POLITEHNICA University of Bucharest

DOCTORAL SCHOOL OF ELECTRICAL ENGINEERING

CONTRIBUTIONS TO THE COMMAND AND CONTROL OF A GAS TURBINE FOR NAVAL APPLICATIONS

PHD THESIS SUMMARY

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Keywords: gas turbine, efficient propulsion, automat control system, turboprop engine, diesel fuel, marine equipment, control, marine technology, optimization, command and control systems

Acronyms and symbols

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
FMU	**F**uel **M**etering **U**nit
JB	**J**unction **B**ox
FADEC	**F**ull **A**uthority **D**igital **E**ngine **C**ontrol
LVDT	**L**inear **V**ariable **D**ifferential **T**ransformer
TPC	**T**ouch **P**anel **C**omputer
OP	**O**perator **P**anel
OPC UA	**O**pen **P**latform **C**ommunication **U**nified **A**rchitecture
XDC	Fuel metering valve position, in percent
PQC	Metering valve dual torque motor command
NH	Speed of engine high pressure compressor
NL	Speed of engine low pressure compressor
NTP	Speed of power turbine
XV2.2	Bleed valve position P2.2

INTRODUCTION

The doctoral thesis aims to research, design and implement a command and control system for a gas turbine for naval applications. The author of the doctoral thesis aims to make an important contribution in this process of achieving a modern propulsion that would replace an old and obsolete propulsion on board some ships. This research will help modernize propulsion control, reduce fuel consumption and reduce ship travel costs.

In this paper, the author analyzes the state of use of gas turbines for naval applications worldwide, as well as the particularities of their command and control systems. The analysis of the equations of turbo engine operation will determine the control relations and the execution of the prototype. The control system is customized for the ST40M gas turbine. Carrying out tests on the bench test will require the validation of the operation of the gas turbine in optimal parameters.

When obtaining good results on the bench test, the command and control system will be transferred together with the gas turbine on the ship. At the end of the work of adapting the command and control system to the ship's automatic control configuration, a number of real tests with the ship will be performed in different modes of operation. The results of these tests will validate the safe and effective operation of the command and control system in the ship's propulsion configuration.

CHAPTER 1

RESEARCH AND DEVELOPMENT OF A CONTROL SYSTEM SOLUTION

The ST40M is a free turbine gas turbine derived from the PW150A engine. The power developed by burning liquid fuel in the combustion chamber is supplied to a power turbine, which can be coupled by a gearbox to the ship's propeller.

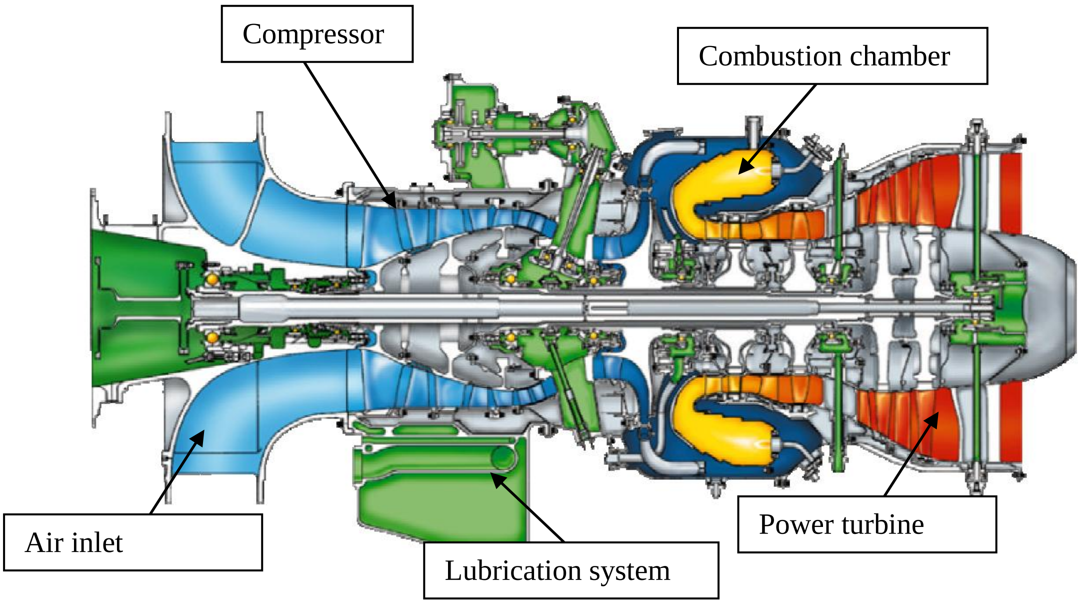

Fig.1.1 Section through the model of ST40M gas turbine [1]

The gas turbine (Fig.1.1) consists of a three-stage axial and one-stage centrifugal compressor, combustion chamber, two-stage power turbine, fuel system, ignition system, lubrication system, accessory box, wiring and transducers.

1.1. Gas turbines equations and their control formulas

In the two-rotor engines the regulated parameter is the high pressure compressor group **NH** speed, the regulating factor being the fuel flow **Mc** in the combustion chamber. As a starting point for the elaboration of the principle scheme of the regulators and the elements of the fuel system are the characteristics that give the variation of the different parameters depending on the regulated parameter.

In the case of control laws, a particular interest is represented by the type functions produced by the parameters at real powers, an example being the one below [2]:

$$M_{c0} = K \times n_0 \times p_{20} \tag{1.1}$$

1.2. Contributions regarding the control of the fuel metering valve of the ST40M gas turbine

The gas turbine ST40M to be controlled does not have the controller included in this application. The control signals for the engine are generated by the control cabinet according to an algorithm that takes into account the characteristics of the turbo engine.

The start-up and control algorithm I have developed taking into account the particularities of the gas turbine. The action of the execution elements is realized in a certain order determined by the time required for the intake and ignition of the air-fuel mixture, as well as its dosing to ensure the desired operating regimes.

Figure 1.2 shows a section through the FMU on the engine that controls fuel flow to the combustion chamber.

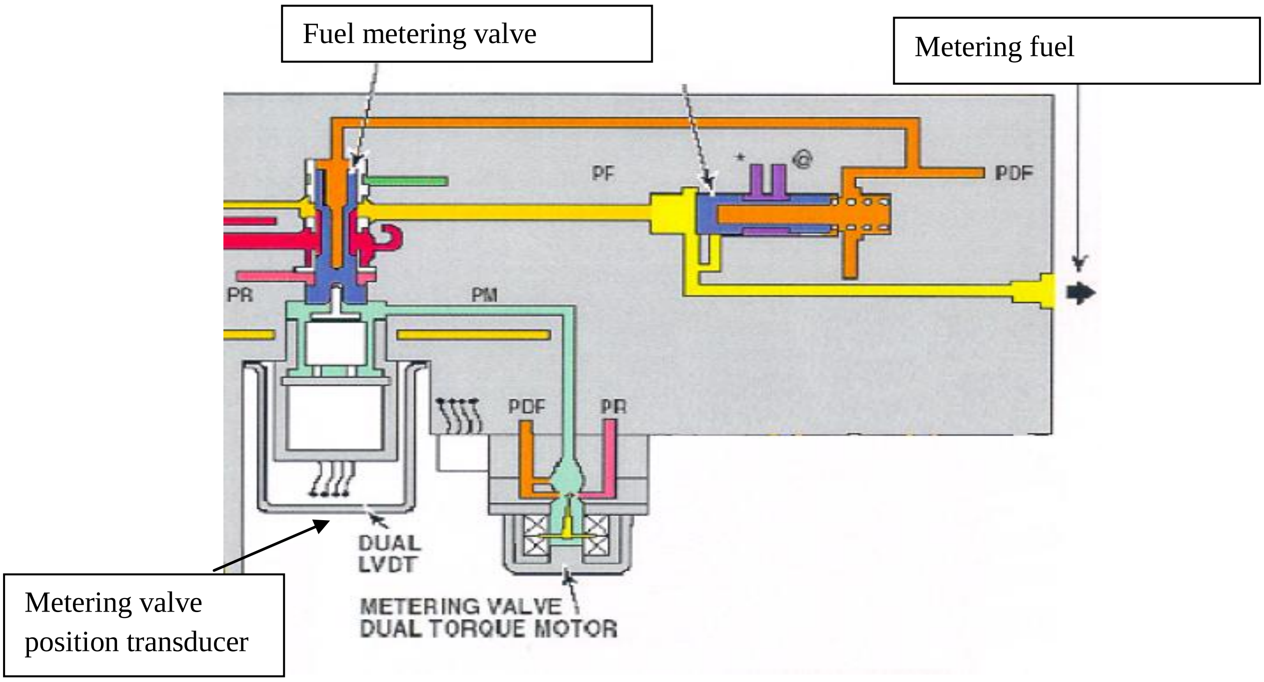

Fig. 1.2 Section through Fuel Metering Unit – FMU (ST40M)

Adjusting the fuel flow is realized by actuating the metering valve dual torque motor PQC. The position of the fuel metering valve, XDC, is read by an LVDT transducer and is expressed as a percentage. There is only one connection between the metering valve dual torque motor and the fuel metering valve through the fuel pressure.

The relationship between the position of the fuel metering valve XDC and the position of the metering valve dual torque motor PQC, I have established to :

$$\Delta XDC = XDC0 - XDCN\ [\%] \quad (1.2)$$

$$\Delta PQC = 0.08 \times \Delta XDC\ [\%] \quad (1.3)$$

$$PQC_n = 5.6 + \Delta PQC\ [\%] \quad (1.4)$$

The graph in this case is shown in the following figure :

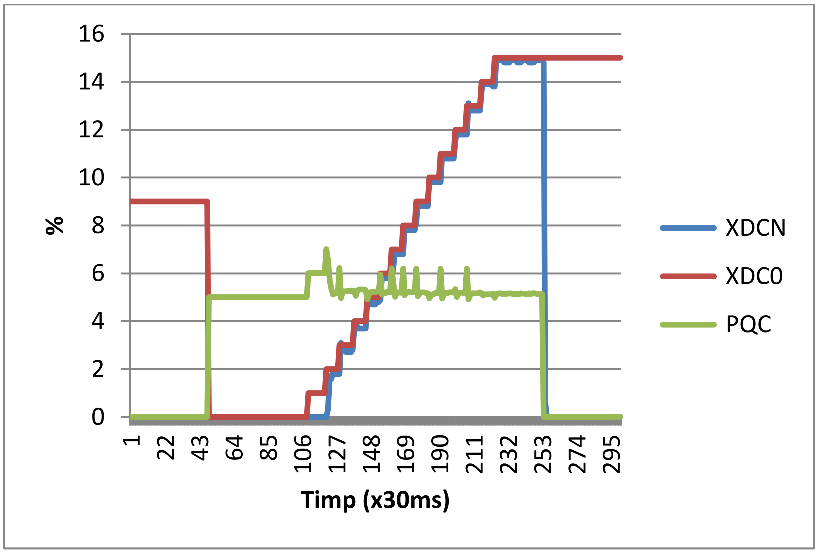

Fig.1.3 The evolution of XDC- position of fuel metering valve and PQC- position of the metering valve dual torque motor

By adding the constant term +5.6 from equation 1.4, we obtain a remarkable improvement of the fuel metering valve setting, namely:

• There is no longer a dead zone between the position requirement, XDC0, and the result obtained XDCN, the latter increasing with the XDC0 signal;

• There is no gap between the two signals;

• The position adjustment is very precise; an imposed position is accurate reproduced by the current position of the fuel metering valve.

In conclusion, we obtained a very important result. Adjusting the position of the fuel valve opened the possibility of **precise adjustment of the fuel and obtaining the desired operating speeds of the gas turbine.**

1.3. Development of the flowchart of the gas turbine steady-state control

The chosen solution was the implementation of a proportional type regulator, but which has the proportionality factor variable with the deviation size. These formulas are as follows:

At each $\Delta t = 0.2$ sec is calculated the deviation of the speed of the high pressure compressor, NH, from the reference speed, NHref:

$$\Delta NH = NHref - NH\ [rpm] \quad (1.5)$$

It is calculated:

$$\Delta XDCC = KNH \times \Delta NH\ [\%] \quad (1.6)$$

The proportionality factor KNH is variable and depends on the deviation from the NHref speed.

- If $\Delta NH < 30$ rpm, then:

$$KNH=0.0002\ [\%/rpm] \tag{1.7}$$

- If $30< \Delta NH < 70$ rpm, then

$$KNH=0.0005\ [\%/rpm] \tag{1.8}$$

- If $[\Delta NH]>70$ rpm, then

$$KNH=0.0008\ [\%/rpm] \tag{1.9}$$

To avoid the rapid acceleration of the gas turbine, which can lead to mechanical problems, it is limited the increase of the deviation of the fuel metering valve position ΔXDCC by fixing the maximum value.

- If NH<25 500 rpm, then

$$KN=0.4 \tag{1.10}$$

- If NH> 25 500 rpm, then

$$KN=0.2 \tag{1.11}$$

It is fixed:

- if $\Delta XDCC > KN$ [%], then

$$\Delta XDCC=KN\ [\%] \tag{1.12}$$

- if $\Delta XDCC< - KN$ [%], then

$$\Delta XDCC=-KN\ [\%] \tag{1.13}$$

It is calculated:

$$XDC0 = XDC_{n-1} + \Delta XDCC\ [\%] \tag{114}$$

The logic diagram of the fuel control in the stationary states of the engine is based on the formulas established for the control of the fuel flow depending on the speed of the NH high pressure compressor

1.4. Development of the control equations of the bleeding valves

In order to avoid certain unstable operating regimes of the engine, characterized by the reversal of the direction of air flow through the compressor, a condition known as bleeding, the two valves provided for this purpose P2.2 and P2.7, are operated:

The P2.2 valve at engine start is open and as the speed of the NL low pressure compressor increases, it closes after a curve given by the following program sequence.

At each Δt = 0.4 seconds calculate the speed of the low pressure compressor NL, corrected with temperature:

$$NLC = \frac{NL}{\sqrt{\frac{273+T1}{288}}} \tag{1.15}$$

Calculate and assign, based on NLC, the value of the reference position XV2.20 of the anti-pump valve P2.2 as follows:

If NLC <20 900 rpm, then:

$$\mathrm{XV2.20} = 105\ [\%] \tag{1.16}$$

If 20900< NLC< 22000 rpm, then:

$$\mathrm{XV2.20} = 1696 - 0.076 \times \mathrm{NLC}\ [\%] \tag{1.17}$$

If 22000<NLC<23200 rpm, then:

$$XV2.20 = 552 - 0.024 \times NLC\ [\%] \tag{1.18}$$

If NLC > 23200 rpm, then:

$$XV2.20 = -10\ [\%] \tag{1.19}$$

During the running of the gas turbine control program, after the calculation of the reference value, the control signal of the motor of the bleeding valve P2.2 is generated, by means of the sequence XV2.2, which consists of:

Valve position deviation calculation:

$$\Delta XV2.2 = XV2.20 - XV2.2N\ [\%] \tag{1.20}$$

Calculation of the deviation of the valve motor signal :

$$\Delta PV2.2 = -0.09 \times \Delta XV2.2\ [\%] \tag{1.21}$$

Calculation of the valve motor signal coefficient, CV22 :

- if NLC <21000 rpm, then:

$$CV22 = 5.4 \tag{1.22}$$

- if NLC >21000 rpm, then:

$$CV22 = 0.001862 \times NLC - 32.77 \tag{1.23}$$

Calculation of the valve motor signal :

$$PV2.2 = CV22 \times \Delta XV2.2\ [\%] \tag{1.24}$$

1.5. Development of the gas turbine starting and control algorithm

The algorithm designed for starting and control was developed taking into account the particularities of the gas turbine. The actuation of the execution elements is done in a certain order determined by the time necessary for the admission and ignition of the fuel mixture, as well as its dosage to ensure the desired operating regimes. The transition graph from one state to another is shown in Figs. 1.4.

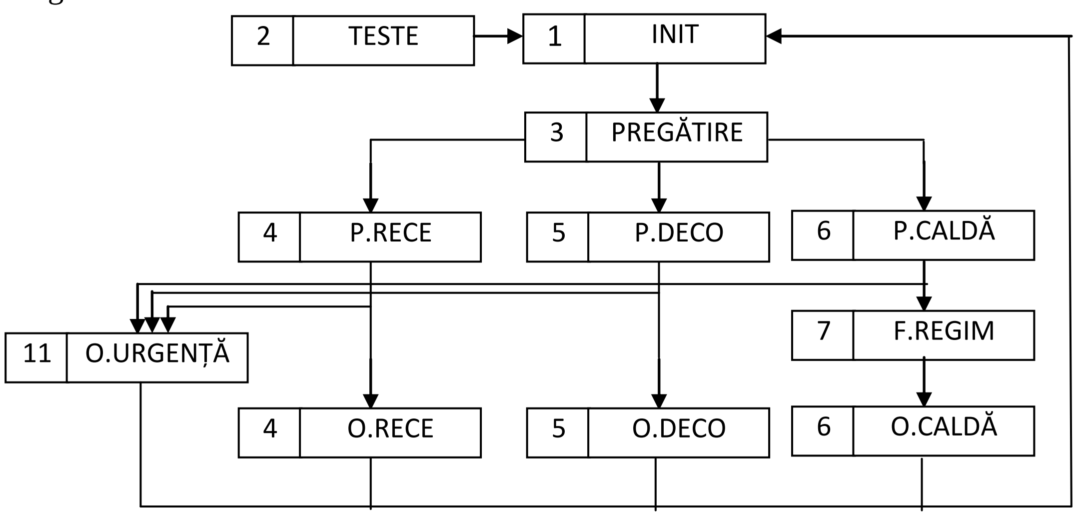

Fig.1.4 Gas turbine states graph

Depending on the starting conditions, there are : Cold Start, Deco Start and Hot Start.

1.6. Development of the HMI

The development of the gas turbine control system with the operator interface takes into account the displayed parameters, the control buttons, the display of the gas turbine status, the display of messages. For this purpose, I thought and created 3 screens:

- The **Main** screen;
- The **Parameters** screen;
- The **Tests** screen.

We designed the **“Main”** screen architecture (Fig.1.5) in order to provide all the information necessary for the operation of the gas turbine.

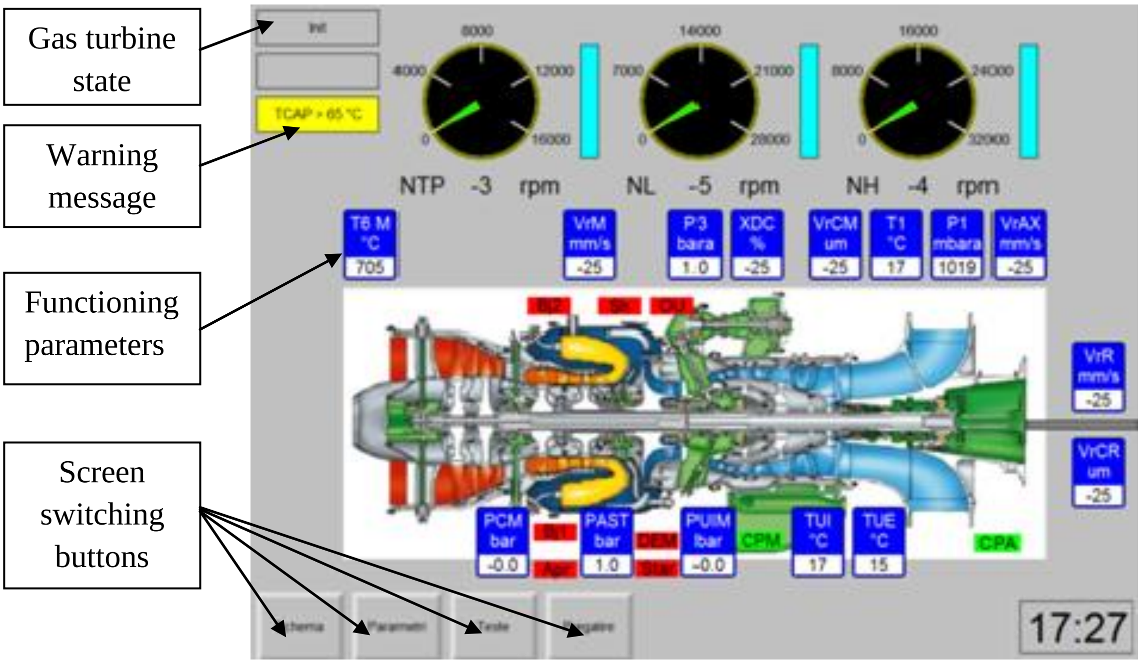

Fig.1.5 Main screen of the control system

On the main screen (Fig.1.5) there are indicators and buttons necessary for the control and supervision of the naval gas turbine. At the top are the main engine speed indicators :

NTP - power turbine speed,

NL - low pressure compressor speed,

NH - high pressure compressor speed.

The parameters are indicated both analog, clock and bar, and digital.

1.6.1. The „Parametri” screen

I designed it for the purpose of presenting in groups the information about the operating parameters of the gas turbine.

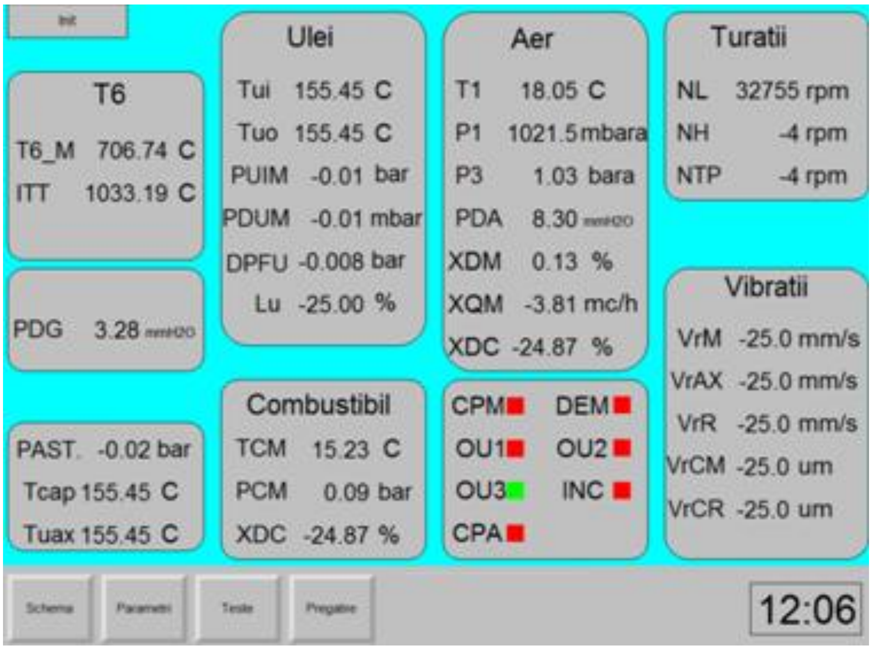

Fig.1.6 The„Parametri” screen

The **„Parametri”** screen (Fig.1.6) shows grouped by categories (air, speed, oil, vibration, fuel) the main parameters of the gas turbine. Each parameter is represented by the symbol, numerical quantity and unit of measure.

At the bottom are defined the screen switch buttons and the system clock.

The status of the gas turbine is displayed in the upper left.

1.6.2. The „Teste” screen

I designed it for testing gas turbine equipment.

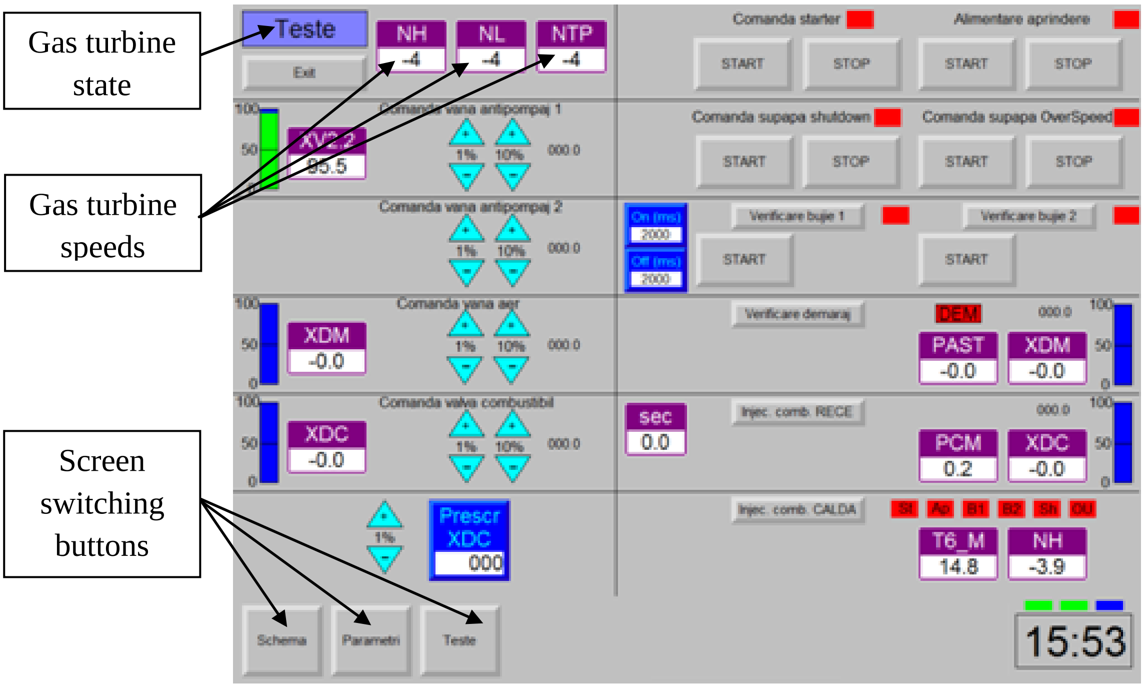

Fig.1.7 The „**Teste**” screen

With the help of this screen (Fig.1.7) different equipment of the gas turbine can be tested.

The creation of these screens meant a very important gain because from these screens it can monitor and control the gas turbine.

1.7. Contributions to the development of the application for control gas turbine

The gas turbine command and control application is the program package loaded in the PLC memory. The application structure, figure 1.8, consists of a main function - _MAIN - which calls the routines that each perform an important function of the command and control system.

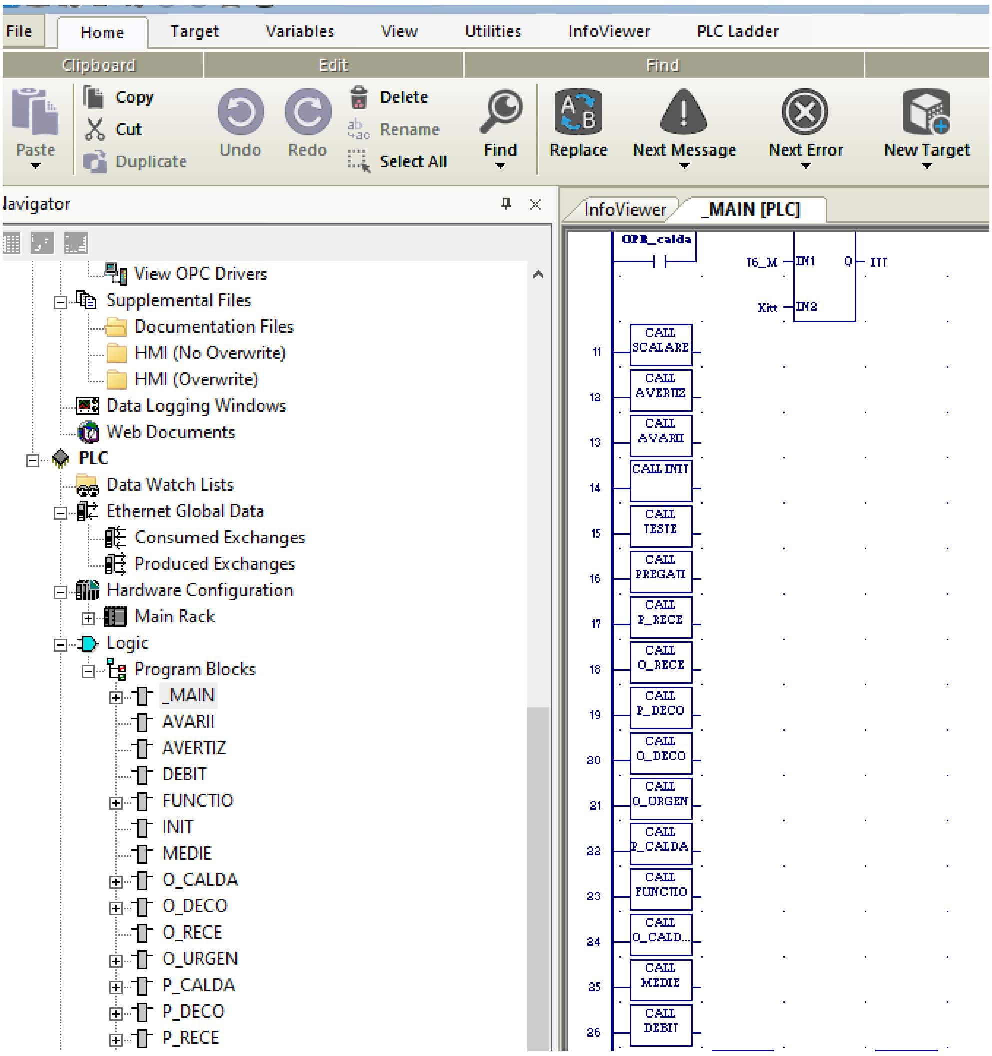

Fig.1.8 _MAIN function structure

Routines run:

- gas turbine control: P_CALDA, P_DECO, P_RECE start, FUNCTIO operation, O_CALDA, O_DECO, O_RECE, O_URGEN stop;
- operations in certain engine states: INIT, PREPARATION, TESTS;
- comparisons: WARNING, PROTECTIONS;
- calculations: SCALING, AVERAGE, FLOW.

The first routine called by the main function _MAIN is SCALE. This routine has the role of scaling the input parameters so that they can be used in the internal memory of the CPU.

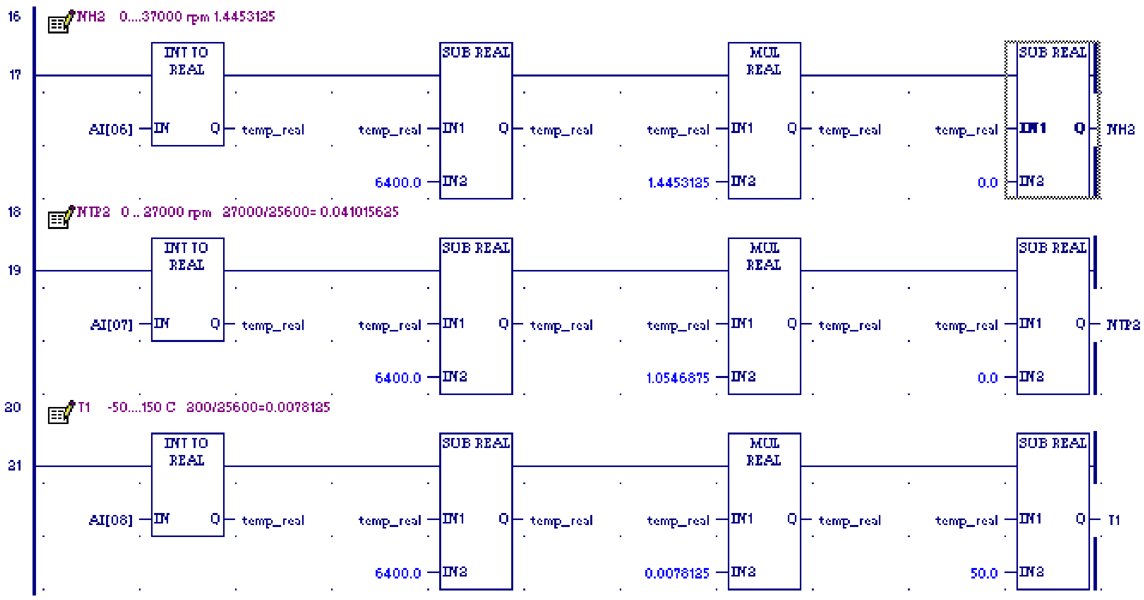

Fig.1.9 SCALARE function structure

For the first parameter in row 17, the **INT TO REAL** module converts the read value on analog input 6 - AI (06), from an integer to a real number, to allow further processing. The second operation performed by the **SUB REAL** module is the subtraction from the number obtained in the previous step of the real number 6400. This is done because the hardware module **IC200ALG264**, used for analog acquisition, is programmed for the range 0-20 mA, to detect current values below 4 mA, in case of broken measuring line. The processed signal takes values in the range of 4-20 mA, therefore from the value acquired is subtracted 6400, as it corresponds to the value of 4 mA. The next module, **REAL MUL**, multiplies the value obtained by a resultant factor, between the represented quantity, **NH** (rpm) and the number of bits it represents, 25600. The last subtraction module, **SUB REAL**, makes a shift of the value obtained when the scaled quantity can be negative as in the case of the temperature in row 21

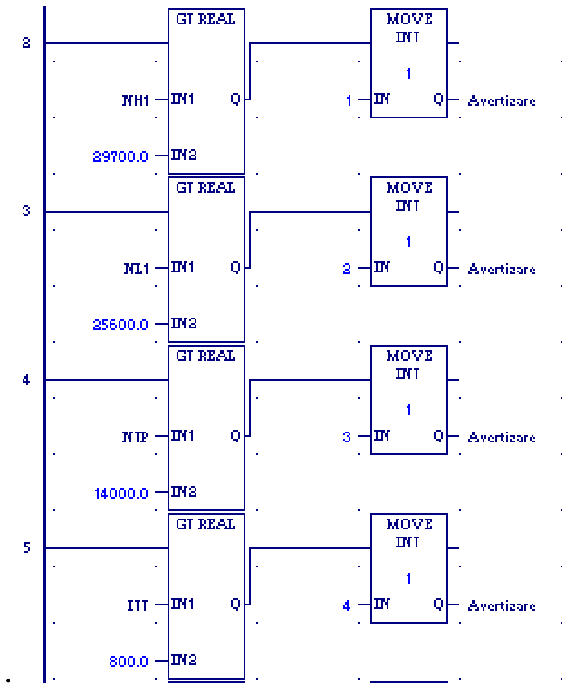

Fig.1.10 AVERTIZ function structure

Another important function I created is the **AVERTIZ** routine, figure 1.10, to signal a warning for certain parameters. In this routine for each parameter its real value is compared at each run of the program in the PLC with the reference value, via the **GT REAL** software module, from the Proficy program library. This module determines whether NH1> 29700, as can be seen in Figure 1.10, row 2. If the comparison is true the output state Q goes from 0 to 1, which causes the next **MOVE INT** module to copy to the **AVERTIZ** memory cell the integer value of on the **IN** input. Thus **AVERTIZ** can take the value 1, 2, 3, 4 and so on and depending on this value the application in the operator panel displays a warning message.

When the protection threshold is exceeded, in order to protect the gas turbine, it is stopped urgently with the help of the **AVARII** function.

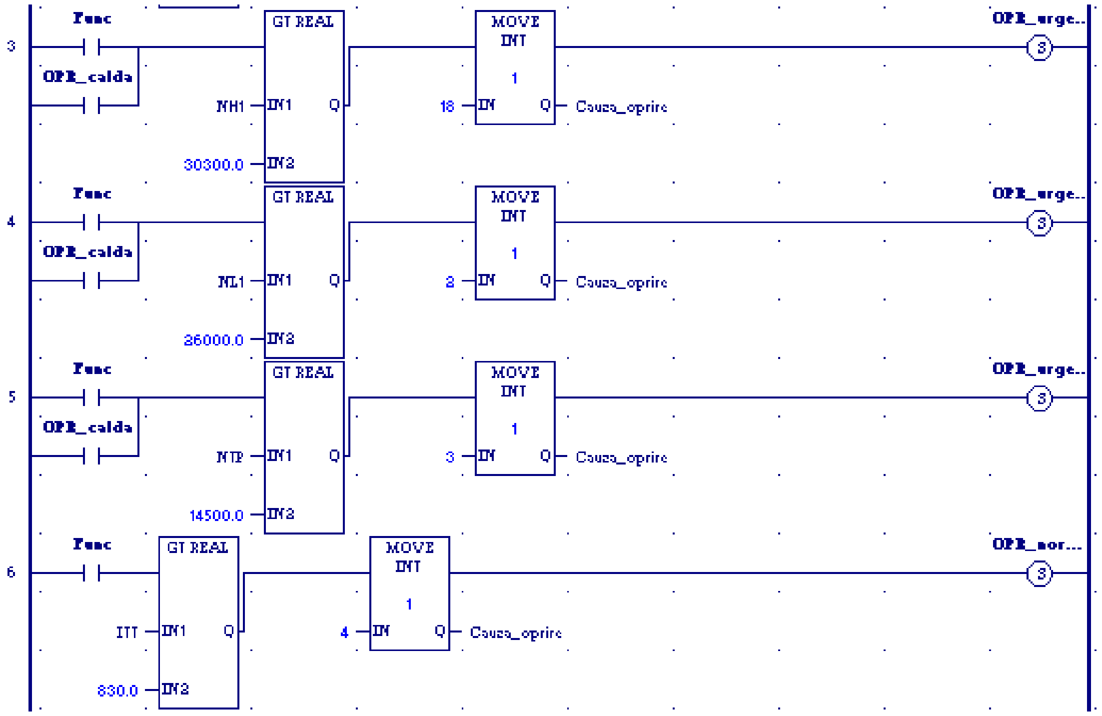

Fig.1.11 AVARII function structure

For **NH** speed the routine works like this:

- If the normally open contact, **Func** or the normally open contact, **OPR_calda** are activated, the comparison is made;
- In the **GT REAL** module the value of the parameter NH1 is compared with the real value 30300;
- If NH1> 30300.0 the Q output of the comparator is transmitted by the **MOVE INT** module to the solenoid **S OPR_urgenta** which is activated, and in parallel the memory cell, **Cauza_oprire**, is set to 18;
- Activation of the solenoid S OPR_urgenta determines the execution of the subroutine O_URGENTA (see figure 1.11 line 21);
- The application in the operator panel displays on the screen the message corresponding to the emergency stop with code 18.

CHAPTER 2

CONTRIBUTIONS TO THE TEST OF THE CONTROL SYSTEM ON THE TEST BENCH

The ST40M gas turbine, used for naval applications, was tested in a special test bench for starting, controlling and monitoring the gas turbines. This test bench has the necessary equipment for this purpose: starter, fuel tank, oil installation, air intake, gas exhaust, dynamometers for gas turbine loading, control system and acquisition parameters.

2.1. Design of the prototype of the gas turbine control system

The block diagram of the gas turbine command and control system, which I designed and built, is shown in figure 2.1.

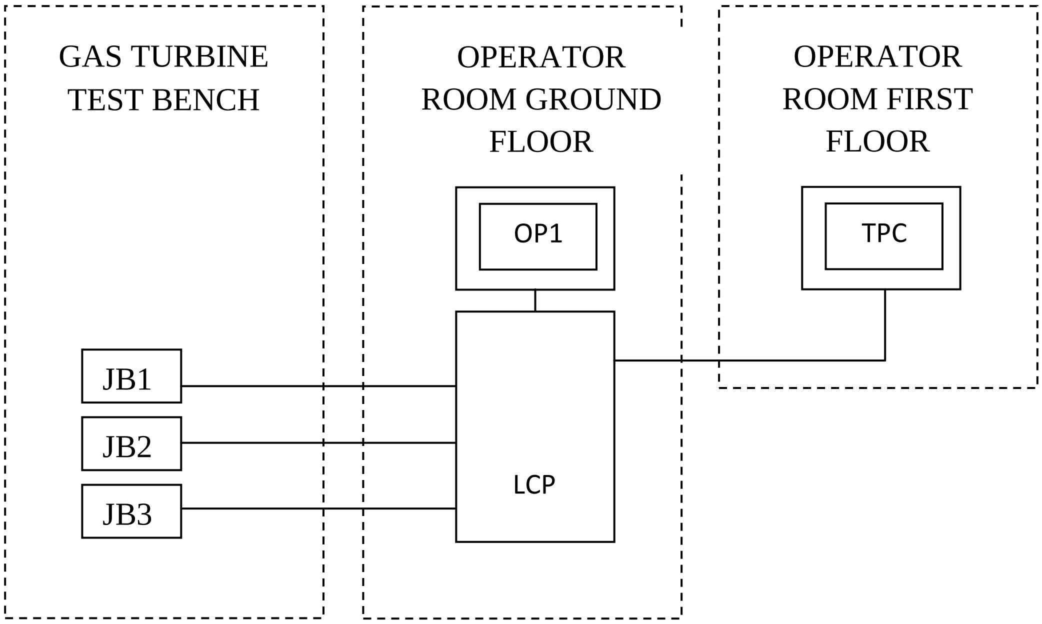

Fig. 2.1 Gas turbine command and control system in test bench – block diagram

Note :

LCP - Local control panel ;

OP1, OP2 - Operator panel ;

TPC - Computer with touch screen ;

JB1 ... JB3 - Junction boxes.

Each module has a well-established role in the system configuration. The main functions of the system components are the following :

a) Junction box JB1

- takes and transforms the temperature signals from the gas turbine and the speed signal from the power turbine;

b) Junction box JB2

- takes and transforms the speed signals from the gas turbine compressor by means of adapters;
- provides control signals for the fuel valve and the bleed valve;

- provides control signals for starter, ignition, shut-off valves;

c) **Junction box JB3**
   - takes the pressure signals from the gas turbine;

d) **Local operator panel**
   - displays the parameters of the gas turbine and can control the engine locally;

e) **Local control panel- LCP**
   - local control panel, contains the PLC, vibration monitor;
   - acquires and processes all signals from the gas turbine or adjacent installations;
   - communicates with the local panel and the one in the control room for the control of the gas turbine.

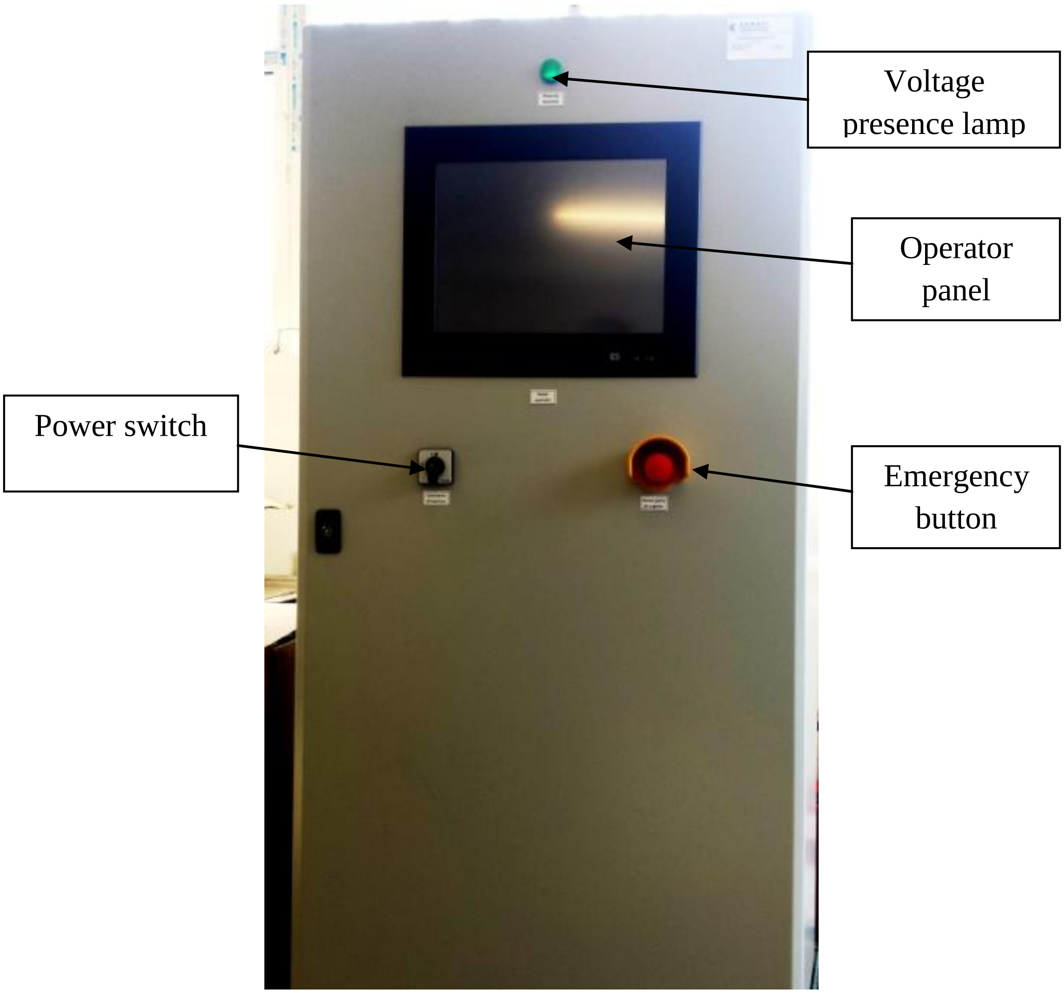

Fig.2.2 Local control panel- LCP

On the front door of the local control panel are located a power switch, an emergency button, the voltage indicator lamp and the operator panel. The display of the parameters and the operation is performed by means of the operator panel type EL PPC 15 1000 / M (Fig.2.3).

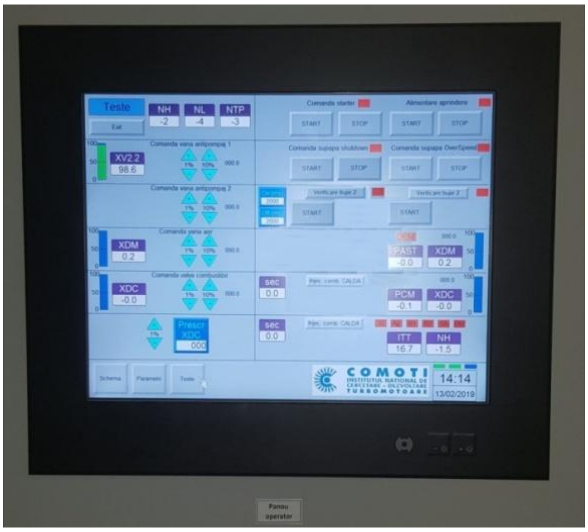

Fig. 2.3 – Operator panel on the local control panel

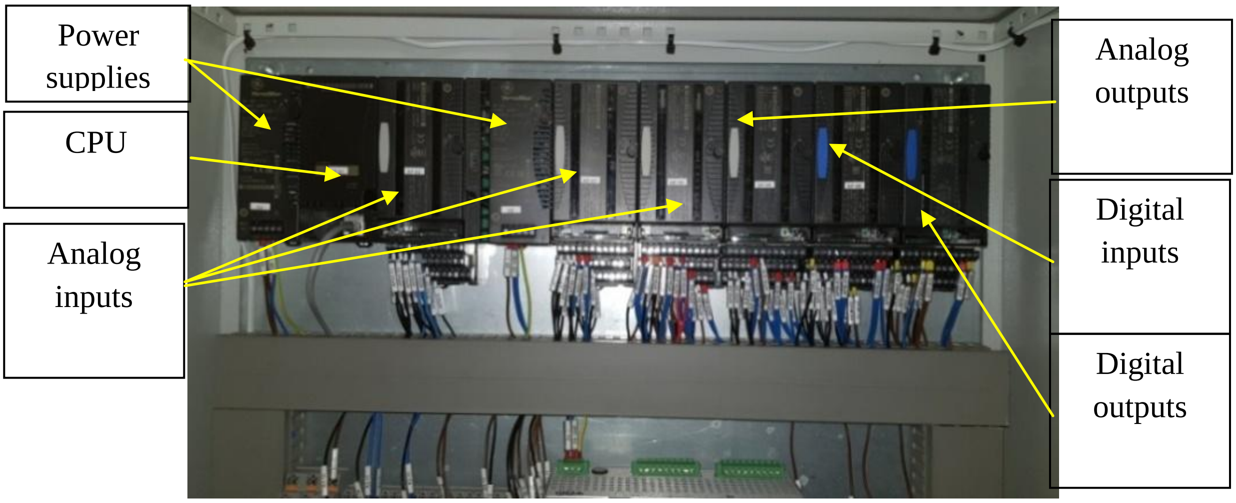

Fig.2.4 PLC from the local control panel

The local control panel (LCP) is based on a VersaMax model (Fig.2.4), produced by GE Fanuc Automation, which runs a program designed to perform the required functions.

f) Remote control operator panel TPC (Touch Panel Computer)

- displays the parameters and remote control of the gas turbine;
- saves the data on the internal hard disk and displays graphs with the evolution of the gas turbine parameters.

The control and supervision of the gas turbine is done from the panel in the engine control room, but it is done, if necessary, from the local control panel.

2.2. Testing of gas turbine control system components

To take over the position of the fuel metering valve and the bleeding valve, we used two LVDT modules. They use a frequency signal to excite a main coil system, take the signal from the secondary coils, rectify it and turn it into current for the PLC input. The control adaptation modules for the fuel metering valve and the bleeding valves P2.2 and P2.7 are electronic modules that convert the unified output signal of type 4-20mA into a current signal corresponding to the control of the respective valve.

2.2.1. Testing the power control lever

The gas turbine must provide a certain power in the load, which depends on the amount of fuel burned in the combustion chamber. For there to be a balance between the gas turbine power output and required power load, the engine must maintain a certain speed turbine power at a given load power consumption. In order to correlate the required load power, in the case of naval applications of the ship's propeller, simulated on the stand by loading the hydraulic brake, in the brake automation I implemented a torque curve so that at a certain speed of the power turbine the power provided by the gas turbine by accelerating it be equal to the power required by the propeller (equation 2.1).

$$Tdem = Tdyno + A0 + A1 \times X + A2 \times X^2 + A3 \times X^n \qquad (2.1)$$

Where:

- $Tdem$ = required torque [Nm];
- $Tdyno$ = manually set torque [Nm];
- X = speed [krpm].

In order to be able to accelerate the gas turbine, the prescribed value of the NH speed reference is entered using the arrows, on the screen or via the power lever (Fig.2.5).

Fig.2.5 Power lever, on test bench, for accelerating gas turbine

The power lever is connected to the gas turbine's command and control system via a signal provided by the electronic lever module. The block diagram of the system is presented in figure 2.6.

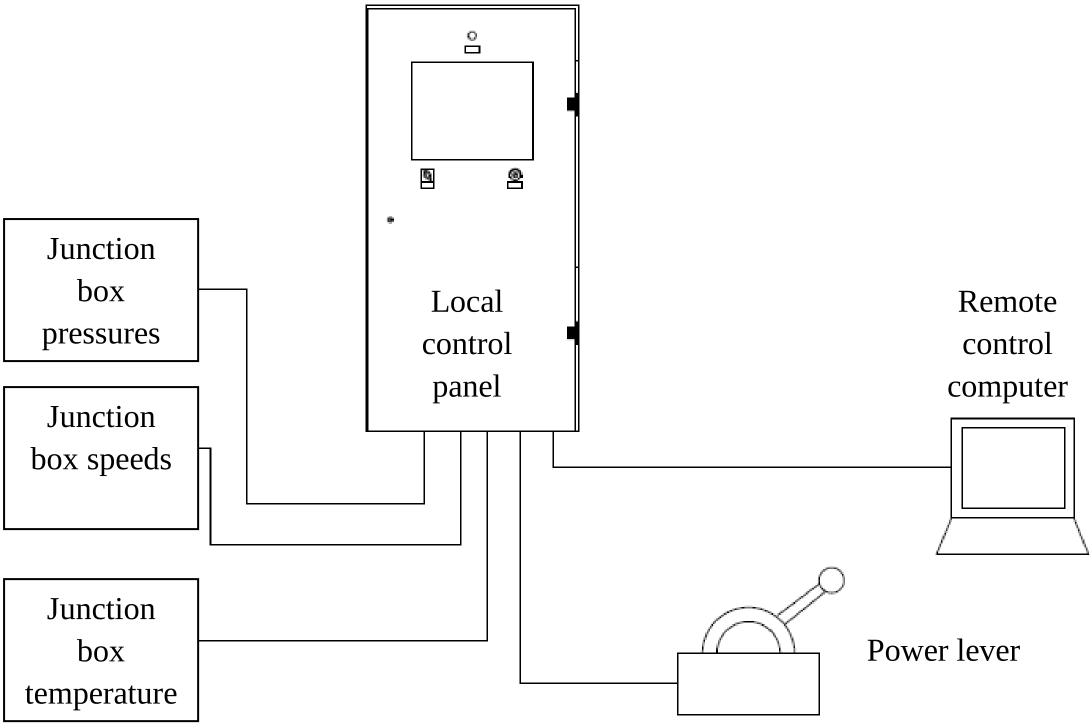

Fig.2.6 Block diagram of the gas turbine control system on test bench

With the help of the lever control we performed several acceleration and deceleration tests of the engine on the test stand. Figure 2.7 shows the graph of acceleration and deceleration of the gas turbine between idle speed **NH = 20000 rpm** and speed **NH = 28530 rpm**, close to the maximum speed.

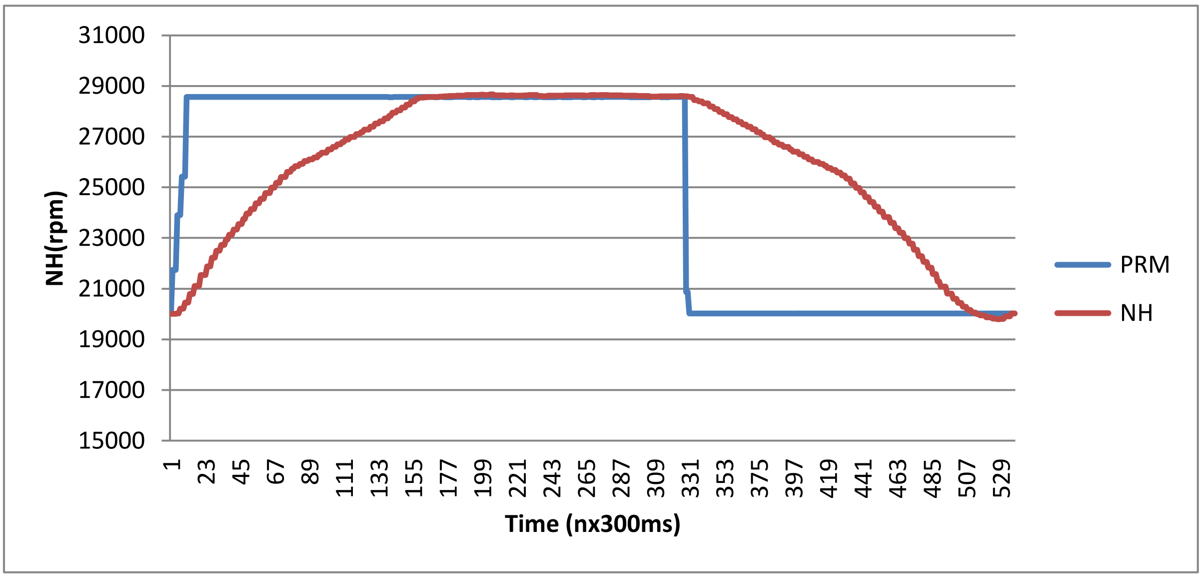

Fig.2.7 ST40M gas turbine accelerating and decelerating on test bench

Notes:

1. The PRM signal corresponds to the signal provided by the power lever and represents the power requirement imposed on the gas turbine;

2. The NH signal is the speed of the high pressure compressor which is proportional to the power developed by the gas turbine.

The following can be seen from the graph:

- The NH signal follows the PRM signal with a certain delay given by the increase and decrease slopes implemented in the gas turbine control application;
- The acceleration time, between NH = 20000 rpm and NH = 28530 rpm, is 46 seconds;
- The deceleration time, between NH = 28530 rpm and NH = 20000 rpm, is 56 seconds;
- These times coincide with the acceleration and deceleration times required for the turbo engine on the ship;
- At point NH = 26000 rpm the slope of the graph has a variation corresponding to the formulas implemented in the program.

The results obtained, illustrated by means of graphs, are important because they show:

a) a stable operation, both in case of acceleration and in case of deceleration;
b) an appropriate slope for safe and smooth command of the ship.

2.3. Analysis of experimental results obtained on the test bench

For the analysis of the experimental data obtained, two relevant tests are compared from the point of view of the transformations of the equations and the corresponding control application

Table 2.1 Analyzed tests

	Test 1	**Test 2**
Date	07.03.2019	13.05.2019
Control algorithm variant	E	E-NH-5
Program variant used	Naval Var 4_6_NH	Naval Var 4_7
Maximum NH speed	28330	27021

During the tests performed, the control of the gas turbine evolved from a proportional control to a proportional control with variable proportionality factor. In order to analyze to what extent this change affected the behavior of the engine regimes, we compared the two tests performed with the gas turbine (table 2.1). The first test was performed on the test bench on 07.03.2019. At that time, the regulation law was proportional. The second test was performed on 13.05.2019 on the test bench and included changes to the control algorithm presented in the second column of table 2.2.

2.3.1. Comparison of control algorithms used

This comparison is presented in table 2.2, where in the left column are the main elements of the control algorithm used in test 1, variant E, and in the right column, the algorithm used in test 2, variant E-NH-5.

Table 2.2 Comparison of ST40M gas turbine operating algorithms

Algorithm E	**Algorithm E-NH-5**
Idle gas turbine output If NH> 19,000 rpm, the gas turbine has reached idle and enters the state **Funcționare la REGIM** In the, **“Funcționare la Regim"** state the fuel flow of the engine is controlled according to the relations: At each $\Delta t = 0.5$ sec it is calculated $\Delta NH = NHref. - NH$ [rpm] $\Delta XDCC = 0{,}002\ \Delta NH$ [%]	**Idle gas turbine output** If NH> 19,000 rpm, the gas turbine has reached idle and enters the state **Funcționare la REGIM** In the, **“Funcționare la Regim"** state the fuel flow of the engine is controlled according to the relations: At each $\Delta t = 0.2$ sec it is calculated $\Delta NH = NHref. - NH$ [rpm]

Is verified: -If NH <25 500 rpm and ΔXDCC > 1,0%, then ΔXDCC = 1,0% -If NH <25 500 rpm and ΔXDCC< - 1,0%, then ΔXDCC = -1,0% -If NH >25 500 rpm and ΔXDCC >1,5%, then ΔXDCC = 1,5% -If NH >25 500rpm and ΔXDCC< - 1,5%, then ΔXDCC = - 1,5%	Is verified: - If [ΔNH] < 30 rpm, then KNH=0.0002 - If 30< [ΔNH] > 70 rpm, then KNH= 0.0005 - If [ΔNH]>70 rpm, then KNH=0.0008 - If NH<25 500 rpm, then KN = 0.6 - If NH> 25 500 rpm, then KN = 0.4
	It is calculated: ΔXDCC = KNH x ΔNH [%] It is calculated: If ΔXDCC > KN [%], then ΔXDCC = KN [%] If ΔXDCC<- KN [%], then ΔXDCC = - KN[%]
Otherwise ΔXDCC takes the value resulting from the calculation It is calculated: $XDC0 = XDC^{-1}+\Delta XDCC$ Each time the program is run, the XDC Algorithm is executed	Otherwise ΔXDCC takes the value resulting from the calculation It is calculated: $XDC0 = XDC^{-1} + \Delta XDCC$ Each time the program is run, the XDC Algorithm is executed
Algorithm XDC It is calculated: 1 ΔXDC =XDC0-XDC [%] 2. ΔPQC = 0,08 ΔXDC [mA] 3. $PQC = PQC^{-1}+ \Delta PQC$ [mA]	**Algorithm XDC** It is calculated: 1. ΔXDC =XDC0-XDCN [%] 2. Is verified: - If ΔXDC < 0,75, then KS = 0,15 - If 0,75<ΔXDC< 2, then KS=0,3 - If ΔXDC>2, then KS = 0,6 3. ΔPQC = KS x ΔXDC [%] 4. PQC = 5.76 + ΔPQC [%]

The algorithm in the right-hand column of Table 2.2, in addition to the limitations of the position deviation ΔXDCC of the fuel metering valve, also has variable sizes of the speed deviation multiplication coefficient ΔNH, as well as the coefficient KS of the deviation of the position of the fuel actuator PQC. Also, the same algorithm is executed faster than the algorithm initially used, presented in the left column of table 2.2.

2.3.2. Comparison of experimental results

Thus, in the first test, the evolution of the speed of the high pressure compressor NH from idling, NH = 20000 rpm, to the speed of NH = 27000 rpm is presented in figure 2.8. The graphs show:

- NHref, the speed of the imposed high pressure compressor of the gas turbine ;

- NH, speed of the high pressure compressor obtained of the gas turbine.

I emphasize that the speed of the high pressure compressor, NH, is the parameter that illustrates the regime in which it operates and implicitly the power it provides. It is proportional to the amount of fuel and air consumed by the gas turbine.

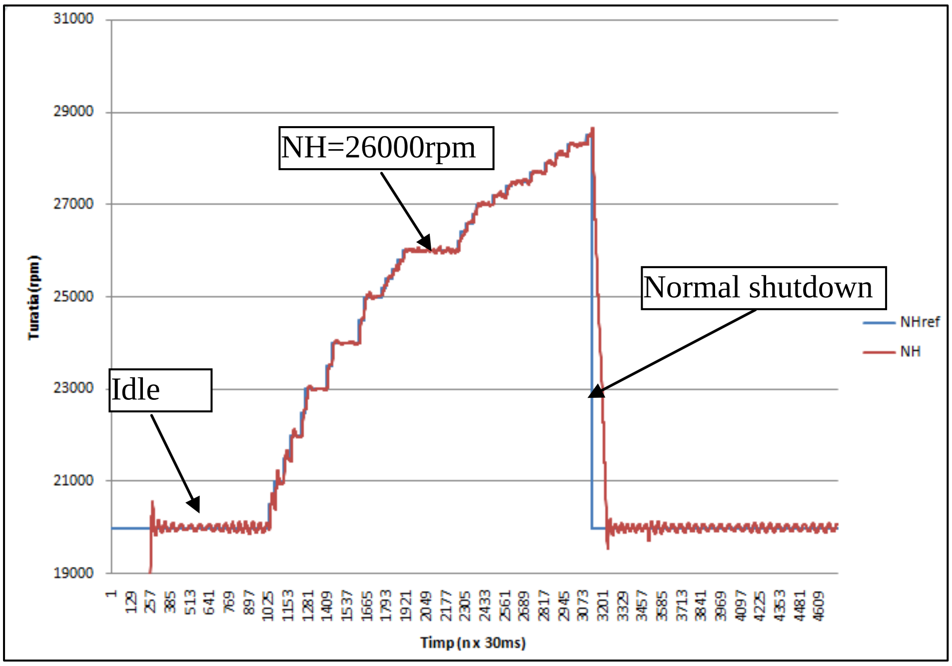

Fig. 2.8 Evolution of NH and NHref speed at test 1

The evolution NH speed at test 2 is shown in the figure 2.9.

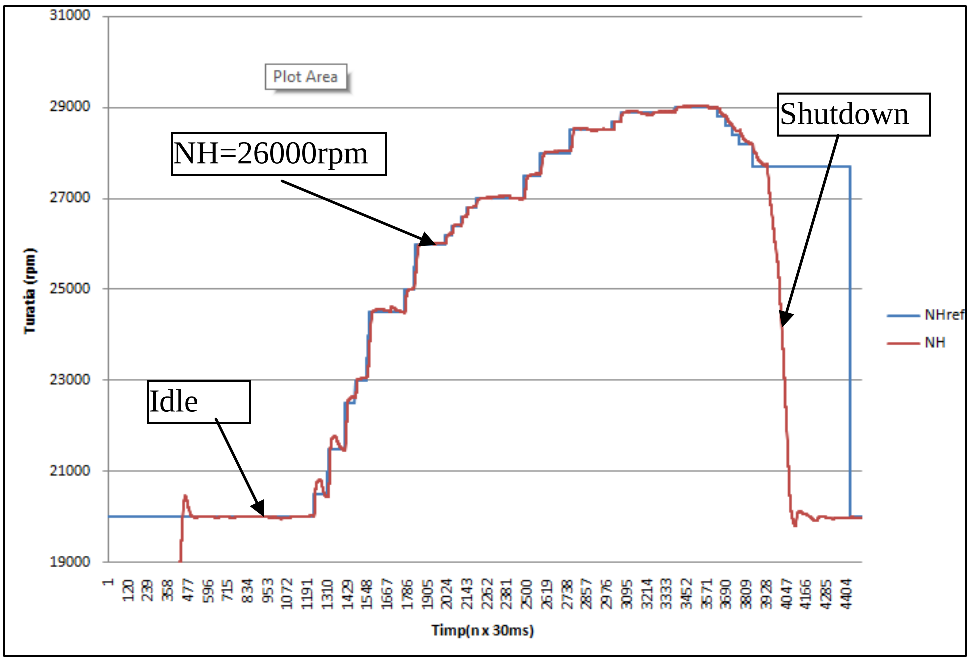

Fig. 2.9 Evolution of NH and NHref speed at test 2

To highlight the effect of changing control algorithms, we compared the evolution of NH speed at two stationary regimes.

A. Idle: NH=20000 rpm

Extracting the data from the two graphs above and representing on the same graph those corresponding to the idling regime, NH = 20000 rpm, we obtained figure 2.10.

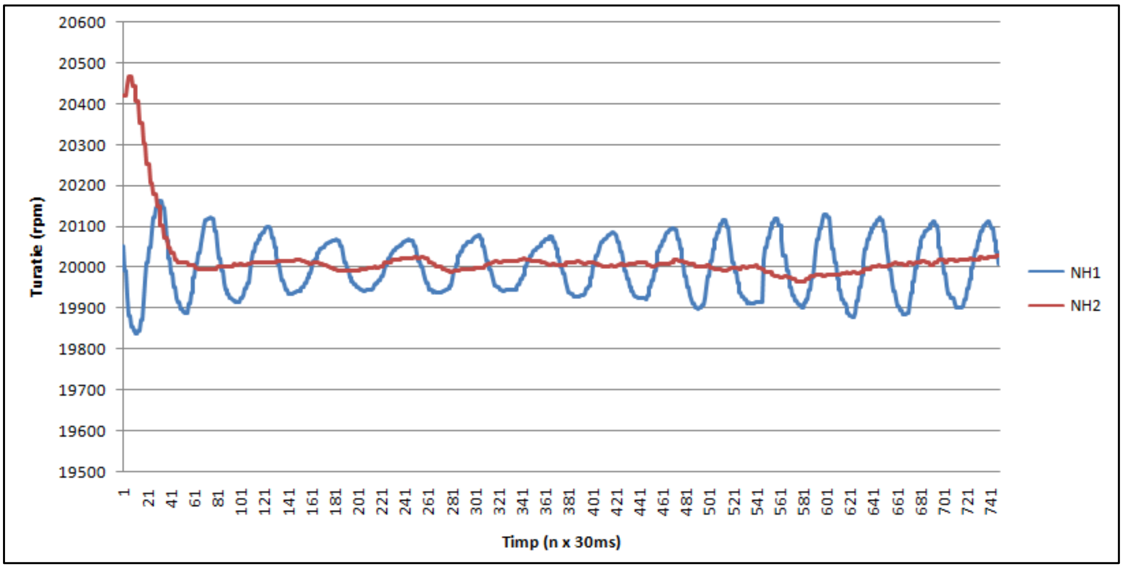

Fig. 2.10 Evolution of NH1 and NH2 speed at idle

Comments from the analysis of Figure 2.10:

- The amplitude of the oscillations in the case of test 2 is 20 rpm, much smaller than in the case of test 1, where the average amplitude is 100 rpm, the decrease being **500%**.
- The initial amplitude peak, higher in the case of test 2 than in the case of test 1, is determined by the increase in speed during the starting period.

B. NH=26000 rpm

Representing the data corresponding to the NH regime = 26000 rpm, we obtained figure 2.11.

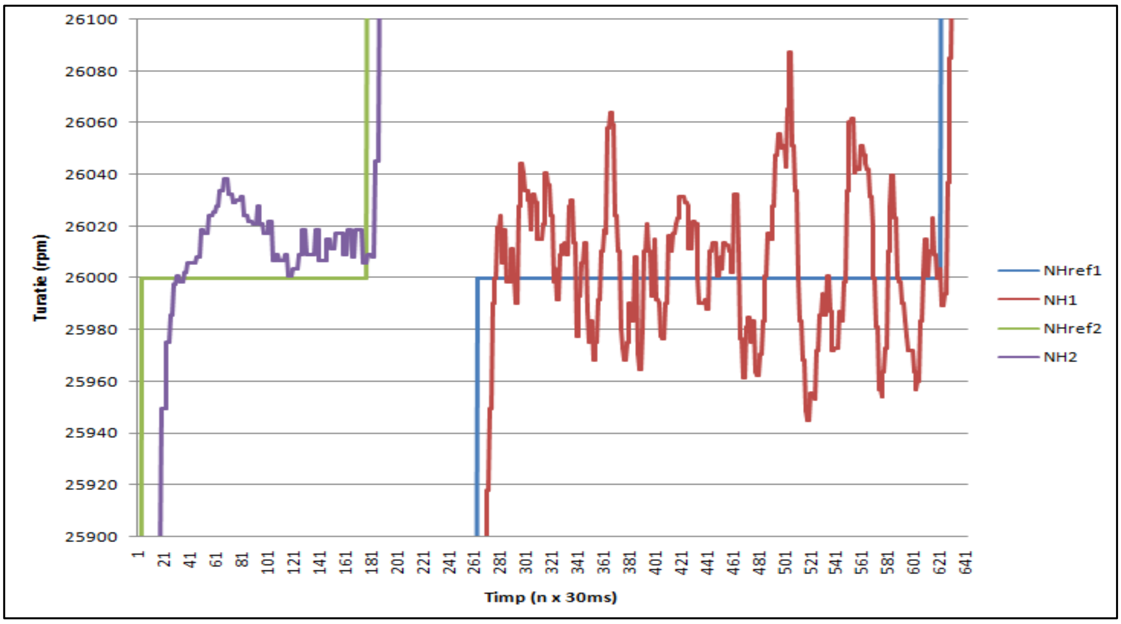

Fig. 2.11 Evolution of NH1 and NH2 speed at 26000 rpm

This figure shows both the required Nhref speed value and the instantaneous NH value for the two tests.

Comments from the analysis of Figure 2.11:

- • The amplitude of the oscillations in the case of test 2 is 20 rpm, much smaller than in the case of test 1, where the average amplitude is 40 rpm, the decrease being **100%**.

Conclusions : The modification of the algorithm from test 1 to test 2 contributed to the increase of the NH speed stability at the stationary operating modes of the gas turbine. During the activity we showed this at idle and at 26000 rpm speed. The decrease of the amplitude of the speed disturbances at constant regime, contributes to its stable operation, which leads to the reduction of the thermal and mechanical stress on the components and the prolongation of the life of the gas turbine.

2.4. Contributions on remote data transmission using an OPC server

This chapter presents the practical realization of the remote transmission of data from a complex of engine test benches at a distance of hundreds of kilometers in the data center of the company that owns the complex.

The engine test assembly includes 3 benches:

- Gas turbine test bench;
- Micro engine test bench;
- Turbojet engine test bench.

The 3 stands have a local control panel and data acquisition (LCP - Local Control Panel), led by a central station panel (SCP - Station Control Panel), which centralizes the data and coordinates the operation of each test bench. Remote data transmission via the Internet to the beneficiary is based on a communication application. The Matrikon OPC UA Tunneller communication application was used for this.

2.4.1. Configuration of the data transmission

The 3 test benches are connected via Ethernet network, figure 2.12. From the stand control panel switch equipment, we created a connection through a firewall to protect the internal network from external threats.

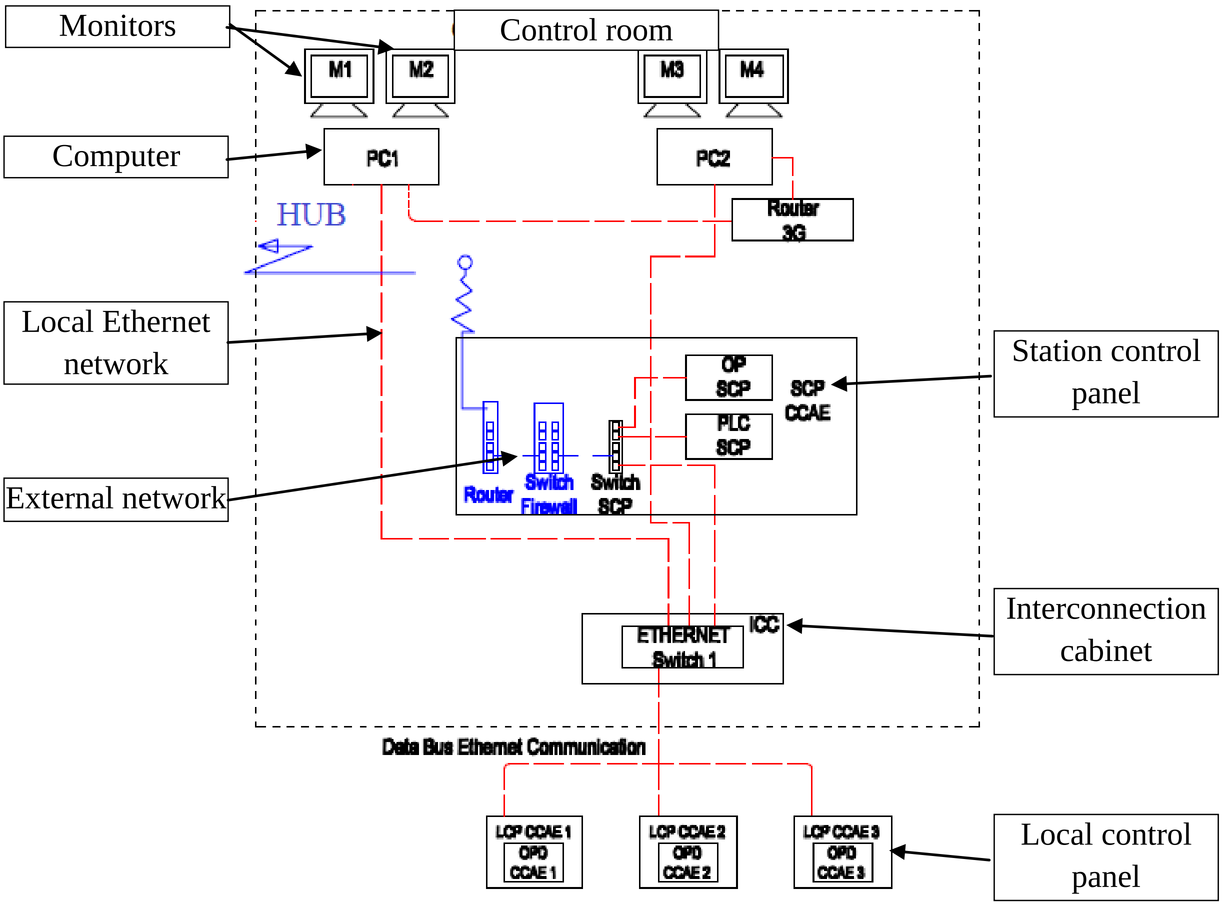

Fig. 2.12 The informational architecture of the test bench complex

From the firewall the connection reaches a GSM router, which provides the Internet connection and through it communicates with the network at the headquarters of the organization. Here the SCADA application takes over and displays the parameters obtained at the installation level.

The data is read from the PLCs of each stand by the computers in the control room of the stand complex, via the Ethernet network. The programs on these computers provide the data through an OPC server. The SCADA application, which runs in the company's control center, accesses the data through a communication application. The programming environment I used to develop the applications running on the two computers in the control room is Proficy Machine Edition. The transmission of the desired stand parameters was done by configuring two OPC servers, one for each monitoring computer in the control room. All desired parameters will be transferred from the two servers.

CHAPTER 3

TESTING OF THE CONTROL SYSTEM ON THE SHIP

The ship on which the gas turbine is installed has an electronic system that controls both the propeller pitch and the engine power to obtain the propulsion force. The ST40M was tested on the ship instead of the ship's running engine, the power developed by the two engines being similar. The tests we performed on the ship involved a minimal intervention in the automatic control of the engines and propeller. The throttle signal of the old gas turbine was used to control the ST40M.

The ST40M tested on the test bench together with the developed command and control system was mounted on the ship. As part of its propulsion system, the gas turbine functions as a marching engine to replace the ship's obsolete engine, a Tyne model developed in the 1950s by Rolls-Royce [3].

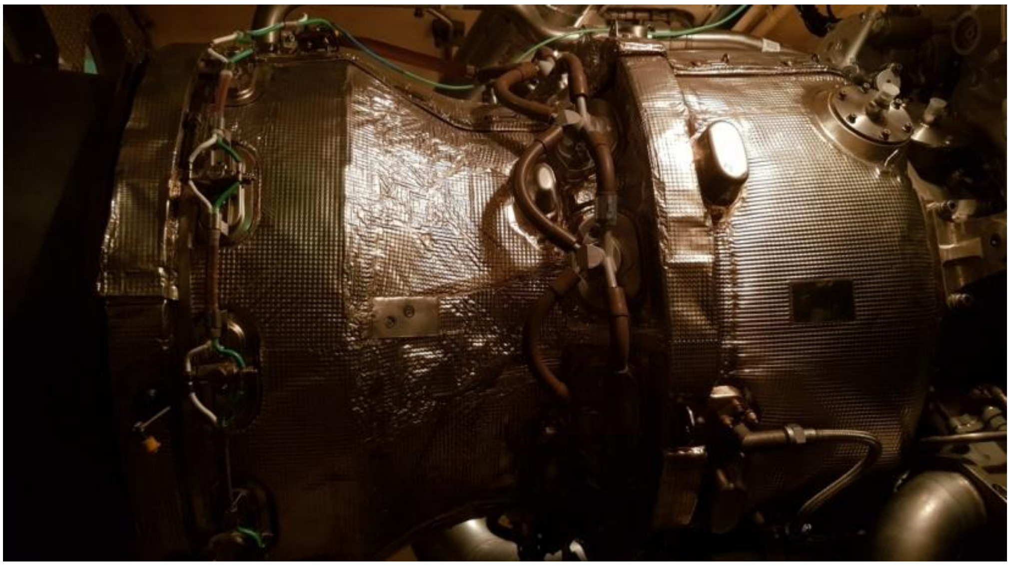

Fig. 3.1 ST40 M gas turbine installed on the ship

Engine control may be performed either from the engine room, via the local control panel, or remotely, from the engine control room on the upper deck of the ship, via a remote control panel. The PLC inside the local control panel (LCP) is connected to power adapters located in the junction boxes in the immediate vicinity of the gas turbine (fig.3.2).

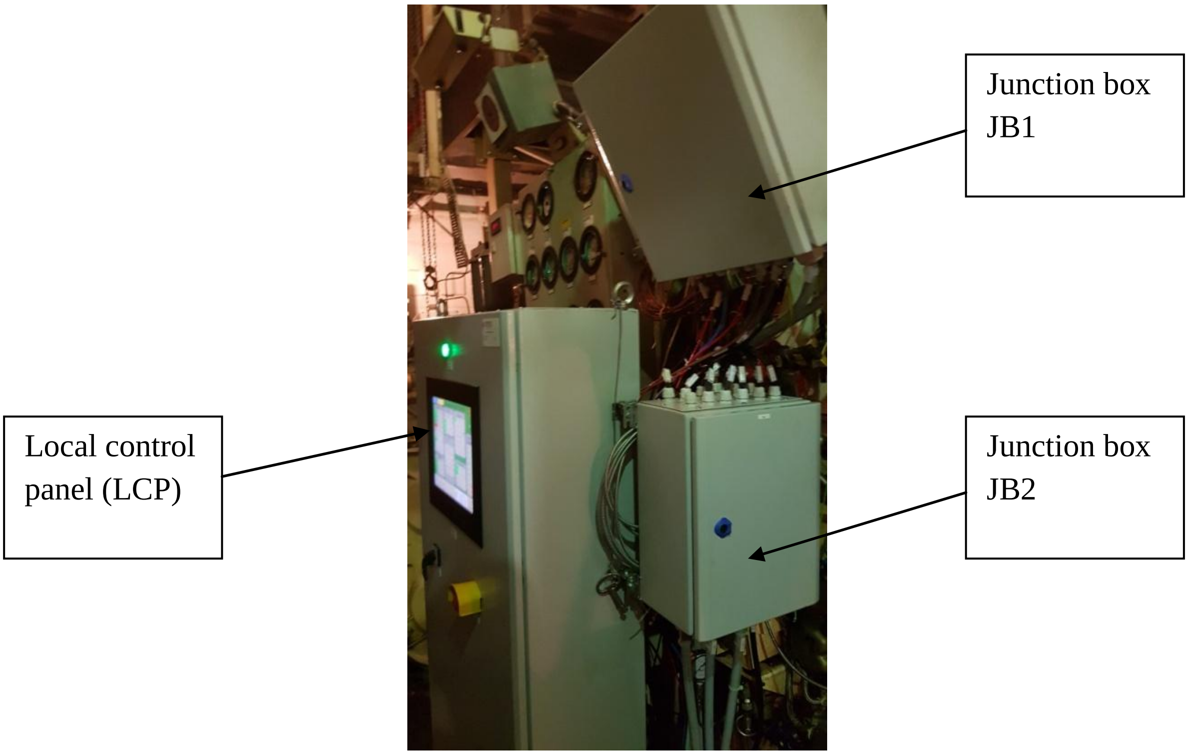

Fig. 3.2 Location of the local control panel and junction boxes on the ship

3.1. Testing the ST40M gas turbine connected to the ship's power lever

The position of the power lever is taken over by the command and control system of the gas turbine by means of a signal provided by the pneumatic converter of the ship's power lever (fig.3.3). The pressure signal, provided by the pneumatic converter, is transformed into a unified current signal, 4-20 mA, by a pressure transducer, PRM. This current signal is acquired by an analog input of the PLC located in the local control panel.

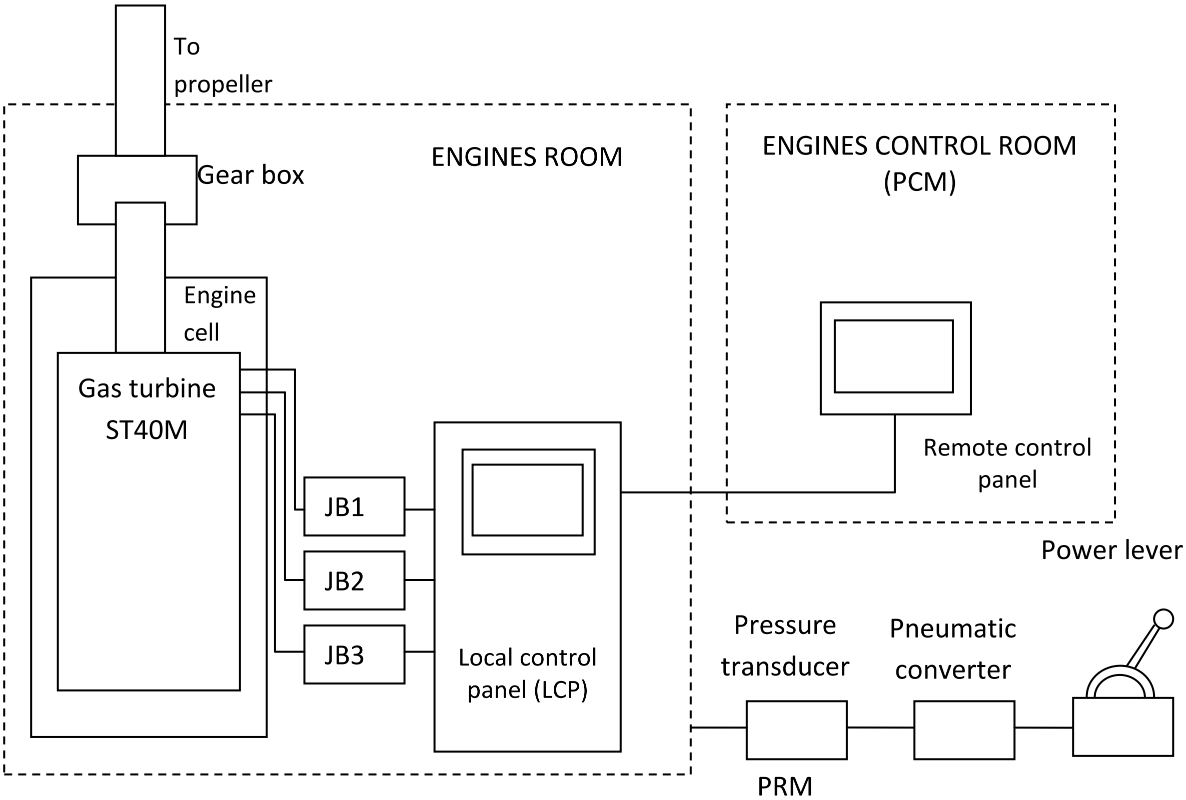

Fig.3.3 Block diagram of the gas turbine control system on ship

The value of the lever position signal is converted, by means of the program implemented in the PLC, into the speed of the high pressure compressor required for the ST40M gas turbine. Based on this signal, the corresponding output of the fuel valve actuator from the ST40M is calculated, obtaining the required power from the engine.

We performed several tests of acceleration and deceleration of the gas turbine on the ship, the ship being tied to the quay, using the power lever (fig.3.4).

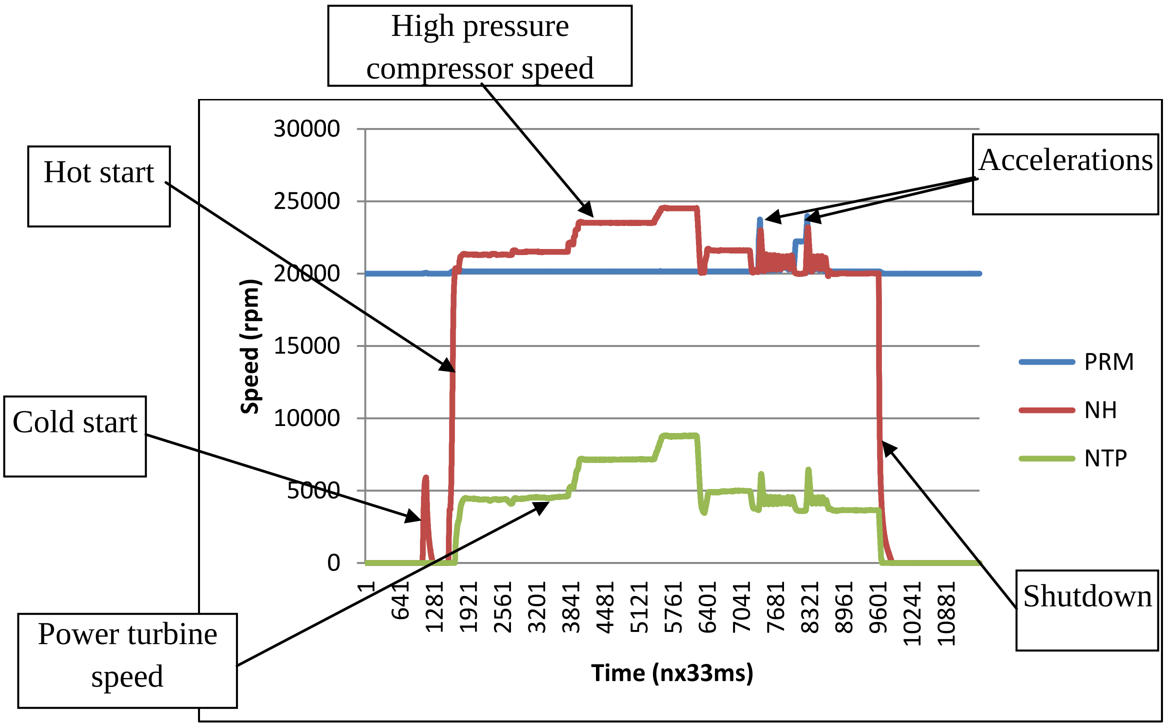

Fig. 3.4 Start-test-stop test with the ship at the quay

Conclusions at the tests with the ship at the quay :

- NTP -power turbine speed curve reproduces the shape of the NH - high pressure compressor speed curve, fig.3.4, the command and control act according to the setting curves established on the test bench, the control software application not being modified.

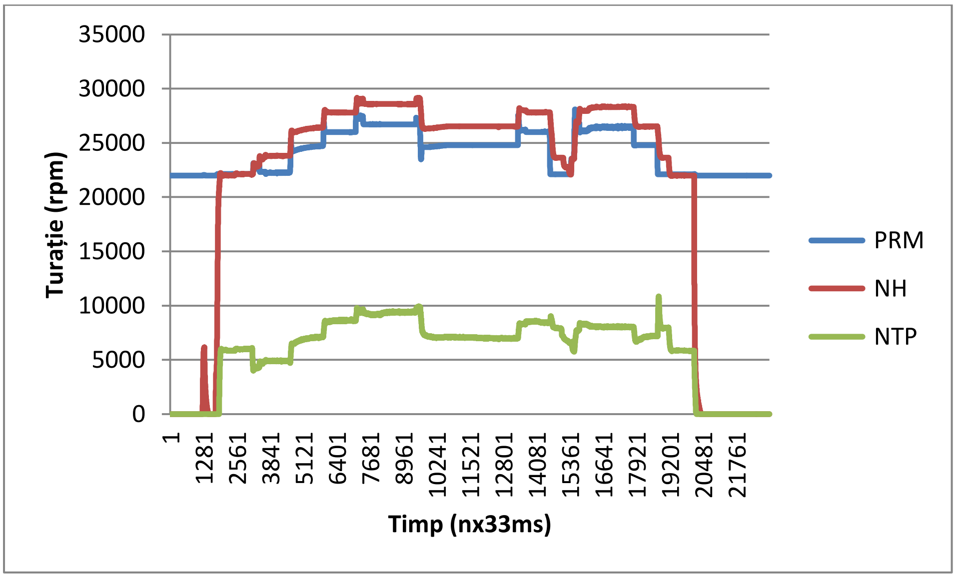

Fig. 3.5 Start-test-stop test with the ship at sea

I performed acceleration and deceleration tests of the gas turbine on the ship, the ship being at sea, using the power lever (fig.3.5). Unlike the previous case, in offshore tests the power of the gas turbine could be maximized, the speed of the high pressure compressor exceeding 25000 rpm.

Conclusions at sea tests :

- NTP - power turbine speed curve, reproduces the shape of the NH - high pressure compressor speed curve over the entire speed range of the gas turbine ;
- It is noticed the appearance of an overspeed in test 2 (fig.3.5) when the abrupt reduction of the imposed speed.

3.2. Adjusting the control parameters of the gas turbine

Compared to the stand, on the ship, the starting sequence of the gas turbine was modified to use the pneumatic starting system of the ship. Thus, on the stand, the compressed air that activates the starter is released by the CAD valve, and then it is varied with the help of the DMM valve. On the ship, the compressed air required for the starter is released by the CAD valve and then regulated by the CAA valve, by opening it obtaining the ignition speed of the gas turbine.

Another adjustment was made for the idle speed reached by the gas turbine after a hot start. In the case of stand tests, the idle speed of the gas turbine was set NH = 20000 rpm, where NH is the speed of the high pressure compressor. On the ship, however, it is recommended that the ship's propeller rotate at least 50 rpm when it is set in motion, in order to make the correct lubrication of its bearings. Therefore, the idle speed was raised to NH = 22000 rpm.

3.3. Increasing energy efficiency by using gas turbines proposed

Following the analysis of the experimental results obtained from the tests performed with the system on board the ship, we found an increase in the overall efficiency of the propulsion solution with ST40M compared to the old propulsion solution with TYNE RM1C of the ship.

From the results presented in Table 3.1, for the same positions of the power levers, the consumption for the propulsion system with ST40M was 12% lower than the propulsion system with Tyne engine.

Table 3.1 Corrected ST 40M characteristic vs Tyne characteristic

Point no.	-	1		2		3		4	
Hour	-	14:19		14: 25		14: 31		14: 41	
Gas turbine		ST 40M	Tyne	ST 40M	Tyne	ST 40M	Tyne	ST 40M	Tyne
Power control lever	div	**24**	**24**	**40**	**40**	**50**	**50**	**54**	**54**
Throttle	%	6	15	42	38	64	58	76	72
Fuel flow	l/min	**5,7**	**7,6**	**10,4**	**11,0**	**14,8**	**17,3**	**17,5**	**19,9**
Propeller speed	rpm	56	54	77	76	97	101	105	108
Propeller pitch	div	32	32	34	34	34	34	34	34
Ship speed	nod	6,0		9,0		11,6		14,1	

3.4. Contributions on improving reliability by adding a redundant module

The redundancy I designed, by adding a redundant local control panel, is based on the ST40M gas turbine ability to have an additional line of controls and provide information about the engine's speed. The addition of the redundant panel allows control and starting of the gas turbine in the critical case, when the troubleshooting team cannot reach the ship. Also, the control duplication allows the gas turbine to be operated if the main local control panel is defective.

Analysis of experimental results obtained at accelerations and decelerations

Tests to check the acceleration of the ST40M were performed by quickly pushing the control power lever from zero to a certain value and after stabilizing the selected mode, the lever was pushed back to zero.

Four tests were performed as follows :

- acceleration by pushing the lever from 0 to 24 divisions and back to 0 ;
- acceleration by pushing the lever from 0 to 36 divisions and back to 0 ;
- acceleration by pushing the lever from 0 to 46 divisions and back to 0 ;
- acceleration by pushing the lever from 0 to 50 divisions and back to 0.

The results obtained are presented in table 3.2.

Table 3.2 Acceleration times of the ST 40M gas turbine

Test / Parameter		UM	Test 1	Test 2	Test 3	Test 4
Test time		h:m:s	15:21: 30	15:22: 39	15:24: 36	15:26: 47
Acceleration	**PCL**	div	0 ÷ 24	0 ÷ 36	0 ÷ 46	0 ÷ 50
	Start time	h:m:s	15:21: 50	15:22: 39	15:24: 40	15:26: 47
	Start NH	rpm	21150	21097	21100	21120
	Regime time	h:m:s	15:22: 05	15:23: 02	15:25: 16	15:27: 30
	Regime NH	rpm	23850	25340	26950	27570
	Acceleration time	s	**15**	**23**	**36**	**43**
Deceleration	**PCL**	div	24 ÷ 0	36 ÷ 0	46 ÷ 0	50 ÷ 0
	Start time	h:m:s	15:22: 06	15:23: 22	15:25: 42	15:28: 01
	Start NH	rpm	23990	25740	26570	27560
	Regime time	h:m:s	15:22: 22	15:23: 43	15:26: 16	15:28: 45
	Regime NH	rpm	22025	22015	22025	22100
	Deceleration time	s	**16**	**21**	**34**	**44**

As can be seen, the acceleration and deceleration times are approximately equal and are close to the acceleration times of the Tyne gas turbine propulsion line, measured in previous tests. The idling speed at which the gas turbine descends is the same, which shows stability in the operation of the propulsion line.

1.1.1. Conclusions on ship tests

- The tests revealed:
- - 100% compatibility between the automatic command, control and data acquisition systems of the ship's propulsion group with the ship's automatic systems;
- - from the point of view of ship propulsion, the resemblance is perfect between the TYNE turboprop unit and the ST40M turboprop unit.

CONCLUSIONS

1. GENERAL CONCLUSIONS

The paper aimed to research, design and test a new command and control system for a gas turbine used in a naval propulsion application.

The studied field is of major importance in the development of modern and efficient naval propulsion systems to replace old and obsolete propulsions. Finding the most appropriate and appropriate means of naval propulsion that is in line with the latest achievements in science will remain the focus of attention around the world.

The author of the doctoral thesis made an important contribution in the effort to achieve a modern propulsion that would replace an old and less efficient propulsion.

The research process started from the basic equations of the gas turbine. Their study revealed aspects of finding the most appropriate automatic regulator formula. Taking into account the theory of electronic regulators, the basic relations of the algorithm implemented in the PLC of the local control panel were obtained.

In addition to these relationships, with the important contribution of the author, the control relationships of the fuel and anti-pump dosing valves have been developed, see Chapter 1, paragraph 1.5. The necessary HMI interface has been created for the operator's interaction with the control system.

In parallel with the development of the control algorithm, numerous tests were performed on the test stand in order to validate the operation of the gas turbine in optimal parameters, but also the command and control system, the command algorithm and the software packages.

The good results obtained allowed the transfer of the command and control system together with the gas turbine to the ship. After an intense work of adapting the systems to the configuration of the ship, a number of real tests were performed with the ship in different modes of operation. After small adjustments of the control software, the ship with the propulsion group consisting of the command and control system created, operated in excellent conditions of speed and consumption parameters. These results will be used to transfer the technology to potential beneficiaries.

2. ORIGINAL CONTRIBUTIONS

The doctoral thesis aims to contribute to the field of naval propulsion by researching, designing and implementing an automation system designed to control and monitor the parameters of a gas turbine. This research contributes, by changing naval propulsions that use old generation gas turbine with a new propulsion system based on the ST40M gas turbine, in order to reduce fuel consumption and respectively the costs of marine transport. Below are briefly presented the original contributions of the thesis in the field studied:

a) **Study on the current state and trends in marine propulsion technology with gas turbines** for fast ships. This analysis had to be done to establish the need and directions for research and development for these areas (see Chapter Introduction);
b) **Determining an algorithm for controlling fuel consumption**. The algorithm determined for the control of the fuel valve is essential in the control and control of the gas turbine. The evolution of the gas turbine in each operating state depends on the fuel metering. Therefore, the determination of the equations according to which the fuel valve operates constitutes a major contribution to the command and control of the gas turbine (see Chapter 1 paragraph 1.3);

c) **Determining an algorithm for controlling bleed valves**. The control algorithm established starting from the fundamental equations was implemented in the command and control system of the gas turbine. Avoiding the bleeding state implies determining the optimal control of the bleed valves and obtaining the maximum power of the gas turbine in the stable operating range (see Chapter 1 paragraph 1.5);

d) **Development of the operator interface.** Through it, the commands are given and the parameters of the gas turbine are monitored. That is why it is very important to be clear and easy to use. The author has made an important contribution to the design of this interface to meet the required challenges. (see Chapter 1, paragraph 1.7);

e) **Elaboration of a software for the implementation of the algorithm.** The algorithm once established was implemented in a Ladder Diagram software developed using the programming environment provided by the company producing the PLC. The author made an important contribution to the development of command and control routines. The author's ideas about structured programming and the use of variable coefficients were translated into the logic implemented in the package of control programs (see Chapter 1 paragraph 1.8);

f) **Proposing a new constructive solution for the turbo engine command and control system.** This was necessary for the realization of the command and control system of the gas turbine for naval applications (see Chapter 2 paragraph 2.2);

g) **Development of a remote data transmission program**. The author contributed to the creation of a program for remote transmission of data from the PLC of the component stands at the headquarters of the organization. This program was developed using an OPC server implemented in the computers that communicate with the local control panels in each stand and by using a specific application (see Chapter 2 paragraph 2.6);

h) **Analysis of the interconnection with the ship's own engine control system.** In order to test the command and control system of the turbo engine on the ship, the author of the doctoral thesis researched the control system of the ship's engines to integrate the turbo engine system in its command functions (see Chapter 3 paragraph 3.1);

i) **Testing of the command and control system on the ship**. The author effectively contributed to the adjustment and testing of the ship's command and control system, following the results in comparison with the replaced propulsion system (see Chapter 3, paragraph 3.3);

j) **Proposing a redundant solution for the turbo engine command and control system**. Although the reliability of the system in the tests did not leave much to be desired, the author proposed and published at a specialized conference a redundant technical solution for the command and control system of the gas turbine (see Chapter 3 paragraph 3.7);

k) **Analysis of the results obtained from the tests on the ship**. Following the analysis performed by the author, the good compatibility of the ST40M gas turbine command and control system in the studied naval application was revealed (see Chapter 3 paragraph 3.8)).

3. PERSPECTIVES FOR FUTURE DEVELOPMENT

The very good results, obtained when testing the control system together with the gas turbine ST40M on the ship, determined the product approval. Following approval, a number of potential customers were interested in the actual installation of the product on certain ships. There are great prospects for contracts to be signed.

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[2] V.Silivestru, Cercetări privind regimurile tranzitorii din motoarele cu reacție, PhD Thesis, Aerospace Faculty, UPB, Bucharest, România, 2001

[3] *** "Rolls-Royce Engines: Tyne - Graces Guide", Gracesguide.Co.Uk, 2019, https://www.gracesguide.co.uk/Rolls-Royce_Engines:_Tyne

ANNEXES

1. PUBLICATION OF THE RESEARCH RESULTS

Contributions to the command and control of a gas turbine for naval applications were disseminated by presenting them at conferences and by publishing them in well-known national and international journals.

1.1 Publications in the field of gas turbine control systems

1. ***F. Niculescu****, C.Vâlcu, C.Borzea*, " Diagnosing of Rotary Blade Machines with the "HolderPPS" system ", published in Turbo Journal Vol. IV Nr.2, Bucharest, Romania, December, 2017
2. ***F. Niculescu****, A.Mitru, A. Săvescu*, " Transmitting data over the network using an OPC server", published in Proceedings of the 22nd International Conference on Circuits, Systems, Communications and Computers (CSCC 2018) Majorca, Spain, July 14-17, 2018
3. ***F. Niculescu****, C.Vâlcu, M.L.Vasile*, " Calculating the power of the electric motor for a single stage turbo blower ", published in Proceedings of the International Symposium on Fundamentals of Electrical Engineering (ISFEE 2018), Bucharest, Romania, November1-3, 2018
4. ***F. Niculescu****, A. Săvescu*, "Aspects Regarding the Control and Regulation of an Industrial Turbine", published in Proceedings of the 11Th International Symposium on Advanced Topics in Electrical Engineering (ATEE2019), Bucharest, Romania, March 28-30, 2019
5. ***F.Niculescu****, M.L.Vasile, C.Nechifor, A.Stoicescu* – "Comparative Analysis between Gas Turbine and Electric Combined Propulsion", published in Proceedings of the Electrical Vehicle International Conference & Show (EV2019)", Bucharest, Romania, October 3-4, 2019
6. *A.Stoicescu, R.Ciobanu, Al.Țăranu, C.Nechifor,* ***F.Niculescu****,* – "Hardware in the loop test platform concept for adaptive turbine engine controller", published in Turbo Journal Vol.VI Nr.2, Bucharest, Romania, December, 2019
7. ***F. Niculescu****, A.Săvescu, M.L.Vasile* – „Adaptive Control for Marine Gas Turbine", published in Proceedings of The 15th International Conference on Development and Application Systems (DAS2020), Suceava, Romania, May 21-23, 2020
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20. *C.Borzea, I.Vlăduca, D.Ionescu, V.Petrescu,* ***F.Niculescu****, C.Nechifor, G.Vătășelu, M.Hanek* **-** " Compressed Air Energy Storage Installation for Renewable Energy Generation ", published in Proceedings of The 8th International Conference on Thermal Equipment, Renewable Energy and Rural Development, Targoviste, Romania, June 6-8, 2019
21. *C.Nechifor, C.Borzea, I.Vlăduca, I.Mălăel,* ***F.Niculescu****,* – "Electrically actuated valves for gas compression installations located in potentially explosive atmospheres", published in Proceedings of The 9th International Symposium on Occupational Health and Safety (SESAM 2019), Petroșani, 3 October, 2019
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2. AWARDS

The Naval Propulsion Group T22-ST40M, which consists of the control system, designed and built by the author of the doctoral thesis, together with a group of specialists of INCDT Comoti, obtained the recognition of the Romanian Engineers Association - AGIR, in the Engineering machine construction section, for the year 2019. The diploma handed on this occasion is attached to the summary.


ASOCIAȚIA GENERALĂ A INGINERILOR DIN ROMÂNIA

PREMIUL AGIR 2019

Secțiunea ***Ingineria construcțiilor de mașini***

Se acordă: ***INCD Turbomotoare – COMOTI***

Pentru lucrarea ***Grup de Propulsie Naval T22-ST40M***

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18 septembrie 2020