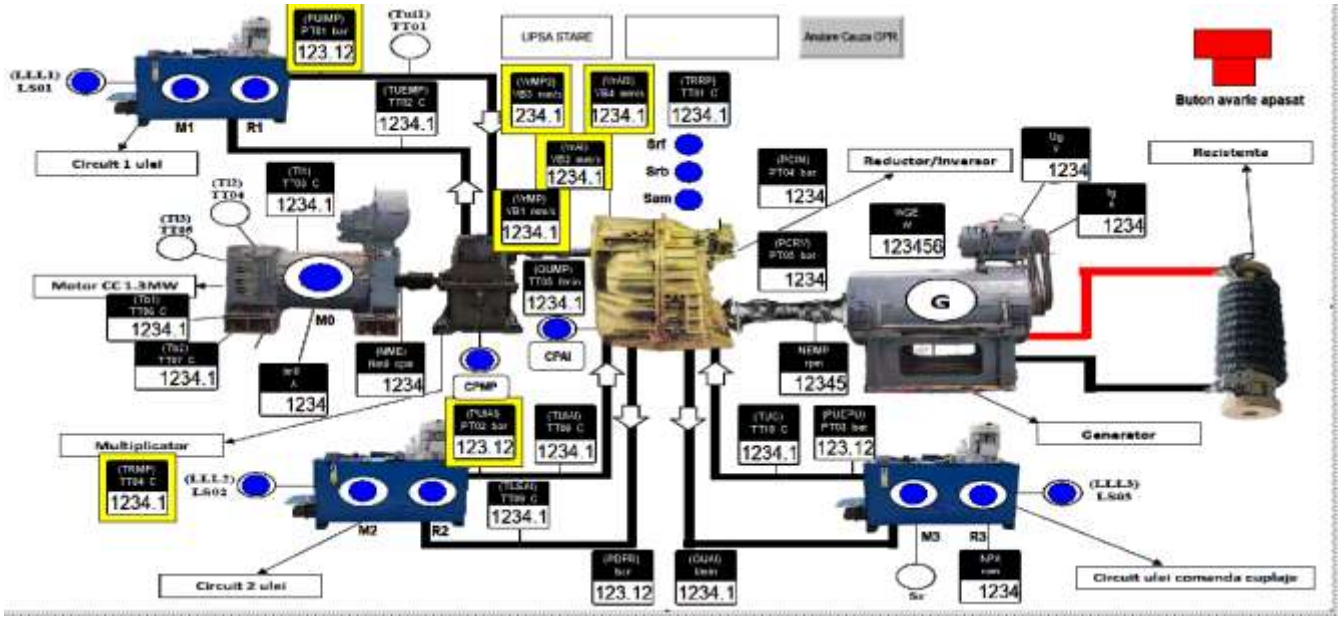


Fig. 3.9. – "Schema" bench screen

The bench can be stopped voluntarily by pressing the STOP button or the red physical button on the cabinet. Also, the bench can stop automatically by fulfilling a fault condition programmed in the AVARII sequence. In this situation, the bench goes from the FUNC operating sequence to the OPR stop sequence.

3.2. Design and automation of the electrical installation for the test bench inverter gearbox

The work aims to research and design the command and control system of the technological demonstrator with a reverse gear on the bench. This research is based on establishing the command and control scheme for performing the coupling conditions: normal left direction - forward machine, normal right direction - reverse machine and uncoupled machine stop on the test samples on the test bench. The transmission ratio of the reverse gear will ensure a speed of the axial line as close as possible to the current speed of the axial line (294 rpm) on the ship.

3.2.1 Design of the automation cabinet

I have designed an automation cabinet for the inverter reducer that helps the operator interact with the machine. It is integrated into the general electrical installation and will provide power to the electrical components at different voltages inside it and automate the bench for testing the inverter reducer. Figure 3.10 shows the electrical diagram for the force in the automation cabinet.

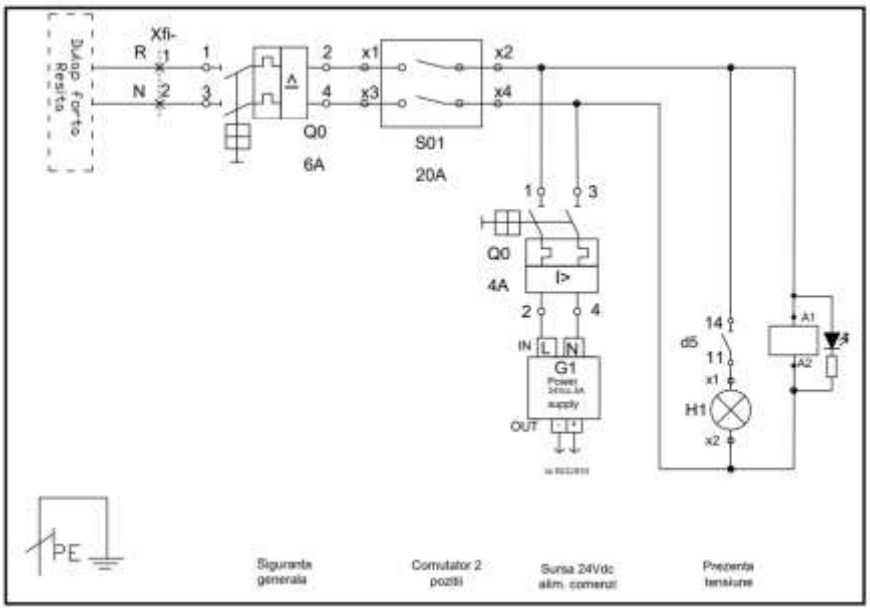


Fig. 3.10. Electrical power diagram

3.2.2 Automation cabinet components

The automation cabinet shown in Figure 3.12 is based on a programmable logic controller type Easy-E4-UC-12RC1 [5], a product of Eaton, which runs an application program of its own design, created to perform the required functions.

The display of parameters and operation is carried out through the operator panel.

The programmable logic controller - process interface is realized by the electrical equipment installed on the test bench of the reducer-inverter.

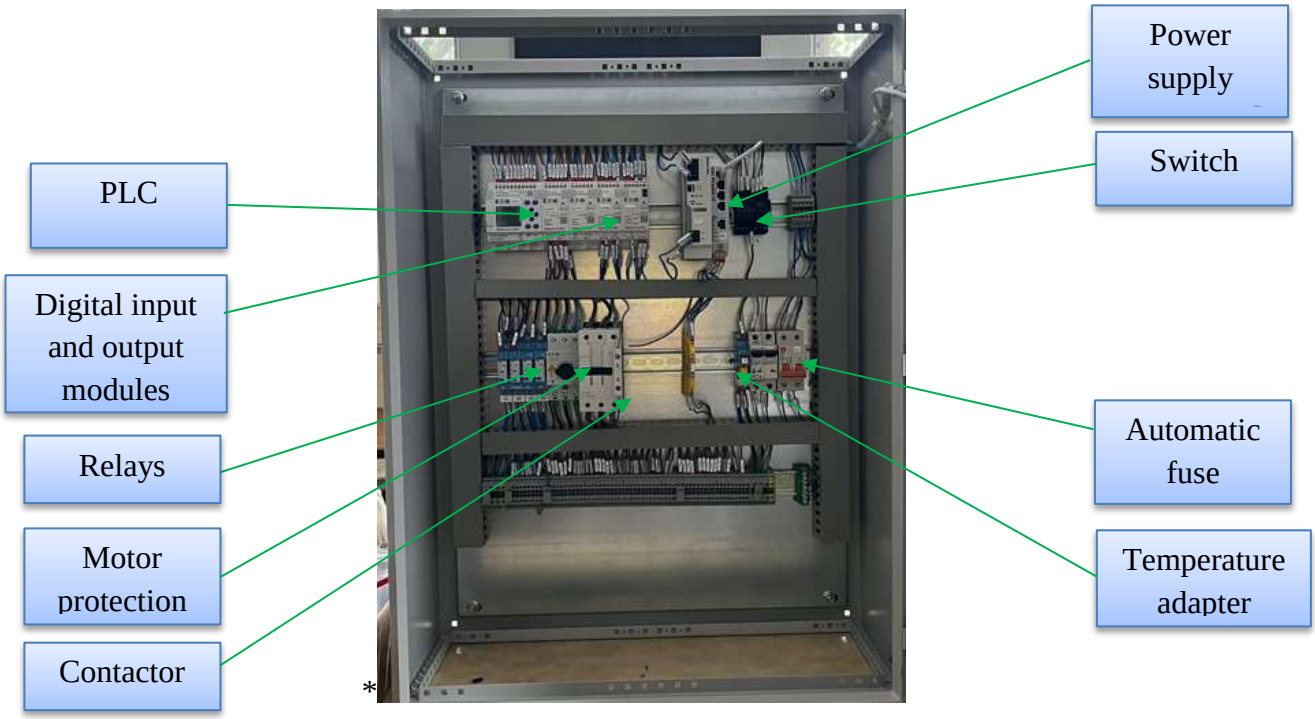


Fig. 3.12. Reducer-inverter gearbox automation cabinet

The elements on the automation cabinet are shown in the figure 3.13.

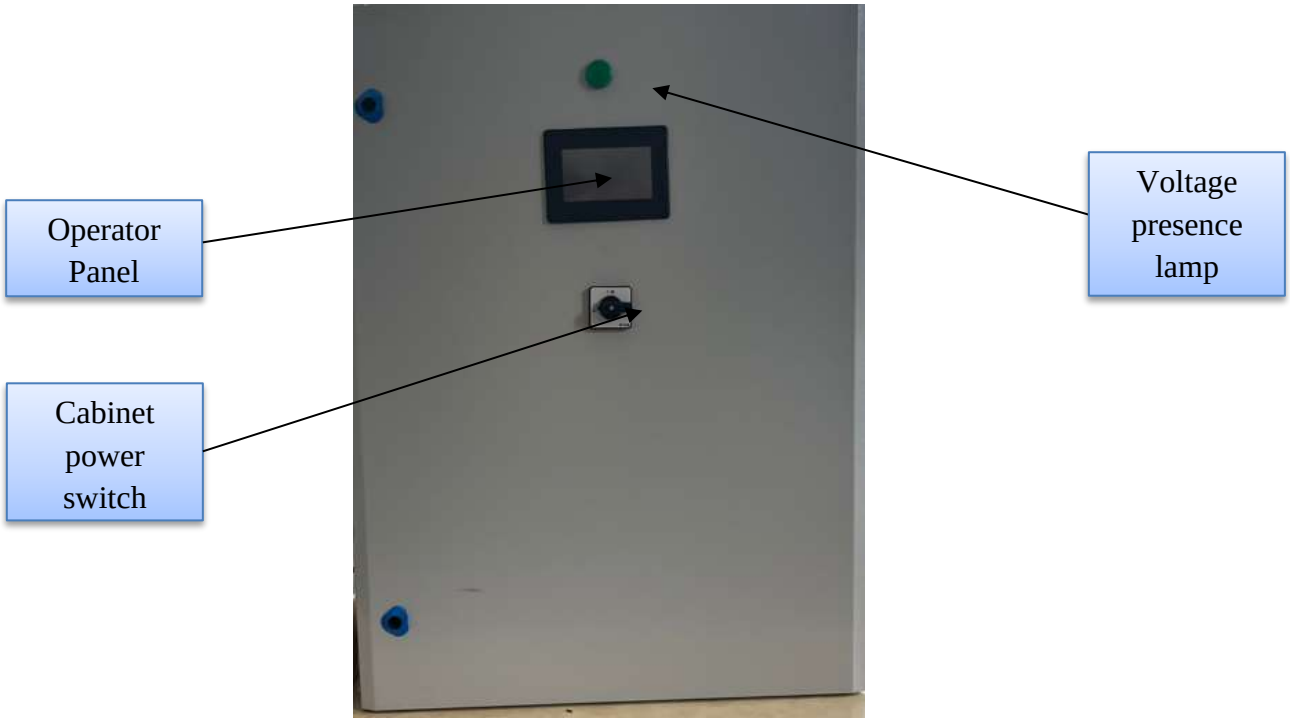


Fig. 3.13. The elements on front door of the automation cabinet

3.2.3 Design of the software application for control and monitoring of the inverter gearbox

The control and monitoring software application was created based on the parameter list and taking into account the starting and operating conditions of the inverter reducer.

3.2.4 Graphical interface. Presentation

When the operator panel is powered on and the software is running normally, several screens are displayed that can be selected using the buttons at the bottom of the screen.

3.2.4.1. Main screen with parameters

Figures 3.14 and 3.15 show the main screen with the parameters and execution elements of the installation, in which the coupling operation mode appears, whether it is engaged or not.

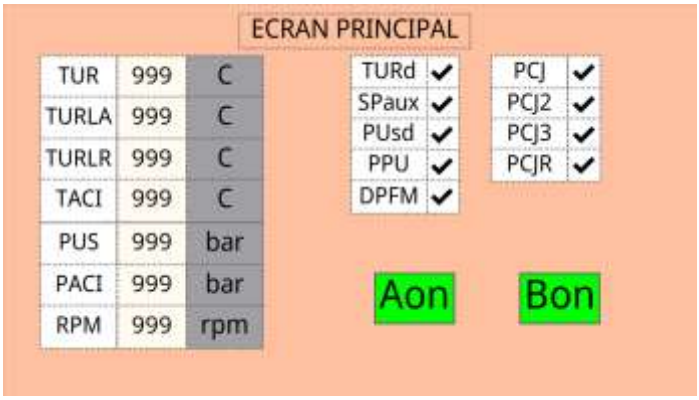


Fig. 3.14. "Principal" screen with coupling "ON".

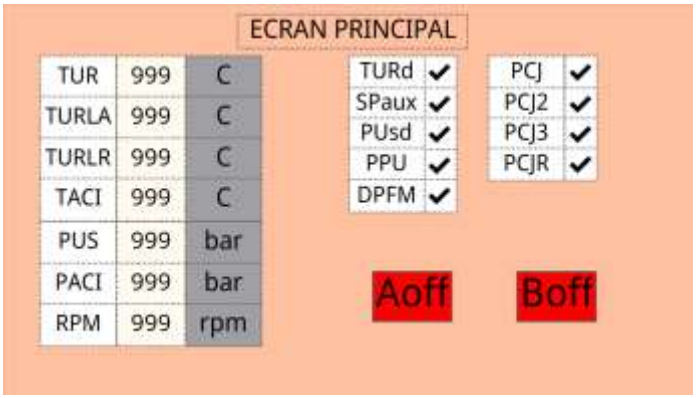


Fig. 3.15. "Principal" screen with coupling "OFF

3.2.4.2. " Legend and warnings" screen:

Fig. 3.16 shows the "Legend and warnings" screen, which presents the parameters, their units of measurement, and the warning conditions in a table format.


ECRAN LEGENDA SI AVERTIZARI

crt.	Simbol	Denumire parametru	U.M.	Avertizare
1.	TUR	Temperatură ulei ungere ridicată	°C	>65
2.	TURLA	Temperatură ridicată lagar radial-axial	°C	>75
3.	TURLR	Temperatură ridicată lagar radial	°C	>65
4.	TACI	Temperatură apă circuit închis	°C	
5.	PUS	Presiune de ungere scăzută	bar	
6.	PACI	Presiune apa circuit închis	bar	
7.	RPM	Turaţie ieşire reductor	rpm	
8.	TURd	Temperatura ulei ungere ridicata	°C	
9.	SPaux	Presiune de ungere scazută	bar	
10.	PUSd	Presiune de ungere scazută	bar	
11.	PPU	Presiune de ungere minimă	bar	
12.	DPFM	Diferenţă de pres. mare pe filtru de ulei	bar	
13.	PCJ	Presiune cuplare joasă	bar	
14.	PCJ2	Presiune cuplare joasă	bar	
15.	PCJ3	Presiune cuplare joasă	bar	
16.	PCJR	Presiune cuplare ridicată	bar	
17.	Aon	Cuplat cuplaj A	19.	Bon	Cuplat cuplaj B
18.	Aoff	Decuplat cuplaj A	20.	Boff	Decuplat cuplaj B

Fig. 3.16." Legendă şi avertizări" screen

3.2.4.3. Teste screen:

The "Tests" screen (Fig. 3.17) displays, in table form, the execution elements of the installation with the possibility of testing their operation. This is useful for commissioning or during maintenance work. In this screen, the operation of the auxiliary pump and the ON/OFF coupling is checked.

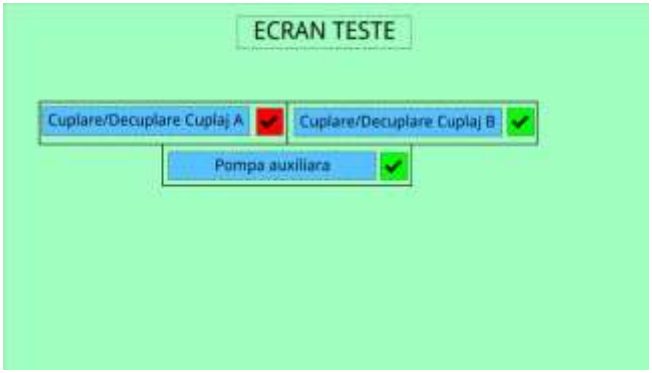


Fig. 3.17. "Teste" screen.

3.2.5. Main program

The main program has the role of controlling the reversing gearbox, ensuring the protection of the equipment by monitoring parameters (speed, temperatures and pressures), controlling the auxiliary pump, automatically controlling the coupling and decoupling and triggering visual alarms in case of faults or parameters outside the allowed limits.

3.2.5.1. Definition of the analogue variables and scaling (4000-20000)

a) Temperatures:

1. *High lubrication oil temperature -**F15** (MBT9110) = **MD1-TUR(IA05)**;*
2. *High radial axial bearing temperature -**F9** (MBT9110) = **MD2-TURLA(IA06)**;*
3. *High radial bearing temperature-**F10**(MBT9110) = **MD3-TURLR(IA07)**;*
4. *Closed circuit water temperature= **MD4-TACI(IA09)**.*

b) Pressures:

1. *Low lubrication pressure -**F16** (Danfoss MBS3100-1811 6AB04 4-20 mA) = **MD5-PUS(IA08)**;*
2. *Pressure = **MD6-PACI(IA10)**.*

c) Speed:

1. *Speed = **MD7-RPM(IA11)**.*

3.2.5.2. Definition of the digital variables

Inputs

a) Temperature:

1. *High lubrication oil temperature -F1(Danfoss MBC 8100) =* ***I01(TURd)****.*

b) Pressures:

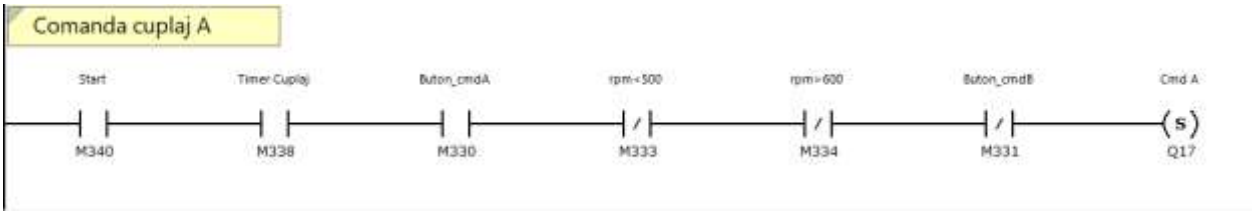
1. *Low lubrication pressure -**F3**(Danfoss MBC 5100) =* ***I02(SPaux)****;*
2. *Low lubrication pressure -**F4** (Danfoss MBC 5100) =* ***I03(PUSd)****;*
3. *Minimum lubrication pressure -**F14**(Danfoss MBC 5100) =* ***I04(PPU)****;*
4. *High differential pressure on oil filter -**F17**(Internormen OE1.2,0.G.1) =* ***I05(DPFM)****;*
5. *Clutch A engaged -**F5** (Danfoss MBC 5100) =* ***I06(Aon)****;*
6. *Clutch A disengaged -**F13** (Danfoss MBC 5100) =* ***I07(Aoff)****;*
7. *Clutch B engaged -**F22** (Danfoss MBC 5100) =* ***I08(Bon)****;*
8. *Clutch B disengaged -**F21** (Danfoss MBC 5100) =* ***I17(Boff)****;*
9. *Low coupling pressure-**F8**(Danfoss MBC 5100) =* ***I18(PCJ)****;*
10. *Low coupling pressure -**F7** (Danfoss MBC 5100) =* ***I19(PCJ2)****;*
11. *Low coupling pressure -**F11** (Danfoss MBC 5100) =* ***I20(PCJ3)****;*
12. *High coupling pressure -**F12** (Danfoss MBC 5100) =* ***I21(PCJR)****.*

Output

1. *Coupling A (Y1) =* ***Q01****;*
2. *Coupling B (Y1) =* ***Q02****.*

3.2.5.3 Development of the software application

The PLC running the application is of the Easy-E4-UC-12RC1 type and has specialized input/output modules. The software application development of the PLC and the command and control panel was done in Easy.Soft.V8.31 in the form of a subroutine (fig.3.18).



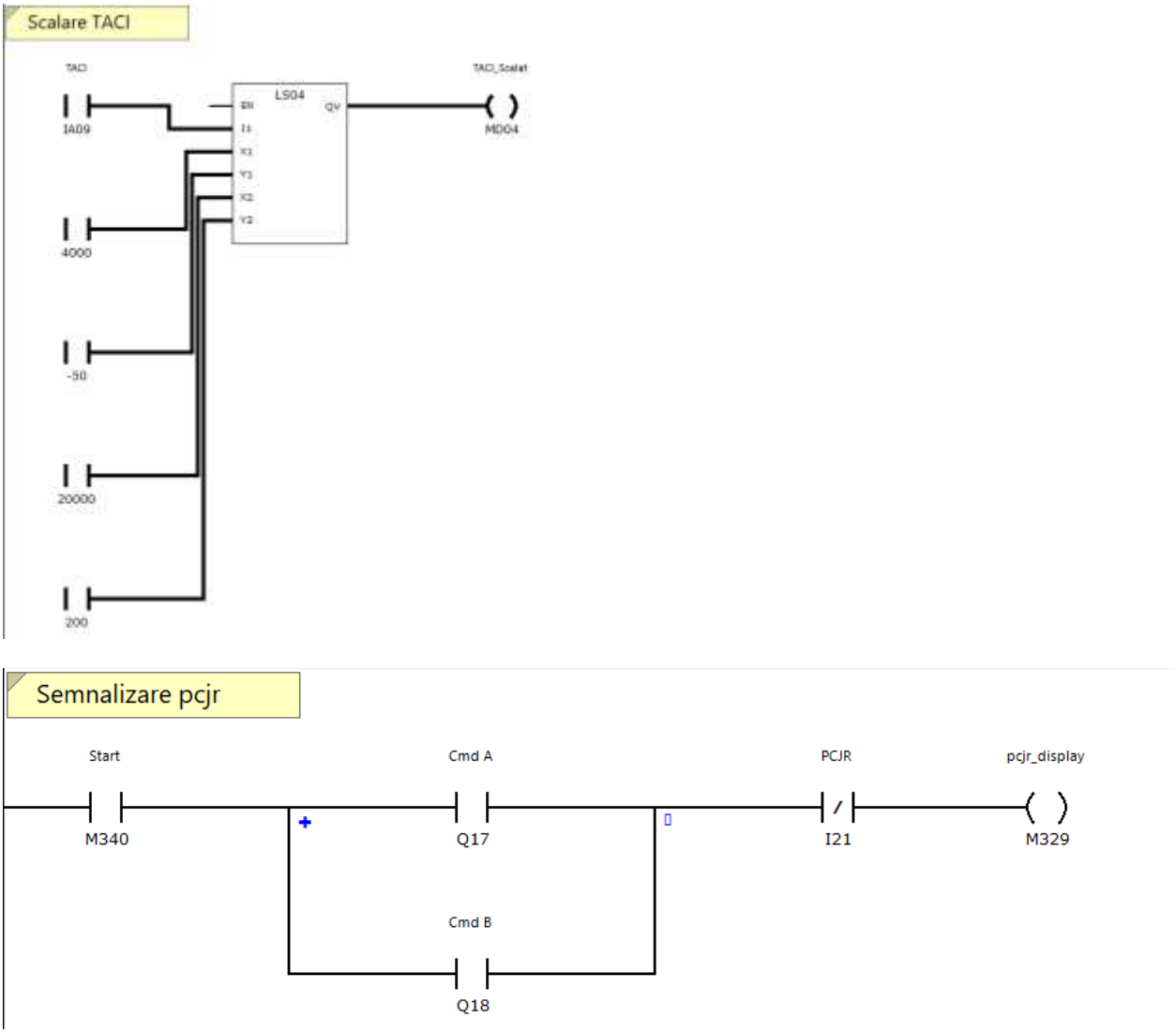


Fig. 3.18. Part of the software program

CONCLUSIONS

1. GENERAL CONCLUSIONS

The field studied by the author of the thesis is of particular importance for the development of modern naval propulsion systems perfectly adapted to the characteristics of the marine vessels on which they will be integrated. Everything starts from the requirements regarding the necessary mechanical power, the most efficient and easy-to-maintain technical solutions are chosen, the control systems are designed and the equipment is tested in conditions as close as possible to reality. In this process, the automation of electrical installations of test stands for naval propulsion plays a very important role.

The author of the doctoral thesis has important contributions in the automation of gas turbine test benches, reducers-inverter gearboxes, reducers or multipliers, that is, all the components that naval propulsions are generally made of.

These contributions refer both to the development of automation equipment and to the development of software applications, essential in the control and monitoring of test benches.

2. ORIGINAL CONTRIBUTIONS

The doctoral thesis aimed to make contributions regarding the automation of electrical installations of test stands for naval propulsion.

The following are briefly presented the original contributions that the thesis makes in the studied field:

a) Study on the current status and trends in the construction and automation of benches intended for testing naval propulsions depending on the type of engine on which they are based. The analysis outlined the research direction in which the investments of time and resources were made (see Chap. Introduction paragraphs 2 and 3);
b) Contributions to improving the operator interface for the naval diesel engine bench. Improving this interface by grouping some parameters and displaying some significant values led to a reduction in testing time and an intuitive interaction with the bench operator panel (see Chap.1 paragraph 1.6.2);
c) Contributions to automating the start-up of the LMDN bench. The automation of the start relieves the operator of the tasks related to following the process and determining the interaction time with the propulsion handled on the bench. The accuracy increases and the probability of missing the start decreases considerably so that the operator can focus on explaining the operation of the propulsion (see Chap.1 paragraph 1.6.1);
d) Contributions to the engine communication with the PLC in the LMDN bench. We have achieved this communication that helps the proper operation of the engine and the entire propulsion assembly. The communication led to the learning of new programs which improved knowledge and helped to integrate them into the operation of this propulsion system (see Chap.1 paragraph 1.6.3);
e) Contributions to the testing of the power indication calculated on the gas turbine bench. The application of the thermodynamic calculations specific to the gas turbine led, for the mechanical power developed by the gas turbine, to a result very close to the power measured by means of dynamometers. We tested these formulas during the turbojet tests at different load regimes, the values for the calculated and measured

power being displayed on the computer screen and recorded in the test files (see Chap.2 paragraph 2.5);

f) Contributions to the testing of the AI reverse gear test bench and the analysis of the recorded data. The reverse gear test bench was created to test this equipment at speed and torque regimes defined by the manufacturer, before being installed on the ship. From the analysis of the recorded data, it was noted that the load on the reducer increases with the increase in the main engine drive speed (see Chap.3 paragraph 3.1);

g) Contributions to the design and implementation of the data acquisition cabinet of the AI reverse gear test bench. The data acquisition cabinet helps to achieve the automation of the reverse gear test bench, testing and automatic acquisition of parameters (see Chap.3 paragraph 3.1.7);

h) Contributions to the design and execution of the automation cabinet. I designed and executed the automation cabinet for the inverter reducer that helps the operator interact with the machine. It is integrated into the general electrical installation, ensures the power supply of electrical equipment at different voltages and the automation of the bench for testing the inverter reducer (see Chapter 3 paragraphs 3.2.1 and 3.2.2);

i) Contributions to the design of the software application for controlling and monitoring the inverter reducer. On the automation side, I created software for the operator panel and software for the PLC that have the role of controlling and controlling the technological demonstrator with the inverter reducer in the bench, visualizing the parameters on the operator panel and the fault and protection signals of the operator panel (see Chapter 3 paragraphs 3.2.4 and 3.2.5).

3. PERSPECTIVES FOR FURTHER DEVELOPMENT

The experience gained in automating the electrical installations of test benches for various types of naval propulsion or their components will be used in future projects. During the development of the doctoral thesis, I studied, designed and built automation equipment necessary for the benches, and the methods used in this work will be replicated for new naval propulsion configurations that will use piston engines or gas turbines.

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ANEXXES

1. PUBLICATION OF THE RESEARCH RESULTS

Contributions regarding the automation of electrical installations of naval propulsion test stands have been disseminated through their presentation at conferences and through their publication in well-known national and international journals.

1.1 Representative works of the doctoral thesis:

1. *F.Niculescu , A.Săvescu,* ***M.L.Vasile*** *- „Adaptive Control for Marine Gas Turbine”* 2020 International Conference on Development and Application Systems (DAS) 21-23 May 2020
2. *F.Niculescu, C.Savescu, A.Săvescu, A.Mitru,* ***M.L.Vasile*** *- „ Automation and Electronic Control of Marine Gas Turbine Engine for Ship Revamp”* Technium: Romanian Journal of Applied Sciences and Technology
3. *F.Niculescu , C.Borzea,* ***M.L.Vasile*** *- „Marine gas turbine for efficient ship propulsion”* EMERG, Volume VI, Issue 3/october ,2020, Romania
4. *F. Niculescu, A.Săvescu,* ***M.L.Vasile*** *–* „*Redundancy in the control of a gas turbine for naval applications*” în Proceedings of the 9th International conference on advanced concepts in mechanical engineering (ACME 2020), Iunie 04 - 05, 2020, IASI, Romania
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9. *D. Lale, C. Săvescu, S. Gogoneaţă, C.Nechifor ,* ***M.L.Vasile,*** *F. Niculescu –* "*Passengers Monitoring System with Infrared Sensors and Microcontroller*" publicat in COMOTI Scientific Journal TURBO, Volume VIII (2021), no. 2
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11. ***M.L.Vasile,*** *G.Dediu, F.Niculescu, C. Săvescu, G.I.Balan –* "Propeller load simulation on gas turbine test stand", International Conference on Electrical, Computer and Energy Technologies (ICECET) 2022
12. ***M.L.Vasile,*** *F.Niculescu, D. Lale–* " Test Bench for Naval Propulsion Gearbox", ASMES 2024 - May 09-12,Tulcea, Romania
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14. ***M.L.Vasile,*** *F.Niculescu, D. Lale, R. Stoica*“ The Replacement of the Gas Turbine in Case of a Marine Vessel”, WSEAS Transactions on Systems Journal, Print ISSN: 1109-2777, E-ISSN: 2224-2678 , Vol.24, 2025

1.2 Other published works

15. *C.Nechifor, M. Roman, D. Lale, R. Stoica,* ***M.L.Vasile*** – “Control system for suction valves within gas compressors skids located in potentially explosive zones”, 11th International Symposium on Occupational Health and Safety (SESAM 2023).
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20. *C.Săvescu,* ***M.L.Vasile****, C. Nechifor*, V. Năvrăpescu, D. Lale, R. Conţiu, F.Niculescu, - „ Automation System of an Educational Test Bench for Naval Piston Diesel Engines”* Revue Roumaine des Sciences Techniques, 2025

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1. Patent application no. A 2025 00051 - Sistem de producere şi stocare energie prin tehnologie CAES folosind carierele de lignit închise, Iulian Vlăducă, Răzvan Edmond Nicoară, **Mirela Letiţia Vasile**, Bogdan Năvligu, Cosmin Petru Suciu, Alexandru Hank, Ramona Manuela Stanciuc, Ştefan Alexandru Şerban, Theodor Mihnea Sîrbu , Mihai Joavină, Adrian Săvescu, Claudia Irina Săvescu, Cristian Valentin Nechifor, Emilia Georgiana Prisăcariu, Sorinel Popescu, Stela Dinescu, Sorin Mihai Radu, Marius-Valentin Drăgoi, februarie 2025.

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