"POLITEHNICA" UNIVERSITY of BUCHAREST ELECTRICAL
ENGINEERING DOCTORAL SCHOOL

DOCTORAL THESIS ABSTRACT

INCREASING NUCLEAR SAFETY BY USING MODERN CONSOLES AND SIMULATING THE OPERATION OF ASYNCHRONOUS MOTORS

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Keywords: Nuclear safety, command control system, asynchronous motor, transfer functions

INTRODUCTION

Problem formulation

Technological progress is the engine of any economy and is part of the development strategy that countries are constantly considering. Supporting industry can be done effectively by providing specialized higher education, by investing in academic and industrial research, by promoting research centers and technological innovation parks, and by providing the necessary electricity. From this point of view, of electricity production, it is found that new technologies have allowed the realization of high-performance power plants with low impact on the environment. Nuclear power is considered a green source of electricity and fully benefits from new technologies to increase productivity and operational safety.

Research objectives

The main purpose of the present doctoral thesis is to increase nuclear safety in the context of using existing nuclear installations operating in Romania by introducing state-of-the-art technologies and by continuous research to know and improve the operation of components with an important role for Nuclear Power Plants. One of the objectives of the thesis is to present how applying new technologies in the control and command room of the Triga SSR 14MW reactor can lead to increased operational safety and minimize the risk of accidents in a nuclear power plant. I have analyzed in detail the functions of the basic system as well as the criteria underlying the design of modern control-command consoles, focusing on how the risks of nuclear accidents are reduced [25-28].

Another objective of the doctoral thesis is to study the static and dynamic behavior of the main parameters of asynchronous motors used in nuclear power for pumps that operate the coolant in the primary circuit of power plants. Simulating the operation of electric motors, establishing with the help of computer programs their behavior in the starting phases as well as in the operation in load is the object of many studies, including in Romania [6]. Together, the two main objectives of the thesis are to increase the operational safety of nuclear reactors, increase confidence in the components and technologies used, achieve an intuitive human-machine interface, and ensure the superior quality of one of the most important safety components for nuclear reactors: the pump motors of the primary reactor cooling system.

The structure and content of the thesis

The thesis is structured in 6 chapters, the first chapter *The safety of nuclear power reactors*, the second chapter *The TRIGA SSR 14MW nuclear reactor control command system*, the third chapter *Increasing nuclear safety by introducing new center console architectures*, the fourth chapter *Asynchronous engine analysis, of the pump in the primary circuit, in permanent regime*, fifth chapter *Estimation of asynchronous motor parameters using the square method of the output measurement error (of the transfer function)* and, in the last chapter, the fifth, *the original contributions and general conclusions of the doctoral thesis.* A bibliography used to write the thesis is presented at the end.

In the first chapter I presented the main elements on which the safety of nuclear power reactors depends. The second chapter of the thesis is dedicated to the control-command system of the TRIGA SSR 14MW nuclear reactor. In its beginning, in subchapter 2.1.,the basic functions of the control-command system with a decisive function in the safety of the reactor are exposed in detail. The chapter continues with the presentation of the main design criteria for the control-command system in subchapter 2.2. The basic elements of the control-command system of the TRIGA SSR 14MW reactor are presented in detail in subchapter 2.3. In the first part of it, in subchapter 2.3.1, I listed the nuclear measuring channels : a logarithmic power measurement channel, of wide range, a linear power measurement channel, of wide range, used to accurately measure neutron power, three percentage measurement channels.

The third chapter of the thesis highlights the importance of the new control consoles that the TRIGA SSR 14MW reactor benefit from. Considering the new architecture, nuclear safety is greatly improved, as presented in subchapter 3.1.1., Reactor Protection System (RPS). In the next subchapter, 3.1.2, I focused on the reactor control and monitoring system. At the end of subchapter 3.1, the criteria and design basis of the new protection and control and monitoring systems are presented. The entire subchapter provides the basis for the design and execution of modern command and control consoles for nuclear reactors.

The thesis continues with the fourth chapter, of great importance for nuclear safety, in which I presented a series of simulations of the operation of the asynchronous motor in different regimes. These simulations help to understand the evolution of some electrical parameters and the power generated by the asynchronous motor used for the pumps of the primary circuit of nuclear power plants. The first subchapter 4.1, *Simulation of the asynchronous motor in permanent regime*, is divided into several subchapters that help to understand and estimate the electrical operating parameters. In the introduction of this subchapter, 4.1.1, I explained the role of asynchronous motors in the cooling circuit of nuclear reactors and the computer programs used. Subchapter continues with 4.1.2, in which the mathematical equations that govern the operation of the asynchronous motor and its electrical parameters are exposed.

The fifth chapter entitled *Estimating Asynchronous Motor Parameters* presents a new method for identifying asynchronous motor parameters. based on certain measurements performed on the actual circuit (system). Starting from the equivalent circuit on a phase of an asynchronous motor (analog circuit) in sinusoidal regime, a transfer function (a performance quantity) is generated in complete symbolic (full) form. The amplitude and phase of the complex transfer function can be measured by supplying the system (circuit) with an independent sinusoidal source of voltage or current, of variable frequency.

Numerical simulations performed highlight the importance of knowing the operation of asynchronous motors both in transient mode and permanently in order to maintain nuclear safety at the highest possible values. After a brief *Introduction*, I presented the method of *Transfer functions*, and finally, *Estimating the parameters of an asynchronous motor based on transfer functions.* The fifth chapter ends with the presentation of the conclusions of this chapter.

The last chapter of the doctoral thesis 6 it is entirely dedicated to the original conclusions and contributions from all chapters of the paper.

CHAPTER 1

SAFETY OF NUCLEAR POWER REACTORS

1.1. Analog signals used in control and safety systems - general scheme for a digital processing equipment

The electronic control and safety systems for nuclear installations ensure the detection of danger states and the triggering of emergency stop mechanisms, the activation of additional mechanisms for cooling the installations and the containerization of the reactor, as well as the triggering of alarm systems to evacuate exposed areas.

Most of the analog and digital systems currently in use perform the above functions with sufficient accuracy and operational safety to enable the operation of nuclear power plants and other nuclear installations within the required design limits. However, these electronic systems have operational deficiencies highlighted by low equipment reliability, false trigger and alarm signals, and the need for laborious maintenance. One of the weaknesses of safety and process control systems, implemented in critical nuclear or non-nuclear installations, is their sensitivity in making unjustified emergency shutdown decisions.

Prolonged operation at safety parameters close to the maximum triggering thresholds inevitably leads to temporary data interpretation errors (industrial parasites, software errors) or temporary hardware and software failures (interruption of data or power channels). The statistics made for nuclear installations indicate the occurrence of a high number of unplanned shutdowns, differentiated according to the type of installation and the degree of complexity of the logical decision systems.

The introduction of fully digitized electronic systems based on distributed control and fault-tolerant operating systems largely removes the reported shortcomings. They allow the introduction of modern digital filtering methods permanently adapted to the operating regimes, as well as advanced algorithms for dealing with transient states and emergency situations [6].

A simplified functional diagram for a digital process microcomputer equipment or PLC (Programmable Logic Controller) for control and nuclear safety (figure 1.1) will necessarily contain a digital analog conversion system, central processing unit, analog outputs to the process, digital outputs and connections to an operator console.

The diagram presented in figure 1.1. has a minimum of self-diagnosis functions by the presence of an analog input-output coupled channel and a digital channel that allows the verification of calculation and conversion functions, as well as by the presence of a watch-dog device to monitor the operation of the digital system. All process inputs and outputs are equipped with analog filter circuits and protection circuits.

The software package used has functions of numerical information filtering and fault tolerance both for the measuring lines [9] and for the hardware and software modules of the equipment. Special self-diagnosis and self-organization procedures are implemented to perform the functions of detecting hardware and software errors and maintaining critical functions in special situations. The digital outputs are configured so that they can be used in a redundant structure with several channels in parallel and a “1 in 2”, “2 in 3” or “3 in 5” voting system.

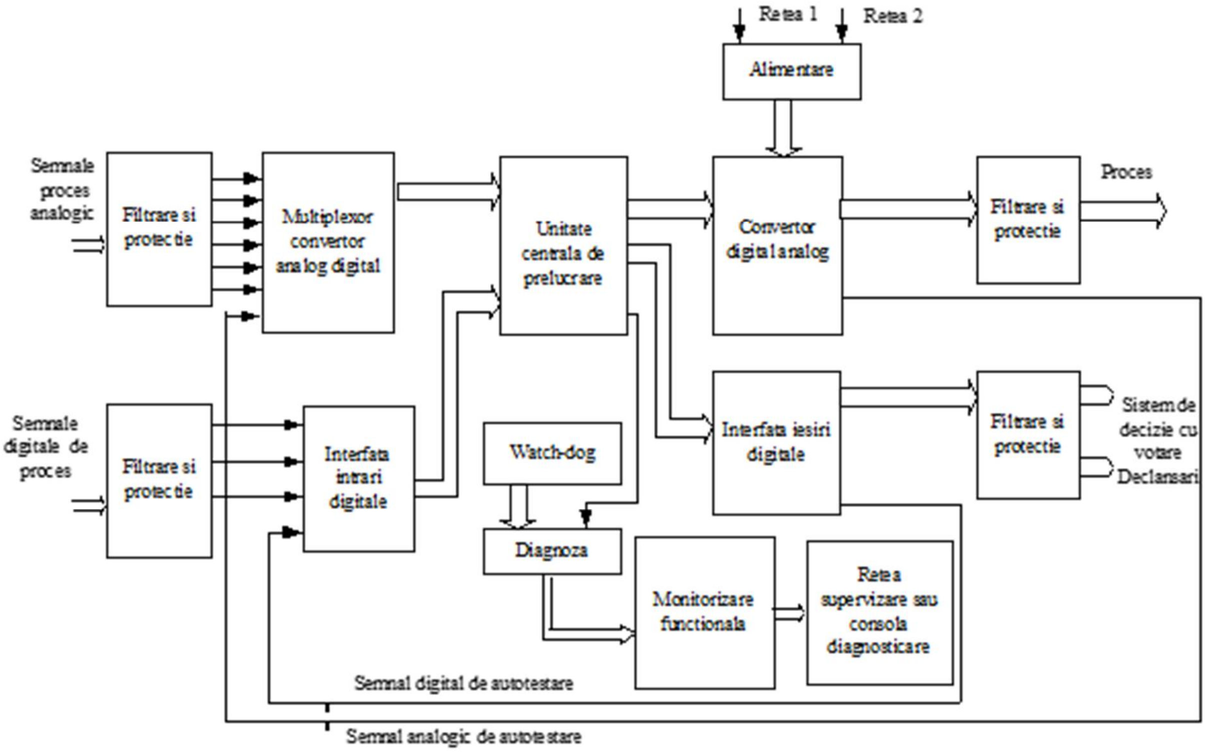


Fig.1.1. General scheme for digital signal processing equipment in nuclear control and safety systems

1.2. Measurement errors of analog signals in control and safety systems

According to their character, there are three categories of measurement errors: systematic errors; random errors and gross errors. Systematic errors have values that can be determined or anticipated and occur due to variations in environmental conditions or equipment aging; these errors can be reduced or eliminated in nuclear installations, by periodic calibration, self-calibration or autozero operations, as well as by the intercomparison and correlation of some measurement channels coupled in parallel with similar functions. Systematic errors are tolerated in nuclear control and safety systems and limits and corrective actions are provided from the design stage. Modern digital systems provide real-time maintenance personnel with estimated values for this type of error and signal that the permissible limits have been exceeded.

Random errors are those that appear randomly having the size and sign difficult to predict; they come from uncontrolled environmental influences, industrial parasites, uncontrolled power supply lines, transient states of installations. Random errors can be reduced by filtering electrical input signals and implementing complex evaluation and decision strategies for control and safety functions. Modern computer systems compile statistics and provide maintenance personnel with data on the occurrence of these events and their probable causes.

Gross errors in signal measurement functions may appear randomly or systematically due to major causes, malfunctions in installations, incorrect interventions during maintenance operations, etc. These errors lead to the total defect of the measured values and can only be eliminated by human intervention or by using fault tolerance techniques in the design of the installations. However, these errors are particularly dangerous and require emergency signaling and sometimes stopping industrial processes to remedy defects and analyze the causes of their occurrence [10].

1.3. Representation methods of signals by decomposition

The Fourier trigonometric decomposition method offers the possibility of decomposing an analog signal into a sum of sinusoids of different frequencies so that, by the superposition method, the output signal can be restored, knowing the response of the system to each component [11] .

Thus any function f L^2 [-1, l] can be represented by a Fourier series which takes the form:

$$f_x = \left(\frac{a_0}{2}\right) \times 1 + \sum_{K=1}^{\infty} \left[\left(a_K \cos\frac{K\pi}{l}\right) x + \left(b_K \sin\frac{K\pi}{l}\right) x\right]_{K \in N} \tag{1.16}$$

where: $\left\{1, \left(\cos\frac{K\pi}{l}\right) x, \left(\sin\frac{K\pi}{l}\right) x\right\}_{K \in N}$

is a family of functions in the space L^2 [-l, l] orthogonal on the interval [-l, l], [43].

Modern digital information processing systems use without exception methods of sampling signals consisting in taking values at set time intervals, converting them and representing them as discrete values in correlation with the time axis. The sampled information may be a sequence of values of the same analog input quantity or ordered sequences of a large number of analog channels to be digitally processed.

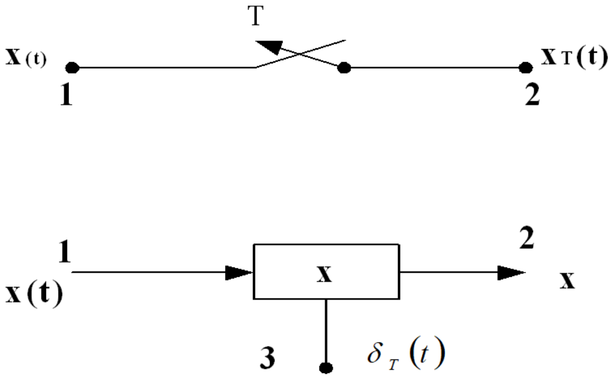
The sampling process is absolutely necessary, as it allows the digital processing of analog input quantities by a single central unit, which executes specific algorithms for each channel, changing the algorithms according to the system status, as well as entering preselected values for self-testing operations. self-assessment of performance.

Modern digital systems for the acquisition and processing of analog information [12] often work at the limit of performance, with signals with characteristics that are difficult to predict, with variable frequency or high evolution speeds.

Sampling systems allow the realization of short-term adaptive structures depending on the input signals, the critical state (Criticality - state of a self-sustaining nuclear chain reaction), as well as the momentary requirements of the operators. Thus keeping the condition in relation (1.25) the sampling interval T can be variable.

$T = T_{Ai},$ where T_A is the value resulting from running the adaptation algorithm, and i is the corresponding channel, i = (1,2 ... K) for which the adaptation is performed. The T_{Ai} will be very low for rapidly evolving or safety-bound channels i. The T_{Ai} will be high for slowly evolving or channels evolving away from safety limits. For the processing of the sampled analog signals X (t) the Z transform method is used as follows:

- sampling of an analog signal can be performed by means of a controlled switch (figure 1.2, a), or by means of a multiplication circuit (figure 1.2, b).



a - cu întrerupător comandat

b - cu circuit de înmulțire

FIG. 1.2 - Methods for sampling an analog signal

1.4. Disruptions and errors specific to the nuclear field

In the nuclear field errors induced by radiation transducers,cables and primary amplification and conversion floors are of interest. Specific to the nuclear field is the use of radiation transducers such as ionization chambers, collectons, photoluminescent detectors and photomultipliers that work with very low electric charges or currents of the order of $10^{-14} \div 10^{-4}$ Amperes.

Very small current measurements in the industrial environment are susceptible to a large number of sources of errors which can lead to unacceptable disturbances in the operation of nuclear installations. The main sources of error in transducers, cables and primary amplification stages are:

- electromagnetic induction of parasitic signals in transducers and measuring lines;
- leakage currents on insulators and cables; these currents of the order of $10^{-14} \div 10^{-6}$ Amperes occur due to the limited insulation resistance of materials, impurities and moisture deposited in their structure or surface, but also to the phenomena of physical aging;
- disturbing signals on ground and ground lines but also on signal lines due to poor connections and improper shielding;
- the noise impedance of the detector and the first amplification stage [6] which is usually a load amplifier or a current-voltage converter with very high impedance, (figure 1.7).

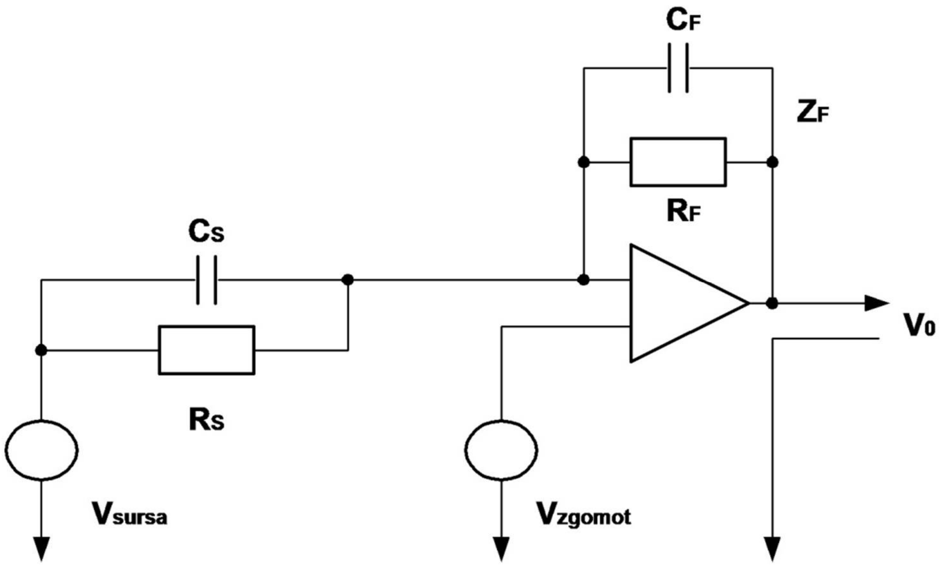


FIG. 1.7 - Primary step of conversion amplification - equivalent noise scheme

1.5. Conclusions

The safety of nuclear power reactors is one of the most important objectives to be considered for the operation of a nuclear power plant. This fact is highlighted by the concerns of specialists since the design phase of a plant, continued in the choise of necessary technologies for the actual achievement of the nuclear objective, the use of the best materials and construction methods, as well as the equipment "state of the art ”(latest generation) used for the control and safety of the reactor.

All these considerations were presented in Chapter 1 together with general problems related to the processing of process signals and their digital processing methods in order to improve the stability and safety characteristics in the operation of the installations. Another direction approached to increase the safety of the installation is the study of the reliability of the safety systems and of the methods of improvement through redundancy, fault tolerance, self-testing and self-configuration. I have highlighted the term of reliability and safety of automatic emergency stop decisions used in nuclear safety systems [14].

The adoption of appropriate system solutions, with proven reliability, the implementation of redundant schemes, fault-tolerant systems with self-assessment and reconfiguration can lead to a substantial increase in functional safety (safety of decisions), as well as a decrease in the volume of maintenance activities.

CHAPTER 2

TRIGA SSR 14MW NUCLEAR REACTOR CONTROL SYSTEM

2.1 Functions of the control-command system

The control-command system of a nuclear reactor must ensure its proper functioning under two main aspects : the first regarding the *operation*, is to allow the reactor to be brought into operation and at the parameters desired by the operator, and the second regarding the *safety* of the reactor and related installations, is to ensure proper operation without exceeding the limits and technical operating conditions imposed by the final safety report.

These two aspects seem to be the exclusive competence of the reactor console that allows the operator both to have information on the values of the operating parameters of the reactor, and the possibility to act in order to correct these values, through control rods, and in the event of a situation that may lead to exceeding the limits and technical conditions of operation, the console is also the one that causes the emergency shutdown of the reactor by triggering the control rods (release of control rods from electromagnets that support them extracted from the active area and their descent by free fall - *scram*).

If in the first case, the operation of the reactor itself is really carried out mainly through the console, in the second case, the safety of the reactor is determined both by the parameters in the active area and its proximity, which are monitored by the instrumentation contained in the console as well as the operating parameters of the installations connected to the reactor,in particular the cooling system of the active zone and the irradiation devices existing in the active zone. Each of these separate control-command systems can cause the reactor to stop by *scram* when the operating limits are exceeded, through the external *scram* chain to which they are coupled [15].

2.2 Design criteria and bases for the control-command system

The parameters that are directly monitored by the control-command system are:

- *neutron power* (neutron flux), measured using 4 fission chambers placed in the 4 corners of the active zone;
- *fuel temperature*, measured by means of thermocouples existing in the instrumented fuel elements;
- *control bar positions*.

The control - command system of the TRIGA SSR 14MW reactor is contained by an operating console. The dimensions of the console allow its positioning so that the operator can observe both the experiment area (reactor hall) and the instrumentation. The electronic modules and relays are contained in sliding drawers or on the back of the doors behind the console giving the possibility of access the equipment for various maintenance or adjustment actions. Measuring and indicating devices, push buttons and recorders are positioned to ensure optimal readability and accessibility. A 10-inch two-pen recorder is used to display linear and logarithmic power values across the entire working range. When designing the console it was taken into account to display and announce only the variables and conditions important for safety and necessary for safe operation [16].

2.3. Control-command system circuits

2.3.1. Nuclear measuring channels

Nuclear measurement channels consist of:

- a logarithmic, wide-range power measurement channel,
- a wide-range linear power measuring channel used to accurately measure neutron power,
- three percentage measurement channels.

For neutron power measurement there are two wide range measurement channels (loops) (one logarithmic and the other linear) that display the power value on a two-way recorder, one logarithmic and the other linear, located on the front panel of the control panel. The linear channel on the recorder measures the power of the reactor as a percentage of the maximum limit of the selected power range. The division of the maximum range, of 30 MW, in the subdomains is imposed by the need to rigorously control the reactor power, starting even from its very low values, from the moment of reaching the criticality.

The signal of the logarithmic power channel, schematically represented in figure 2.1, is also used on the one hand to establish the minimum counting rate (minimum flow) that allows the actuation of the control rods at start-up and on the other hand to determine the reactor period, which is indicated on the left panel of the desk, on an analog instrument with a non - linear scale, graduated from - 30 sec to + 3 seconds. The minimum period threshold (3 seconds) that determines the reactor *scram* is also provided on the reactor period measurement channel [17].

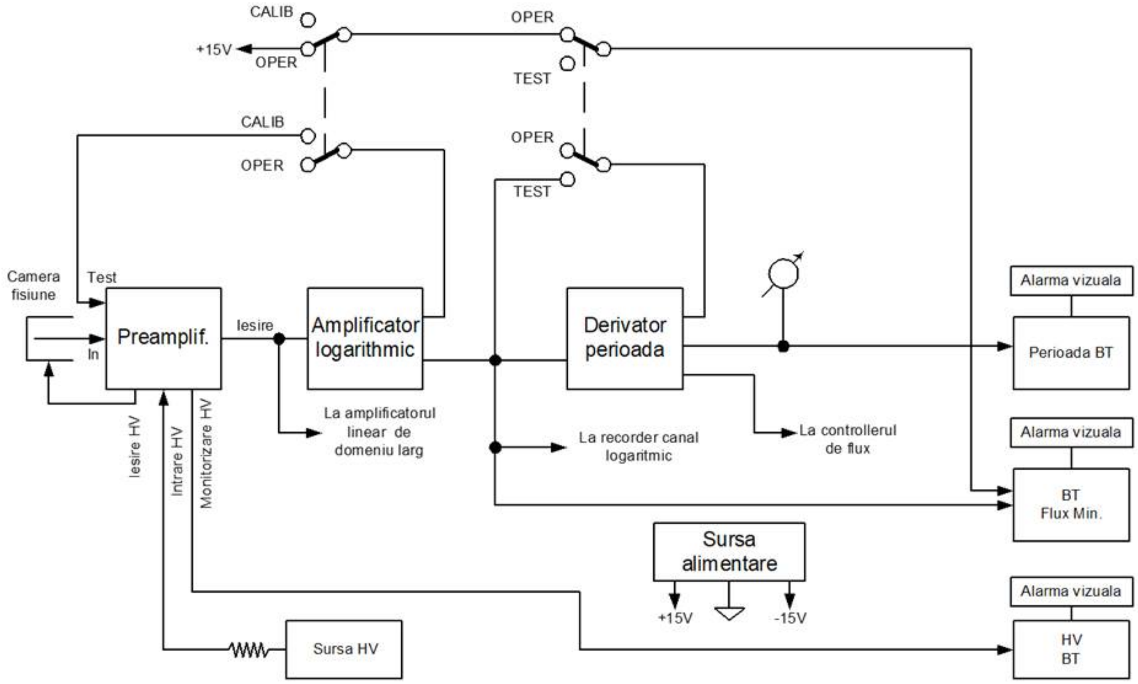


Fig 2.1. Wide range power logarithmic channel,

The wide range power logarithmic channel uses Campbell's counting methods or statistical techniques to accurately read power over 10 decades. The output signal of this channel is displayed on the recorder by one of its pens.

The period signal is derived from the logarithmic power signal, displayed and used as a input for *scram* in the circuit containing the safety logic. A tripping flip-flop, driven by the wide range channel output, provides the interlock signal that prevents the control rod (s) from being removed from the active area if the measured neutron flux is below a certain preset value.

The linear power measurement channel uses the signal from the logarithmic power measurement channel preamplifier. This channel uses Campbell's counting techniques and operates for 10 decades. I thus obtain a measurement accuracy between ± 1.5% and ± 2.5% over the 19 decades. The good accuracy and lack of sensitivity to the presence of the gamma background led to the adoption of this solution instead of using the method with compensated ionization chamber and picoameter.

2.3.2. Non-nuclear measurement channels

The measurement of the temperature in the fuel is performed through three identical measuring channels, represented schematically in figure 2.4, each receiving the signal from the thermocouples located in the instrumented fuel elements, by means of a switch that allows each channel to monitor two thermocouples. The measured temperature value is displayed on three analog indicator instruments (one located on the left panel and the other two on the right panel of the control panel).

Achieving safe operation of the reactor from the point of view of nuclear safety means complying with the technical limits and operating conditions imposed by the final safety report, limits and conditions which are annexed to the operating authorization issued by the regulatory body. The values of these limits are set in such a way as to actually ensure the integrity of the fuel element, so that it retains fission products inside it.

Among these limits, the fuel temperature is in fact of paramount importance, because in case of exceeding it the integrity of the fuel element can no longer be guaranteed, the limits imposed on the other parameters being in fact subordinated to this purpose.

Therefore, in the safety function, the three channels for measuring the temperature in the fuel are introduced by logic 1 of 3, if any of the 3 measured temperatures would exceed the switching threshold of the bistable tilting circuit associated with the channel, determines the triggering of the control rods - scram reactor [17].

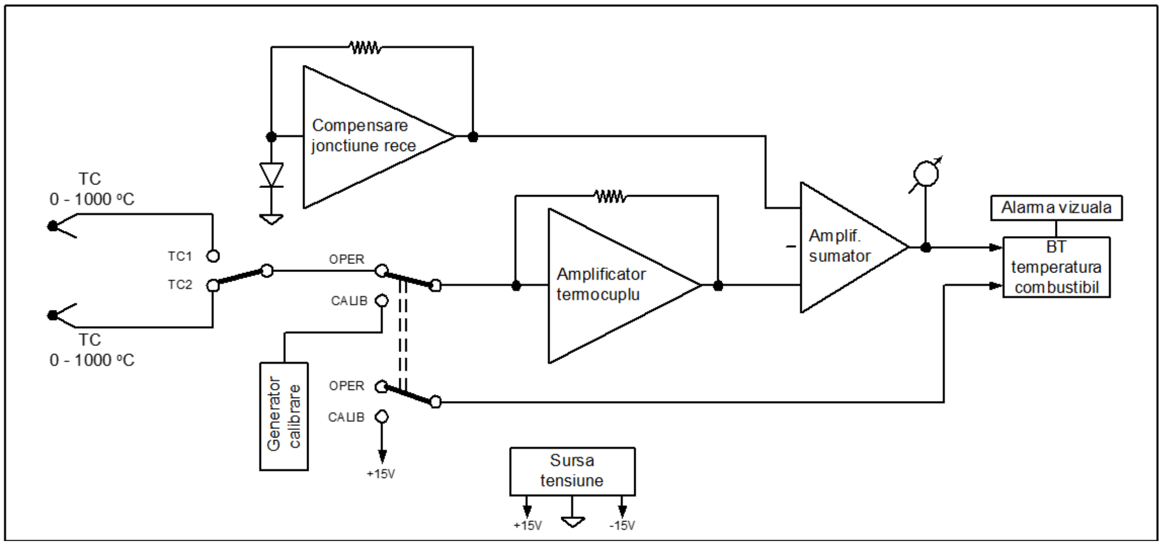


Fig 2.4. Fuel temperature measurement channel

2.3.3 Automatic operation

The TRIGA SSR 14MW reactor can be operated in automatic mode: the instrumentation, interlocking and safety circuits described below operate (operate) only in automatic mode. In automatic mode, the control rod used for adjustment is automatically controlled by a servo amplifier that tracks power and period signals. The power of the reactor is compared to the power required at predefined time intervals. The value of the required power is fixed by means of a switch, whose position fixes the power range and a potentiometer, whose position determines the value (in percentages) of the required power, within the fixed power range. The period control signal that is applied to a servo amplifier makes it possible to change the power at regular intervals in order to automatically maintain the required power over long reactor operating intervals.

Maintaining the reactor power at a constant value is performed by the flow controller. The flow controller can work in two ways:

- automatic mode,
- gradually.

In automatic mode, the flow controller is a classic closed-loop control system. The control rod used for adjustment is moved to keep the reactor power at a constant value; the change of the power value is made at equal time intervals. The input circuit of the power control system (see figure 2.7) compares the current value with the required value of the reactor power. The power signal (in the range 0 - 10V), provided by a picoameter, is proportional to the value of the reactor power, selected from the REACTOR POWER switch on the operating console [16].

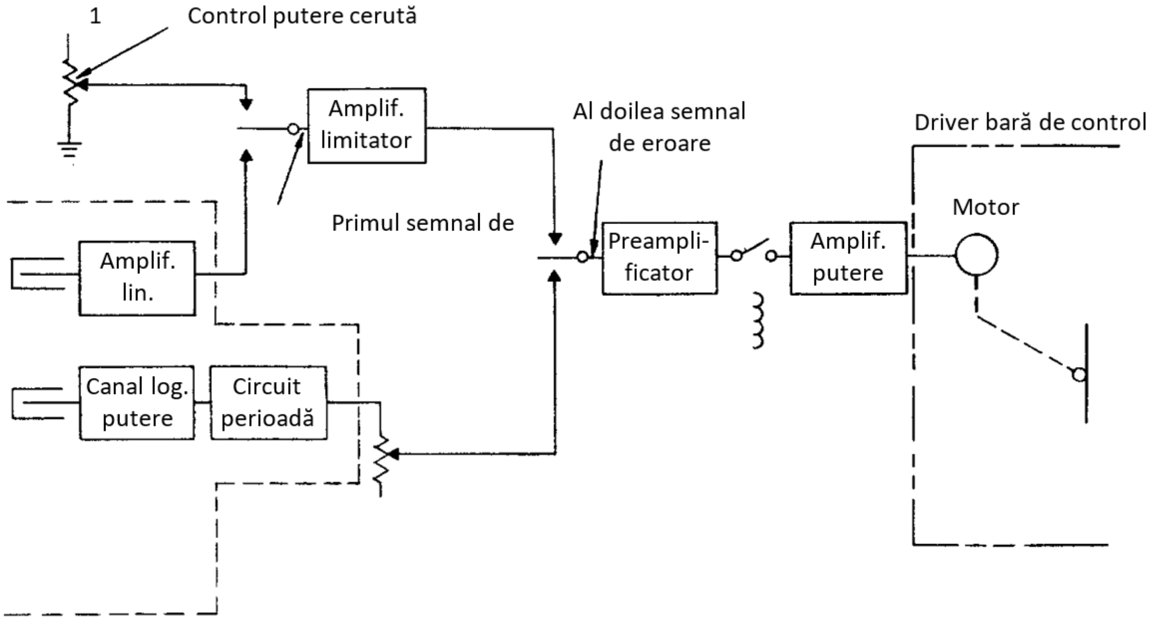


FIG. 2.7. Power control system input circuit

2.4. Conclusions

The TRIGA SSR 14 MW reactor control system allows the safe conduct of research activities using the neutron flux generated by the reactor. Following the conducted study I drew the following conclusions:

- The functions of the reactor control console allow the realization of the two purposes for which it was designed: operation of the reactor and ensuring nuclear safety;
- The control command system ensures the monitoring of the three important parameters for nuclear safety: neutron power (neutron flux), measured with 4 fission chambers placed in the 4 corners of the active area, fuel temperature, measured with thermocouples in the instrumented fuels elements and control rod positions;
- The circuits of the control command system include both nuclear and non-nuclear channels that provide the necessary information for operational safety;
- The automatic operation of the reactor is a high safety facility that allows its safe operation by permanent analysis of the power of the reactor with preset values.

CHAPTER 3

INCREASING NUCLEAR SAFETY THROUGH THE INTRODUCTION OF NEW ARCHITECTURE ON THE CENTRAL CONSOLE

3.1 Functions of the new protection, control and monitoring systems

3.1.1. Reactor Protection System (RPS)

The role of the reactor protection system is to detect deviations from the normal operating conditions of the plant and to initiate actions to maintain nuclear safety. The system is also responsible for initiating the signals that trigger the scram action in case of anticipated operating events, conditions or basic project accidents.

The protection system contains all redundant electrical equipment and circuits involved in generating signals to initiate the protection function. The protection function initiated by the protection system is the action of scram (falling control rods). The protection system also manages the interlocks and system configurations required to operate the reactor in different modes. Interlocks appear in:

- Reactor operating modes;
- Domain of work of nuclear channels;
- Activation of the neutron flux increase period signal;
- Reactivity control system management.

The protection system consists of:

- Sensors;
- Transmit;
- tripod bistables;
- voting and protection modules (V&PL);
- Final trigger logic (FAL).

Once a scramble action is initiated, it will run until completion, without the possibility of bypassing. Return to operation requires deliberate action by the reactor operator [20].

3.1.2. Control and Monitoring System - CMS (Control and Monitoring System)

The control and monitoring system, classified as a class 2 nuclear system, offers the reactor operator the possibility to control the flow in the active area of the reactor with the help of control rods and nuclear channels and to monitor the process variables. This system contains an autopilot, used to keep the reactor power level at a constant value. Also, the control and monitoring system participates in the implementation of interlocks:

- Prohibition of individual extraction of control rods (RWP - Rod Withdrawal Prohibition)
- Prohibition of withdrawal of control rods in bank (BWP - Bank Withdrawal Prohibition).

Alarms related to the signals acquired by this system can be triggered, validated and stored.

The main functions of the control and monitoring system are:

- Acquisition of data from nuclear instrumentation in the field of measurement;
- Alarm management and display;

- Storing data in electronic archives (process variables, recorded alarms, events occurring in operation), displaying operational history;
- Generation of operating reports;
- Supervision of the parameters related to the reactor pool;
- Automatic control of reactor power;
- Operation of the reactivity control system;
- Communication with the control and monitoring system of the primary circuit;
- Self-diagnosis and display of its own operating status;
- Access control to the operating console and to change its own operating parameters [21].

3.1.3. Criteria and bases for the design of new protection and control and monitoring systems

From a design point of view, the reactor protection system (RPS):

- contains only hardware components,
- is a class 1 nuclear safety system,
- contains modules that meet the criteria of safe failure,
- provides conservative margins.

In order to meet and maintain the security requirements for systems and components, the protection system shall comply with the criteria of:

Redundancy: the protection system contains redundant components, starting with neutron flux detectors (fission chambers) and ending with the final trigger logic.

Tolerance to single failures: a failure does not result in the loss of the system's ability to perform nuclear safety functions.

Independence: each of the redundancies can perform the required functions and is not affected by the operation or failure of equipment that is not part of its composition.

Functional isolation: interactions between system redundancies that could occur in normal operation or when a fault occurs in any of the system components will be avoided. Such interactions can be caused by electromagnetic inductions, electrostatic discharges, short circuits, open circuits or grounding problems [22].

3.2. Description of the new protection, control and monitoring systems

Most system components are in the control room and are accessible even during reactor operation. All system components can be functionally tested. The architecture of the protection system is modular in order to increase the reliability and availability, to reduce the periods allocated to repairs.

The three nuclear channels have the possibility of self-testing by means of a test current generating module. This generator provides a current signal for simulation, a signal that can have a fixed (predefined) or variable (period) value. If one of the nuclear channels is switched to "test" mode, the protection system triggers a scram signal internally. An indicator called a "Defective nuclear channel" signals to the operator that the channel measurement module is in "test" mode, or that the fission chamber source is not properly supplying a power signal. This signal requires scram in logic 2 of 3.

Temperature measuring channels have the possibility of self-testing by means of a temperature generating module. If one of the temperature channels switches to "test" mode, the protection system triggers a scram signal internally.

The reactor protection system is qualified seismically according to the local seismic values, similar to the CANDU reactor [24].

3.3. Operation of the control and monitoring system (CMS)

3.3.1. General considerations

CMS (Control and Monitoring System) is implemented in an industrial platform Step7 (Siemens) that can manage any distributed application, from the simplest to the most complex systems that can contain multiple data servers, supervisory units, PLC or controllers and I / O units.

Typical applications include hardware and software for process control, field-mounted sensors, human-machine interface and actuators. The application receives signals from the field or indirectly, through intermediate systems and equipment, displays operator information and triggers actions following commands given by the operator or based on procedures programmed at different levels of the system.

Figure 3.9 shows a typical architecture of such a system, defined hierarchically of three levels. Each level has a specific function, Data acquisition and actuation for the field level, Control logic for the control level, Man-machine interface and historical registers for the supervision level.

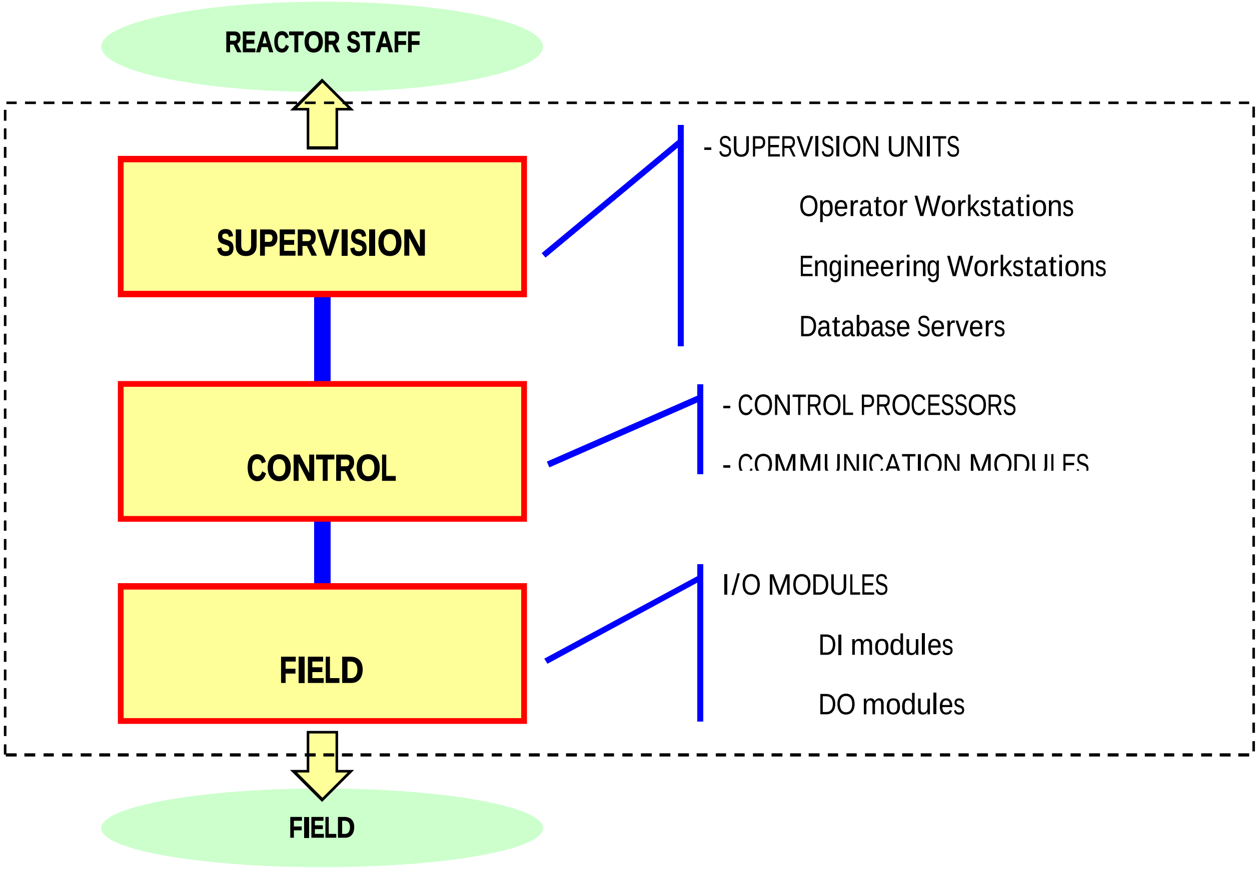


FIG. 3.9. Generic architecture

3.4. Intercomparison analysis and evaluation of systems safety

From a safety point of view, the new reactor protection system implements the recommendations contained in IAEA document SS35-S1, “Code on Safety of Nuclear Research Reactors: Design”. The reactor protection system must be automatic and independent of other systems. This system must contain an input signal for manually shutting down the reactor

The reactor protection system must be so designed that, once initiated, the necessary safety actions can no longer be canceled by manual actions. Where physically possible, the redundancy and diversity criteria must be applied when designing the reactor protection system so that each required event can be detected in at least two different ways.

The reactor protection system must contain at least two completely physically separate and functionally independent channels so that single faults do not lead to the loss of the safety function by the system. The reactor protection system must be designed in such a way that the occurrence of a common mode fault to end with getting the reactor in a safety state.

All system components must be testable. Once initiated by the protection system, the actions will be completed until completion. There should not be possibile to self-reset them.

The design of the system must ensure that trigger thresholds can be set with a safety margin over the operating limits so that the system can control the process before the operating limits and conditions are reached.

In addition, these margins must take into account:

- instrumentation errors,
- calibration uncertainties,
- response time of the instrumentation and the system.

By design, means and solutions are implemented to prevent the bypass of tripping or interlocking signals. ” Therefore, the protection and control and monitoring systems provided by INVAP are electrically, functionally and physically independent. The signals of the protection system are transmitted to the monitoring system through galvanic isolators; the protection system receives from the control system only a signal to check the functionality of the latter, but also by means of a galvanic isolator. Figure 3.14 briefly illustrates this separation.

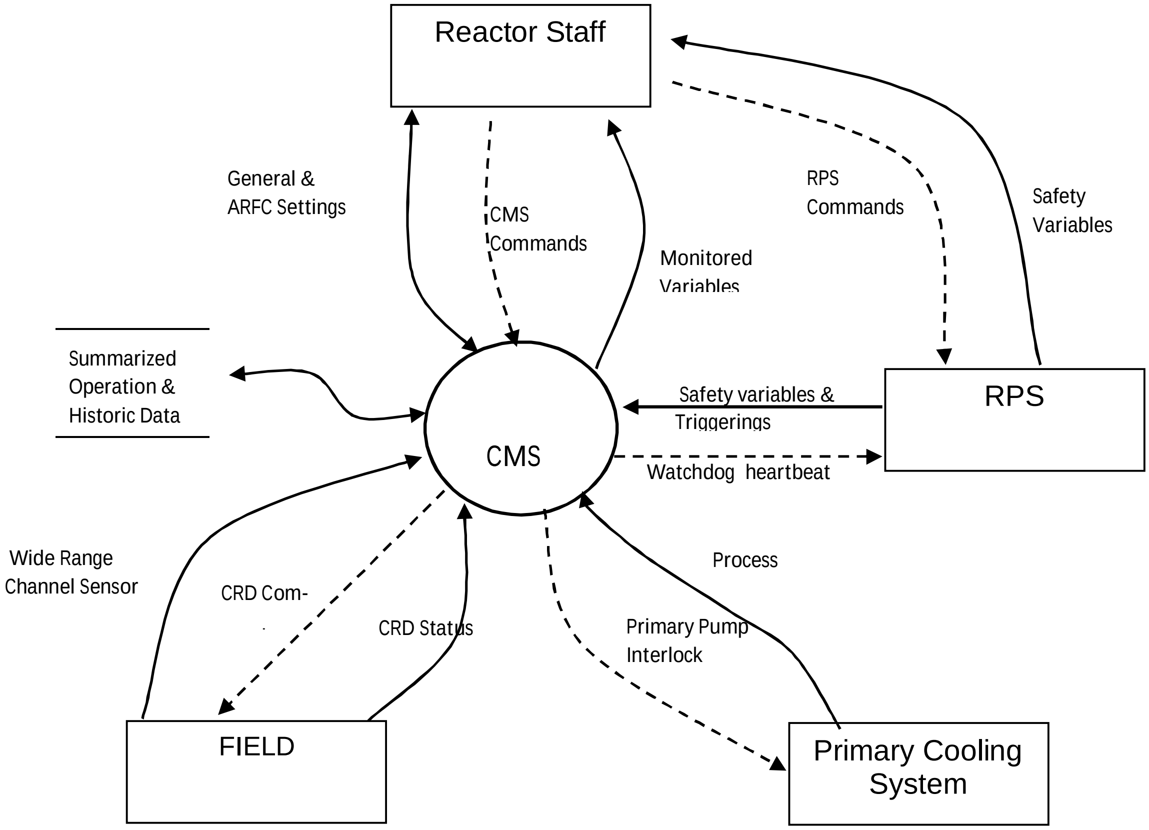


FIG. 3.14. Physical and functional separation between protection and control and monitoring systems

The reactor protection system contains two (redundant) modules that perform the protection and voting logic (V&PL 1 and V&PL 2), connected to a module that performs the final trigger logic (FAL). Therefore, the voting logic of the FAL module is 1 in 2.

The safety (redundant) signals from the field are connected to the two V&PL modules, and the signals with implications for nuclear safety (non-redundant) are multiplied by relays and connected directly to the FAL.

The first category of signals includes:

- Nuclear signals: 3 nuclear channels,
- Fuel temperature signals: 6 temperature signals (3 fuel elements, 2 measuring channels on each element),
- Coolant flow in the primary circuit: 2 measuring channels,
- Emergency pump coolant flow: 2 measuring channels,
- Water level in the reactor pool: 2 measuring channels,
- manual SCRAM: pushbutton on the console and pushbutton on the bridge in the reactor hall,
- Reactor status selector (Shutdown / Operation),
- Reactor operating mode selector (Natural Convection / Low Power / High Power).

The second category of signals includes:

- Control and monitoring system unavailable,
- Short period in the wide domain channel (WRC),

- Signals from experimental devices (4 signals),
- Signals from the seismicity monitor,
- Signals from the gaseous effluent monitor,
- External SCRAM signals from the primary circuit.

The final triggering logic, performs the final voting of the signals from the reactor protection system and acts directly on the electromagnets of the control rods. Although the scram logic remained unchanged, its implementation separately from the reactor control system leads to increased nuclear safety and reactor availability.

The final voting logic is "1 in 2": each signal in the reactor protection system is connected to one of the independent redundancies in the final trigger logic. In the case of signals with implications for nuclear safety (non-redundant), each of them is multiplied in the area of the auxiliary circuits by means of safety relays.

3.5. Comparative analysis of the performance of non-nuclear, redundant measurement channels

The non-nuclear measuring channels of the reactor are the channels for measuring the temperature in the fuel. Achieving safe operation of the reactor from the point of view of nuclear safety means complying with the technical limits and operating conditions imposed by the final safety report, limits and conditions which are annexed to the operating authorization issued by the regulatory body. The values of these limits are set in such a way as to actually ensure the integrity of the fuel element, so that it retains fission products inside it.

Among these limits, the temperature in the fuel is in fact of prime importance, because in case of exceeding it the integrity of the fuel element can no longer be guaranteed, the limits imposed on the other parameters being in fact subordinated to this purpose.

In the current operating console, the three channels for measuring the temperature in the fuel are introduced by logic 1 of 3, if any of the 3 measured temperatures exceeds the switching threshold of the flip-flop associated with the channel, would trigger the control rods In reality, there are six temperature signals from six thermocouples mounted on six fuel elements. A switch selects three measurement channels from the six.

The new protection system provided by INVAP introduces a logic 1 out of 6 for fuel temperature measurement channels. The six signals come from two thermocouples, mounted on the same fuel element. In this way I obtained a double redundancy on each line of temperature measurement, which has as consequences:

- compliance with the IAEA recommendations on increasing the degree of nuclear safety in operation,
- increasing the reliability and availability of the reactor.

In the current console, the measured temperature value is displayed on three analog indicator instruments (one located on the left panel and the other two on the right panel of the control panel). On the console provided by INVAP, the value of the measured temperatures is displayed on:

- six digital indicators mounted on the left vertical panel of the console,
- center console monitor.

The display mode and the fact that the indications are placed in the same area make it easier for the operator to read the temperature values. On both consoles, each temperature measurement channel has the possibility of testing. When selecting the "test" mode, a signal simulator provides predefined values for testing the transmitter and comparator. When the measuring channel is in test mode or when the temperature transmitter detects the disconnection of its thermocouple, the protection system provides a scram signal.

The difference occurs in case of failure of a thermocouple: in the current console, the replacement of a defective thermocouple is more difficult to achieve; in the new console, the replacement of a thermocouple involves only connecting the wires in a series of clamps located on the front panels of the cabinets containing the reactor protection system. [31]

3.6. Architecture of new reactor protection and control and monitoring systems

The new systems provided by INVAP are completely physically and functionally independent. Figure 3.15 shows the arrangement of the indicating devices and equipment of the new operating console displays.

FIG. 3.15. The new TRIGA SSR 14MW operating console

Figure 3.16 shows in detail the location of the equipment in the three cabinets of the reactor protection system. It can be seen that, for security reasons, the redundancies of a measuring channel are placed in separate cabinets. [31]

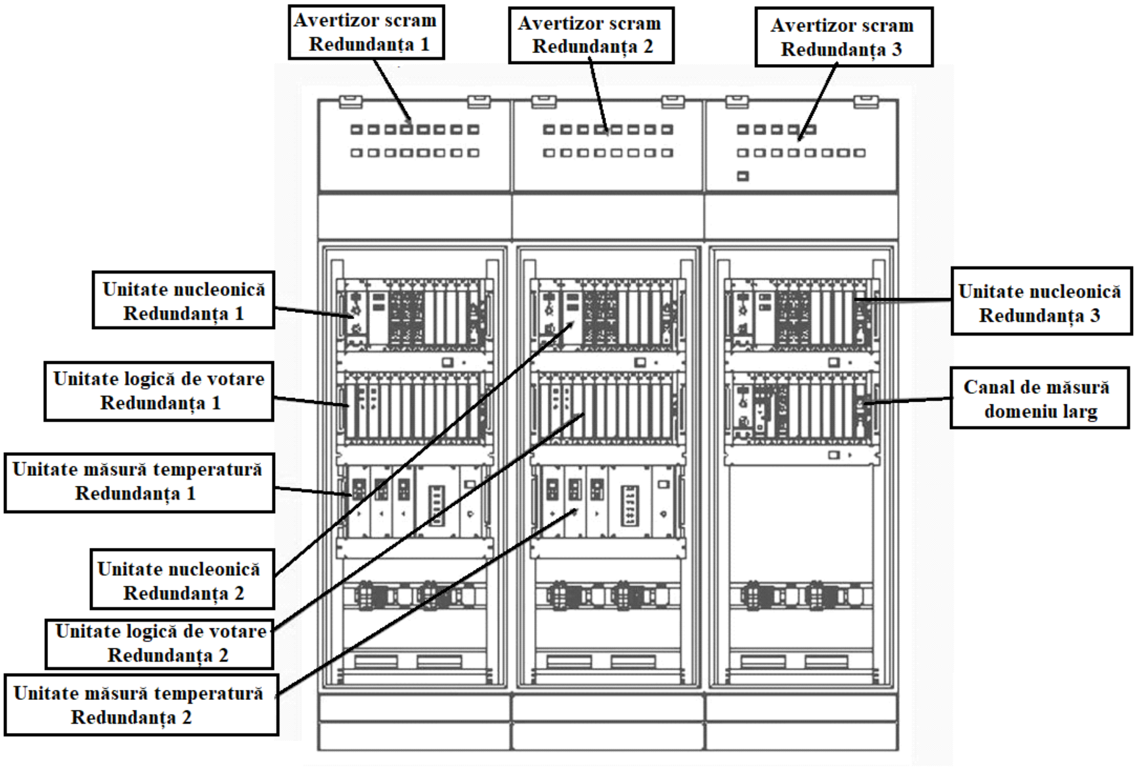


FIG.3.16. Location of equipment reactor protection system cabinets

Figure 3.18 shows the home page which displays general information on the operation of the reactor and its condition.

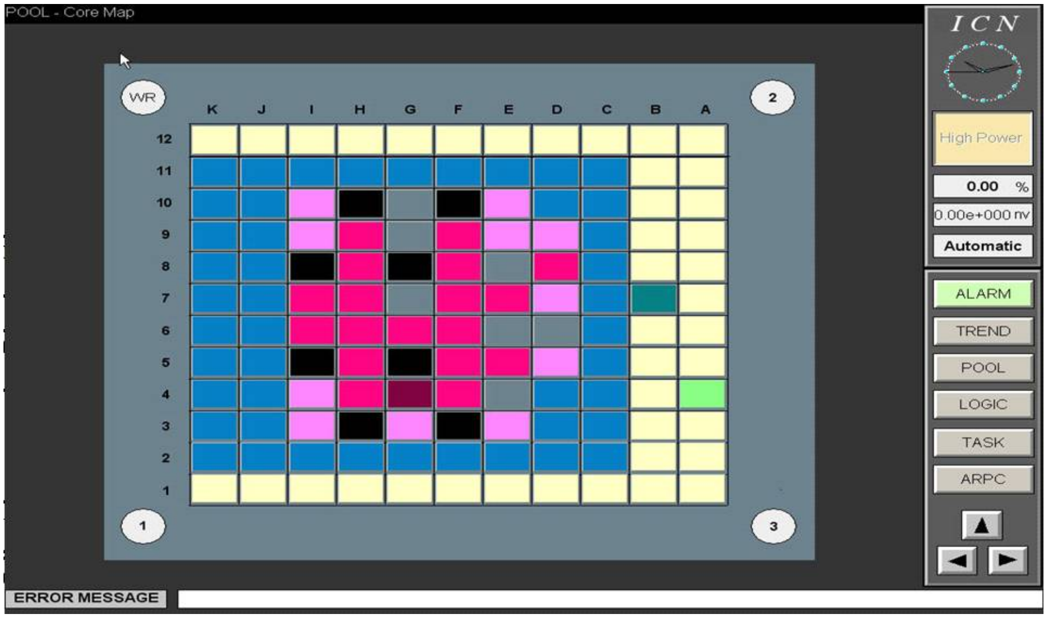


FIG. 3.18. Start page

The reactivity of the reactor appears in a window similar to the one shown in figure 3.19.

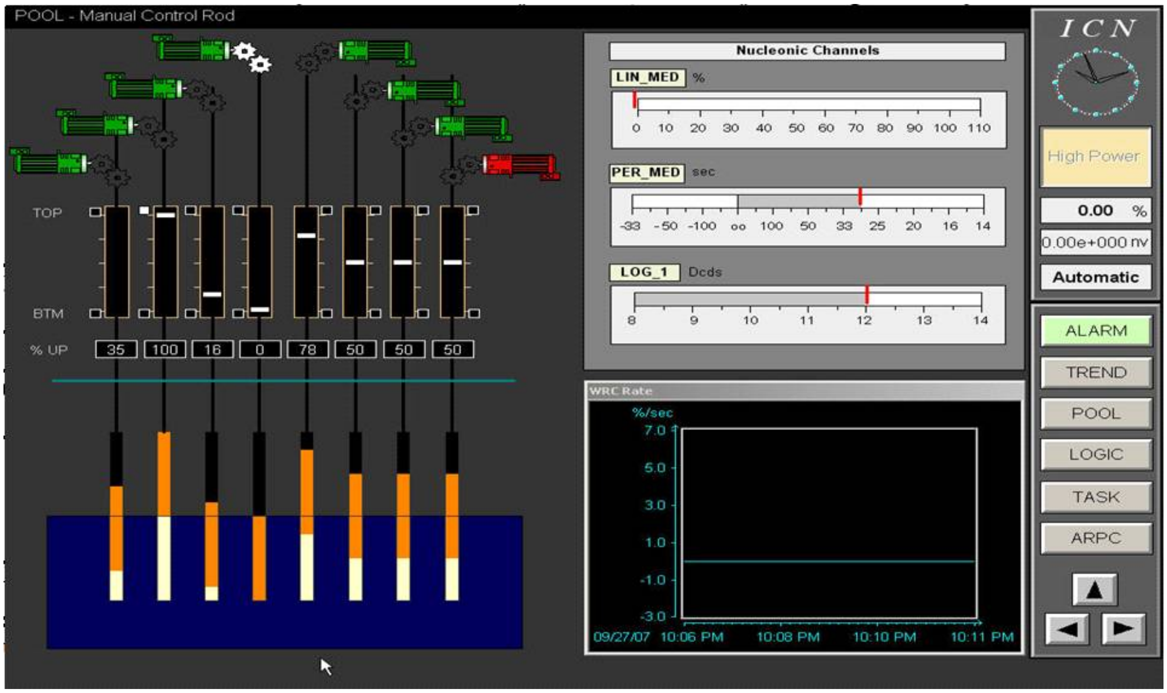
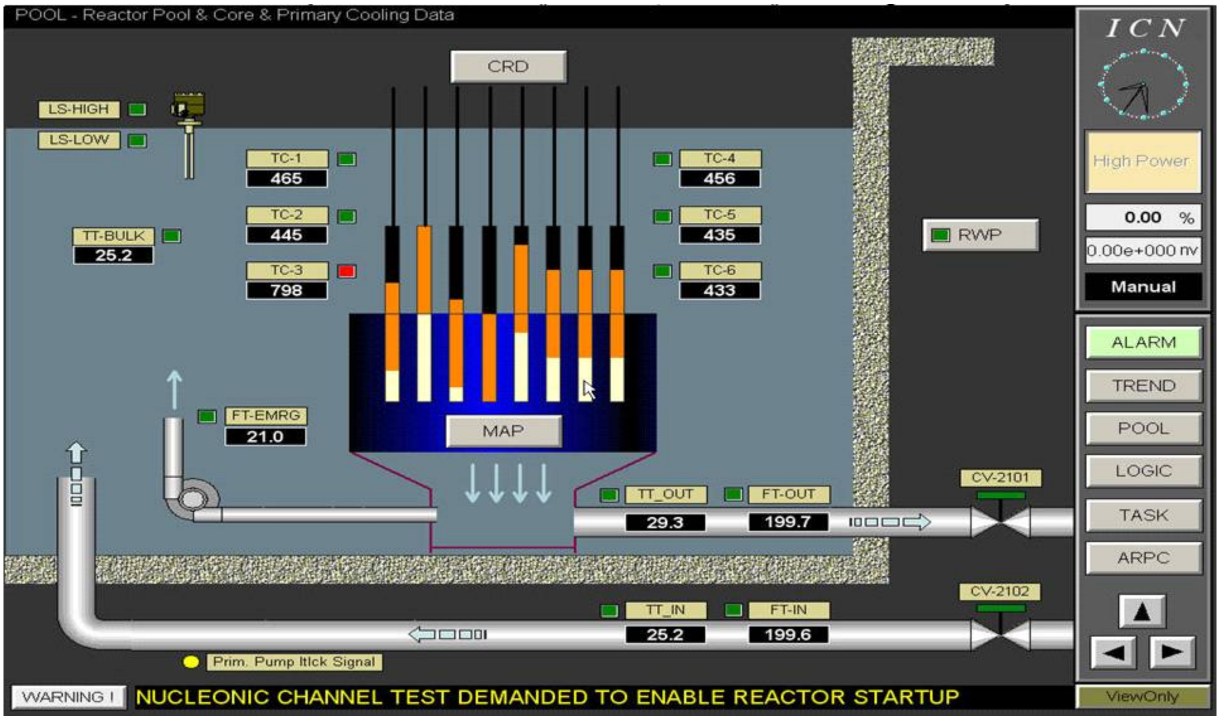


FIG. 3.19. Reactivity Control System Status Display Page

The configuration of the active area is very well represented in the window shown in figure 3.20, having also displayed the temperatures, including a very high one, of 798°C, well signaled by the assigned red color. [31]



WARNING ! NUCLEONIC CHANNEL TEST DEMANDED TO ENABLE REACTOR STARTUP

FIG. 3.20. The display page of the current configuration of the active area

3.7. Conclusions on the role and benefits of the reactor protection system

The main roles of the new reactor protection system (RPS) are:

- Takes the necessary protective measures in order to stop the operation of the reactor, to calm and store the radioactive materials and to minimize the consequences of a nuclear accident;
- Controls interlocks in order to ensure protection against erroneous operations, when the conditions necessary for safe operation have not been met;
- Keeps the reactor parameters within the limits allowed for operation, without reaching the safety limits;
- It provides and displays to the reactor operator sufficient information for the rapid determination of the state of the protection system (self-diagnosis), in order to make the correct decisions with implications for nuclear safety.

The design of the reactor protection system was aimed at:

- Obtaining a high reliability;
- Minimization of personnel exposure during reactor operation;
- Rigorous classification of systems in terms of nuclear safety;
- The single failure criterion;
- Minimizing the possibility of common defects by physical separation, functional independence and diversity of equipment used;
- The use of certified technologies, experience and tests and the introduction of security margins;
- Implementation of intrinsic and engineering nuclear safety functions;
- Application of design concepts to obtain safe failure states.

CHAPTER 4

ANALYSIS OF THE ASYNCHRONOUS MOTOR OF THE PRIMARY CIRCUIT PUMP, IN PERMANENT REGIME

4.1. Introduction

The components of a nuclear installation are subjected to several stages of verification of functionality, some of them from the design phase. Thus, the simulations of the operation of the installations with the help of computers and specialized programs are an important part of the design work, necessary to reach the quality standards in the nuclear field. Because the nuclear accident scenario in which the coolant was lost, LOCA (Loss Of Coolant Accident), is very serious, there is a risk of melting the reactor core, the operation of the pumps in the cooling circuits is simulated and intensively researched.

The asynchronous motor is used for the primary circuit pumps and the analysis of these simulations in permanent regime can be performed by the following methods:

- Using equations of state in which derivatives with respect to time are canceled out except for the equation of motion. Integrate the equation of state corresponding to the equation of motion over a period of time (until the permanent mode is obtained);
- The equivalent circuit on a sinusoidal phase is analyzed completely symbolically. In this way the characteristic dimensions of the motor (currents, voltages, electromagnetic torque, Joule losses, mechanical power, power factor, etc.) can be obtained depending on all motor parameters R_s, L_s, R'_r, L'_r, Lm, $R_{Fe} = R_w$ and sliding s. This analysis is performed with the program ASINOM - Symbolic Analysis with Modified Nodal method [32];
- Analyzing in transient mode the equivalent circuit corresponding to the induction motor using the equations of state or the nodal equations modified in dynamic regime (semi-state equations), in which the resistor R'r / s is considered as a parametric circuit element (time variable) until the permanent regime is obtained - the brute force method [32-34].

In all three procedures two cases can be considered:

- Constant rotor parameters in relation to the frequency of rotor currents;
- Rotor parameters variable with the frequency of rotor currents, due to the skin effect.

The two cases can also be studied when considering the effect of magnetic saturation by considering nonlinear magnetization characteristics.

4.2. The equations of state of the induction motor in permanent sinusoidal regime

The equations in permanent sinusoidal regime are obtained from the state equations in which the first order derivatives are canceled in relation to time, the mechanical pulsation ω at the rotor axis is kept as an independent variable and the equation of motion is considered identical to equation (4.1, e). Therefore, the equations, in permanent sinusoidal regime, become:

$0 = -R_s\left(\frac{1}{\sigma L_s}\left(\phi_{sd} - \frac{L_m}{L'_r}\phi'_{rd}\right)\right) + \omega_s\phi_{sq} + \sqrt{2}U_1,$	(4.1, a)
$0 = -R_s\left(\frac{1}{\sigma L_s}\left(\phi_{sd} - \frac{L_m}{L'_r}\phi'_{rd}\right)\right) + \omega_s\phi_{sq} + \sqrt{2}U_1,$	(4.1, b)
$0 = -R_s\left(\frac{1}{\sigma L_s}\left(\phi_{sd} - \frac{L_m}{L'_r}\phi'_{rd}\right)\right) + \omega_s\phi_{sq} + \sqrt{2}U_1,$	(4.1, c)
$0 = -R'_r\left(\frac{1}{\sigma L'_r}\left(\phi'_{rq} - \frac{L_m}{L_s}\phi_{sq}\right)\right) - (\omega_s - \omega)\phi'_{ra}$	(4.1, d)
$\frac{d\omega}{dt} = \frac{3p^2}{2J}\left(\phi_{sd}\frac{1}{\sigma L_s}\left(\phi_{sq} - \frac{L_m}{L'_r}\phi'_{rq}\right) - \phi_{sq}\frac{1}{\sigma L_s}\left(\phi_{sd} - \frac{L_m}{L'_r}\phi'_{rd}\right)\right) - \frac{pM_r}{J},$	(4.1, e)
$\omega_2 = \omega_r = \omega_s - \omega.$	(4.1, e)

The electromagnetic torque can be calculated with one of the relations:

$M = \frac{3p}{2}\left(\phi_{sd}i_{sq} - \phi_{sq}i_{sd}\right) = \frac{3p}{2}\left(\phi_{sd}\cdot\frac{1}{\sigma L_s}\left(\phi_{sq} - \frac{L_m}{L'_r}\phi'_{rq}\right) - \phi_{sq}\cdot\frac{1}{\sigma L_s}\left(\phi_{sd} - \frac{L_m}{L'_r}\phi'_{rd}\right)\right)$	(4.2)
$M = \frac{3p}{2}\left(\phi'_{rd}i'_{rq} - \phi'_{rq}i'_{rd}\right) = \frac{3p}{2}\left(\phi'_{rd}\frac{1}{\sigma L'_r}\left(\phi'_{rq} - \frac{L_m}{L_s}\phi_{sq}\right) - \phi'_{rq}\cdot\frac{1}{\sigma L'_r}\left(\phi'_{rd} - \frac{L_m}{L_s}\phi_{sd}\right)\right)$	(4.3)

The currents through the three stator phases i_A, i_B, i_C and the currents of the three rotor phases can be expressed as a function of the stator and rotor currents in the axes d, q with the relations (4.4):

$i_A(t) = i_{ds}(t)\cdot cos(\omega_1 t) - i_{qs}(t)\cdot sin(\omega_1 t) + i_{0s}$	(4.4)
$i_B(t) = i_{ds}(t)\cdot cos\left(\omega_1 t - \frac{2\pi}{3}\right) - i_{qs}(t)\cdot sin\left(\omega_1 t - \frac{2\pi}{3}\right) + i_{0s}$	
$i_C(t) = i_{ds}(t)\cdot cos\left(\omega_1 t + \frac{2\pi}{3}\right) - i_{qs}(t)\cdot sin\left(\omega_1 t + \frac{2\pi}{3}\right) + i_{0s}$ Usually i_{0s}=0,	
$i'_a(t) = i'_{dr}(t)\cdot cos((\omega_1 - \omega)t) - i'_{qr}(t)\cdot sin((\omega_1 - \omega)t) + i_{0r}$	
$i'_b(t) = i'_{dr}(t)\cdot cos\left((\omega_1 - \omega)t - \frac{2\pi}{3}\right) - i'_{qr}(t)\cdot sin\left((\omega_1 - \omega)t - \frac{2\pi}{3}\right) + i_{0r}$	
$i'_a(t) = i'_{dr}(t)\cdot cos\left((\omega_1 - \omega)t + \frac{2\pi}{3}\right) - i'_{qr}(t)\cdot sin\left((\omega_1 - \omega)t + \frac{2\pi}{3}\right) + i_{0r}$ Usually i_{0r}=0,	

4.3. Permanent sinusoidal analysis when using the equivalent scheme and the *ASINOM* program - symbolic analysis with modified nodal method

The analysis in permanent regime was performed on an asynchronous motor whose characteristics are given by the manufacturer: P_n = 100 kW; U_n = 560 V; I_n = 130 A; f_{1n} = 60 Hz; n_1 = 1200 r/m; s_n = 2,6 %; m_p = Mp/Mn = 1.1; $m_n = M_{max}/M_n$ = 1.8; $\cos\varphi_n$= 0.87; $i_p = I_p/I_n$ = 3; star connection; U_{fn} = 323.32 V; I_{fn} = 130 A.

The parameters of this engine are: $Z_b = Z_n = U_{fn} / I_{fn}$ = 2.48 ; R_s = 0.053; ; L_s= 1,034 mH; mH; L = 28.1 mH.

The reactances at 50 Hz are: ; ; X = 10.59 .

The parameters in relative units have the values: r_s = 0.0214; $x_s = X_s/ Z_n$ = 0.157; .

The cyclic inductances are: mH; mH; L = Lm = 28.1 mH.

Calculate the apparent power S_n = 128094.8 VA; nominal torque M_n = 817 Nm; idle current A; nominal speed rpm. Moment of inertia J = 3.38 kg.m^2.

The electrical parameters of the considered motor rotor have the expressions from relation 4.6:

$$\begin{gathered}
\sqrt{\omega_{rx}} = 9;\ \ L_s = 0.029134\ H\ ;\quad R_s = 0{,}053\Omega\ ;\quad L_\mu = 0{,}0281H\ ;\\
L_r' = 0{,}0281 + \begin{cases} 0{,}000955H\ ; & \omega_r \in (0;\ 81) \\ 0{,}000155 + 0{,}0072\dfrac{1}{\sqrt{\omega_r}}\ ; & \omega_r > \ 81\ ;\quad \omega_r \le \omega_1 = 120\pi \end{cases}\\
R_r'(\omega_r) = \begin{cases} 0{,}065434\ ; & \omega_r \in (0;\ 81) \\ 0.000904 + 0{,}00717\ \sqrt{\omega_r}\ ; & \omega_r > \ 81\ ;\quad \omega_r \le \omega_1 = 120\pi \end{cases}
\end{gathered} \tag{4.6}$$

The rotor parameters are initially considered constant in relation to the frequency and after are considered variables. The input file has the following structure:

```
8
6
1 2 R1
2 3 L2
3 4 L3
4 5 R4
5 6 R5
3 6 L6
3 6 R7
6 1 e8
```

Figure 4.2 shows the dependence of the motor torque when the rotor parameters are constant with the frequency and in figure 4.2b when they are variable.

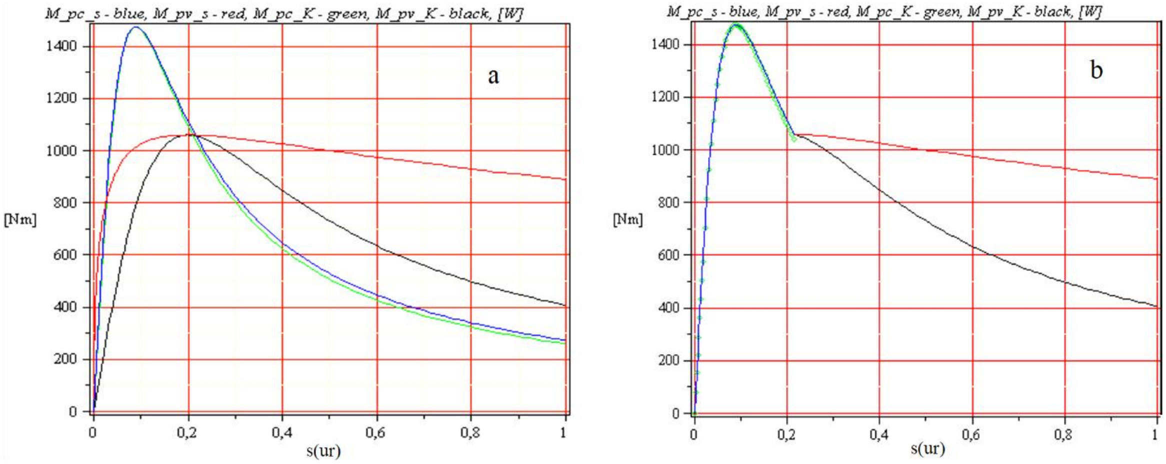


FIG. 4.2. Asynchronous motor torque when rotor parameters are constant (a) and variable (b)

Figure 4.3 shows the evolution of electric currents through the components of the asynchronous motor when the slip is variable or constant.

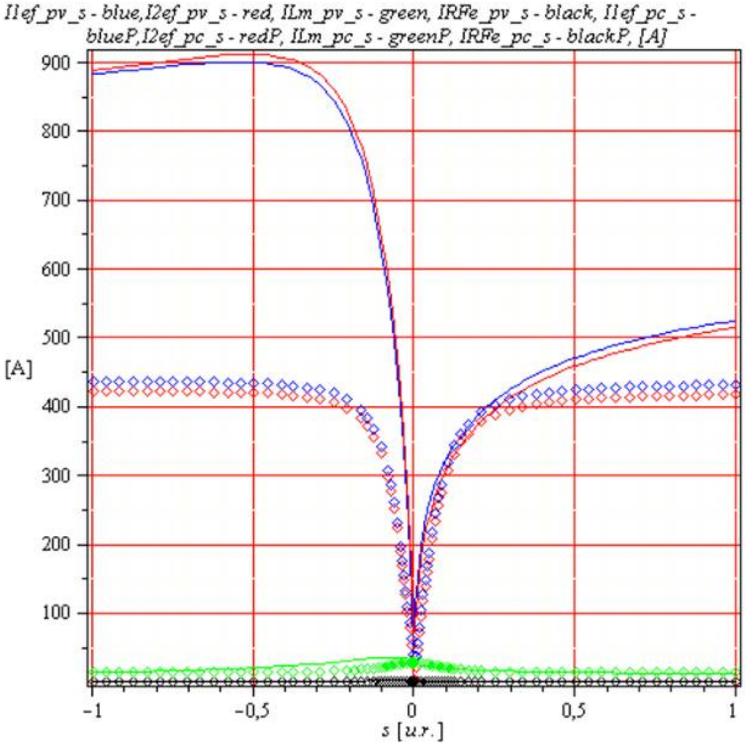


FIG. 4.3. Current currents through asynchronous motor components

The variation of the asynchronous motor power according to the rotor parameters and the constant or variable slip is shown in figure 4.4.

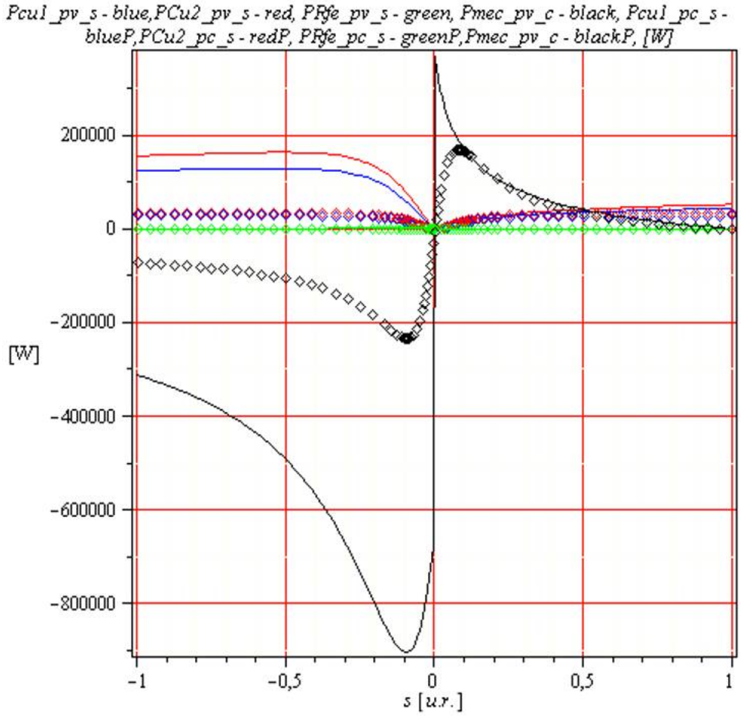


FIG. 4.4. Variation of asynchronous motor power depending on variable or constant slip

The results obtained by simulating the asynchronous motor in permanent sinusoidal regime, using the equivalent motor diagram in figure 4.1, allow us to determine some differences between the results.

4.4. Permanently sinusoidal analysis when using state equations in the Matlab programming environment

The permanent sinusoidal regime of the asynchronous motor is analyzed with the help of programs PACEN - Program for Analysis of Nonlinear Electrical Circuits, [28] and PGESEST - Program for Symbolic Generation of State Equations, [34].

Running the Matlab program, which integrates the equation (4.1, e), I obtain the results presented in figures 4.5 - 4.12 where on the left, denoted by (a) are the dependence of the values when the parameters and are constant in relation to the pulsation of the rotor currents r and on the right, denoted by (b) the values when parameters are variable in relation to the pulsation of rotor currents r. Figure 4.5 shows the pulse dependence as a function of time for the parameters constants (4.5a) and variables (4.5b).

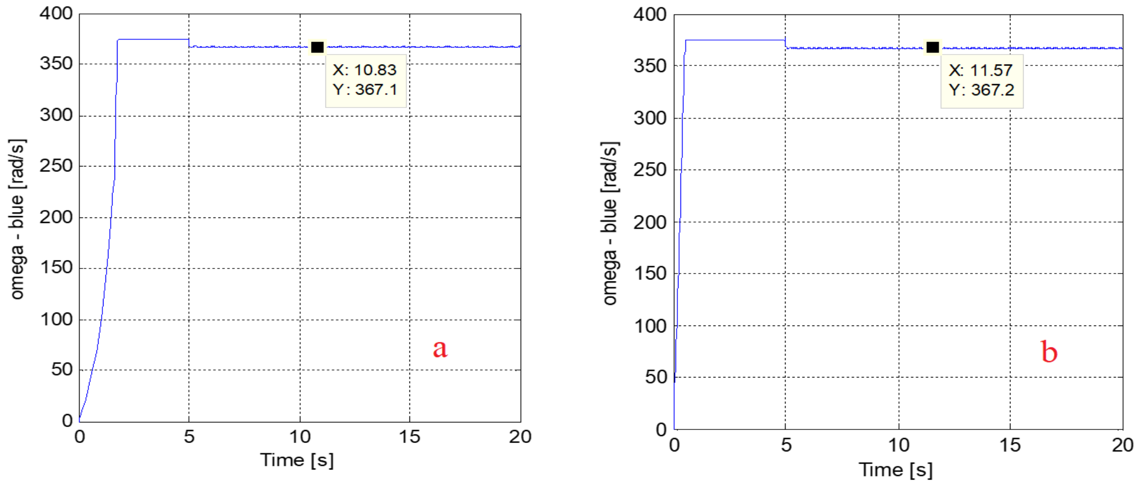


FIG. 4.5. Pulsation as a function of time for parameters and constants (a) and variables (b)

The pulsation of the rotor according to the two situations studied is presented in figure 4.6.

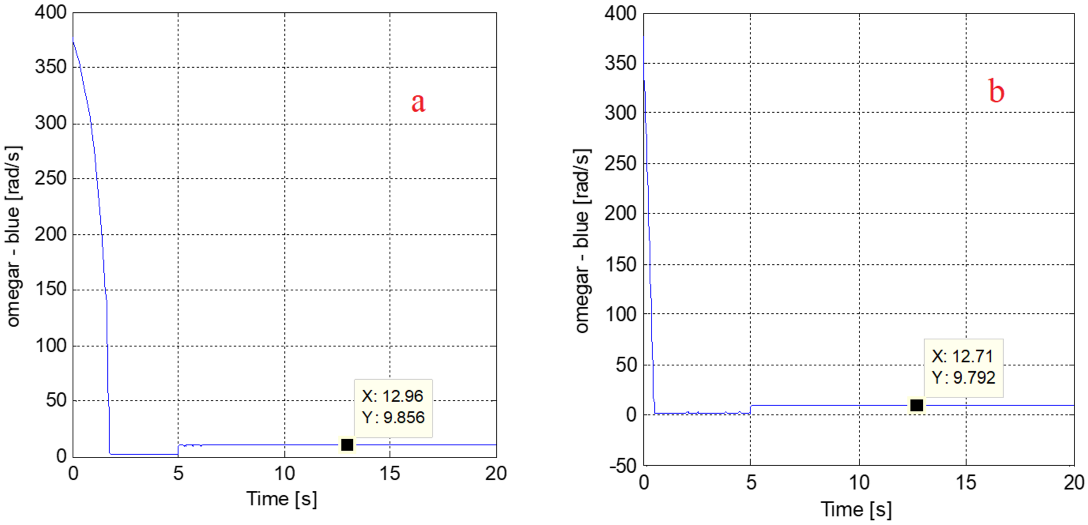


FIG. 4.6. Rotor pulse as a function of time for parameters and constants (a) and variables (b)

Figure 4.7a shows the dependence of the stator current when parameters are constant and the same dependence in figure 4.7b if they are variable. The same dependencies are shown for the rotor current in figure 4.8.

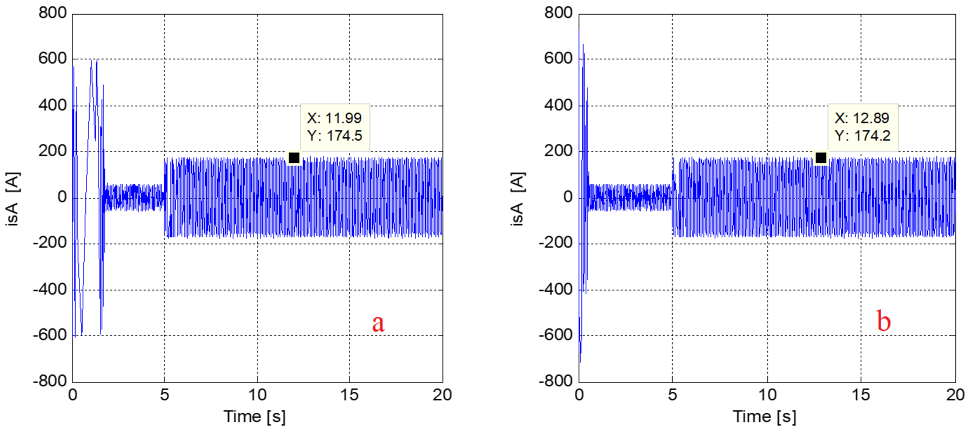


FIG. 4.7. Stator current as a function of time for constant (a) and variable (b) parameters

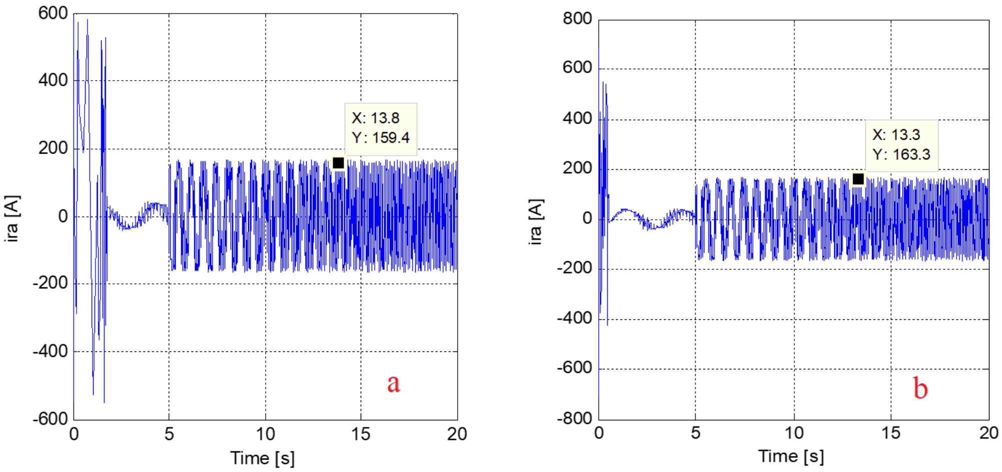


FIG. 4.8. Rotor current as a function of time for constant (a) and variable (b) parameters

The rotor speed in the two situations analyzed is shown in figure 4.9.

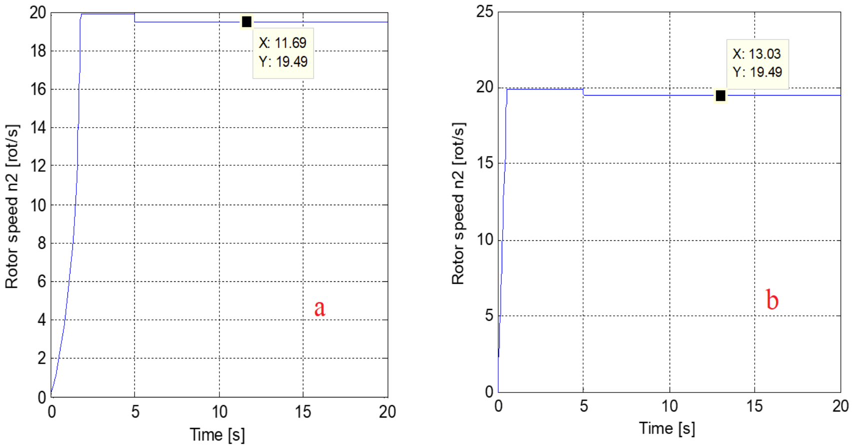


FIG. 4.9. Rotor speed for constant (a) and variable (b) parameters

4.5. Dynamic analysis when using state equations in the Matlab programming environment.

It is considered the moment of inertia *J*= 60 kg.m2, fr = 60 Hz and the resistive torque varies according to the relation (4.13), and the rotor parameters vary with the rotor frequency according to the expressions (4.11). The resistant torque Mr varies with the rotor speed n according to relation 4.8.

$$M_r = \begin{cases} 800, \text{ pentru } n \in [0,1] \\ 800 - 100 \cdot (n-1), \text{ pentru } n \in (1,5]. \\ 400, \text{ pentru } n > 5;\ n \rightarrow \text{rot/s};\ M \rightarrow \text{Nm} \end{cases} \qquad (4.8)$$

The routine ec_difma_J60_F30_MrV_PV.m and the main program Test_MA_lin_N_MrVn1.m (both in Matlab) are presented in Annex A. Running the program Test_MA_J60_F30_MrV_PV.m the graphs obtained were presented in figures 4.14 - 4.35.

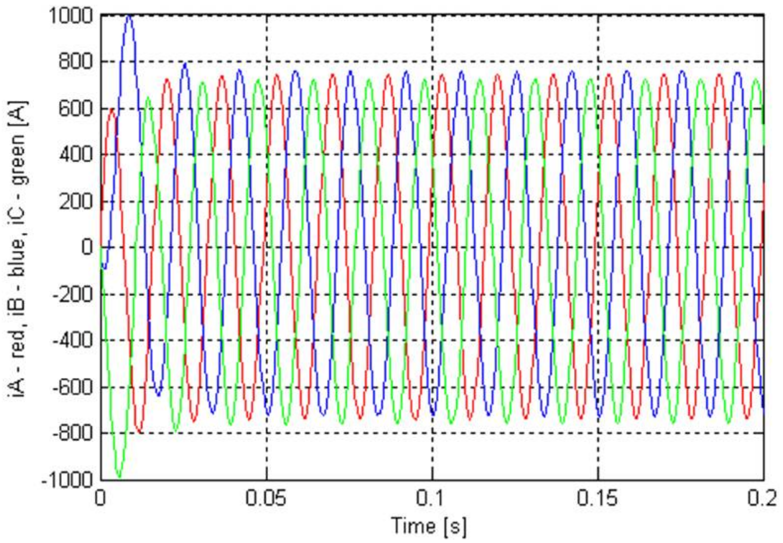


FIG. 4.14. Simulation of current evolution in the range 0-0.2s

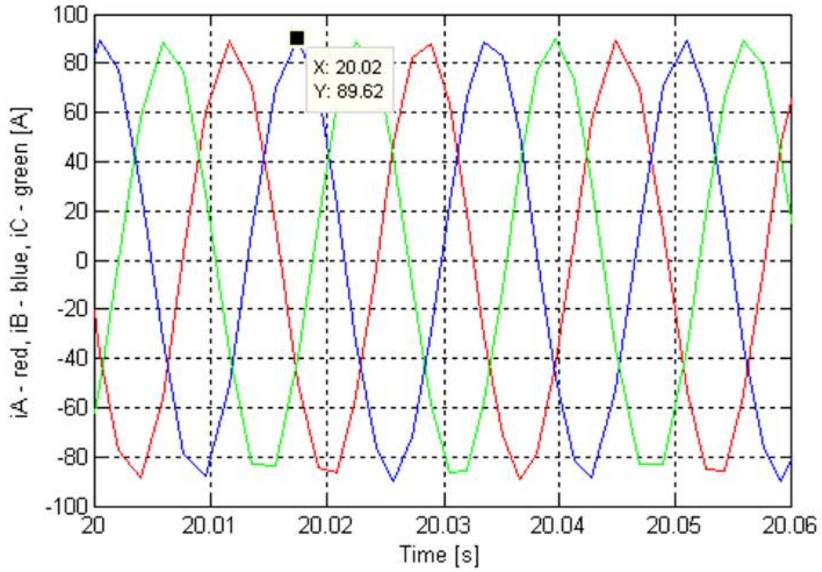


FIG. 4.15. Simulation of the evolution of currents in the time interval 20-20,6s

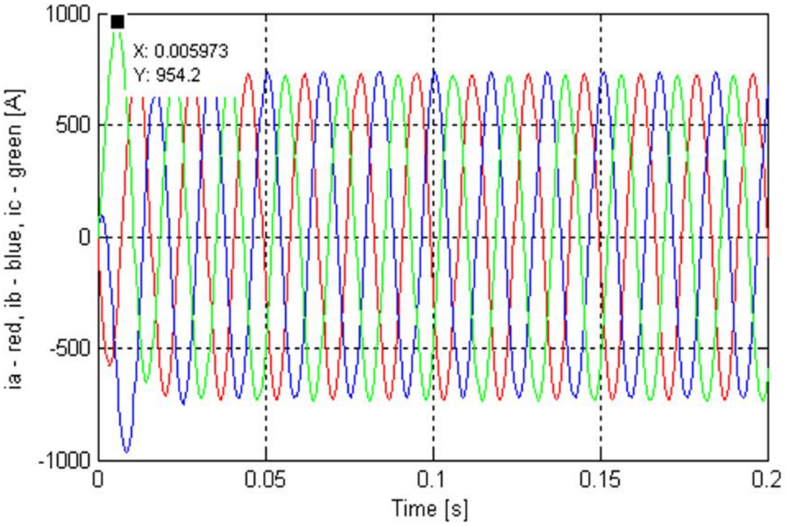


FIG. 4.16. Simulation of the evolution of currents in the time interval 0-0.2s

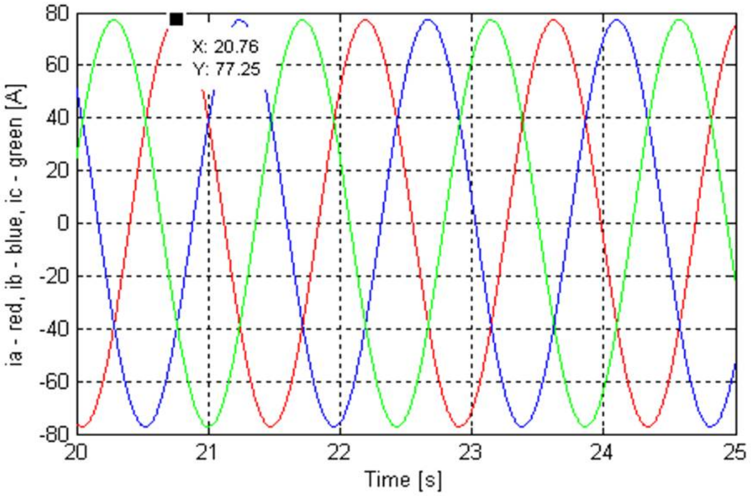


FIG. 4.17. Simulation of the evolution of electric currents in the range of 20-25s

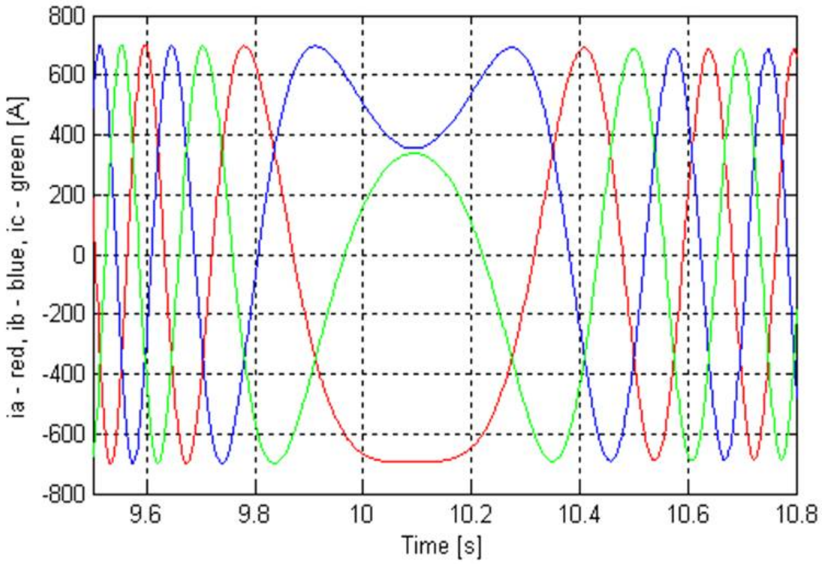


FIG. 4.18. Simulation of current evolution in the range of 9.4-10.8s

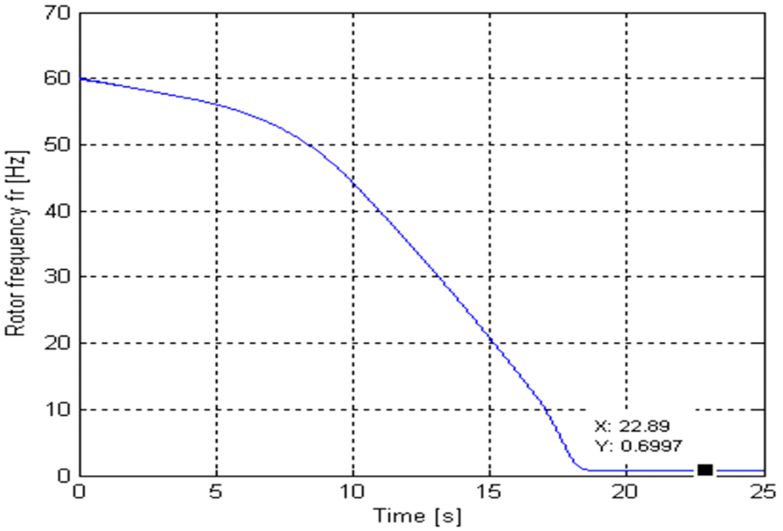


FIG. 4.19. Rotor frequency dependence in the time range 0-25s

4.6. Permanent analysis of the asynchronous motor with the brute force method

For the analysis in permanent regime of the asynchronous motor with the brute force method, the state equations for the equivalent circuit from figure 4.36 are used, in which the saturation phenomenon is taken into account. The nonlinear coil Lm is considered to be current controlled (ci), and the resistor R5 is a parametric resistor (variable in time).

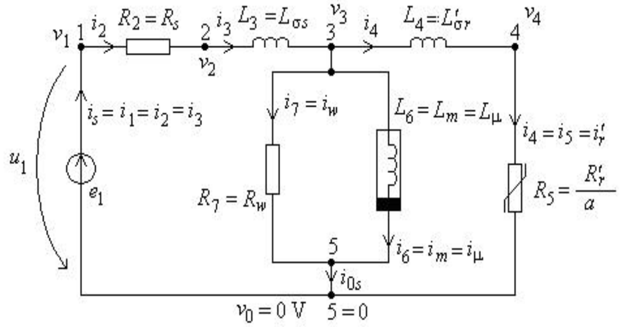


FIG. 4.36. Equivalent asynchronous motor circuit.

Nonlinear magnetization characteristic $_{Lm}$(iLm) is given by points (fig. 4.37, a) and characteristic R_2 (t) = R'_r / s (t) of the parametric resistor R_2 is also given by points (fig. 4.37, b).

The structure of the nodal equations corresponding to the time moment $t_{j+1} = t_j + h$ (h being the time step) and the iteration k + 1.

UNKNOWN OF THE SYSTEM

V1 (j + 1) V2 (j + 1) V3 (j + 1) V4 (j + 1) I1 (j + 1) I6 (j + 1)

SYSTEM OF EQUATIONS

+ (+ G2) * V1 (j + 1) + (-G2) * V2 (j + 1) + (-1) * I1 (j + 1) = 0

+ (-G2) * V1 (j + 1) + (+ G2 + h / L3) * V2 (j + 1) + (-h / L3) * V3 (j + 1) = -I3 (j)

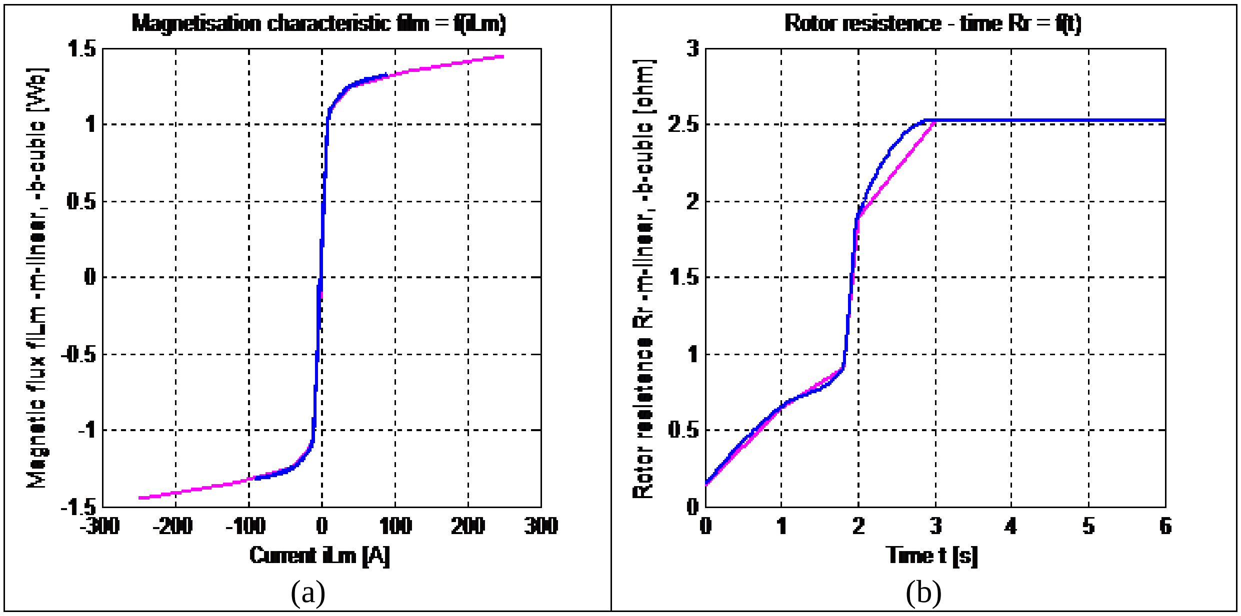
+ (-h / L3) * V2 (j + 1) + (+ h / L3 + h / L4 + G7) * V3 (j + 1) + (-h / L4) * V4 (j + 1) + (+1) * I6 (j + 1) = + I3 (j) -I4 (j)

+ (-h / L4) * V3 (j + 1) + (+ h / L4 + Gp5) * V4 (j + 1) = + I4 (j)

+ (-1) * V1 (j + 1) = -E1 (j + 1)

+ (+1) * V3 (j + 1) + (-Ld6 (s) (j + 1) / h) * I6 (j + 1) = -F6 (s) (j + 1) / h-Ld6 (s) (j) * I6 (j) / h-F6 (s) (j) / h

Consider the frequency f_1 = 50 Hz and another magnetization characteristic (fig. 4.38, a).

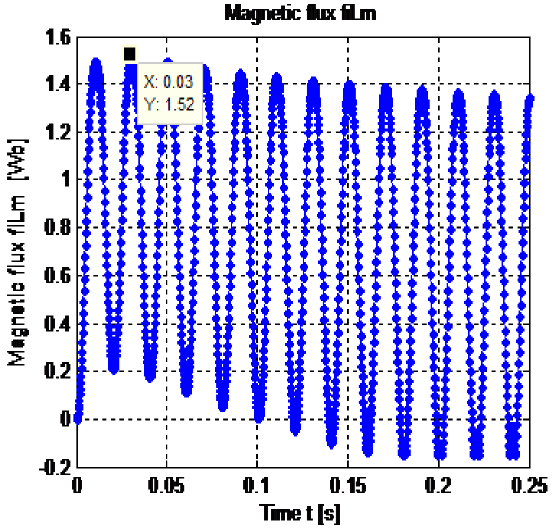
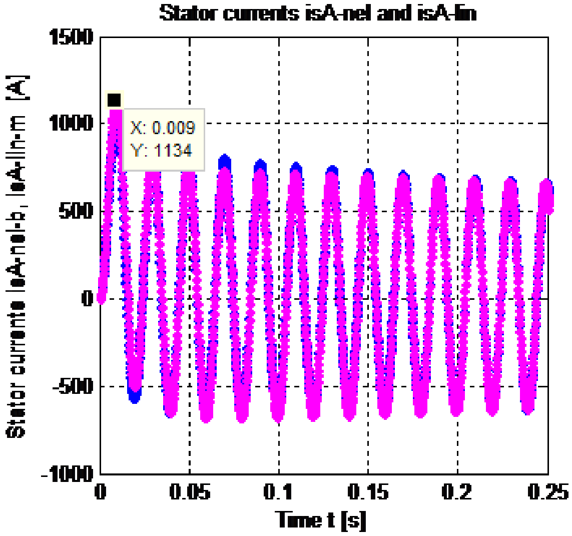
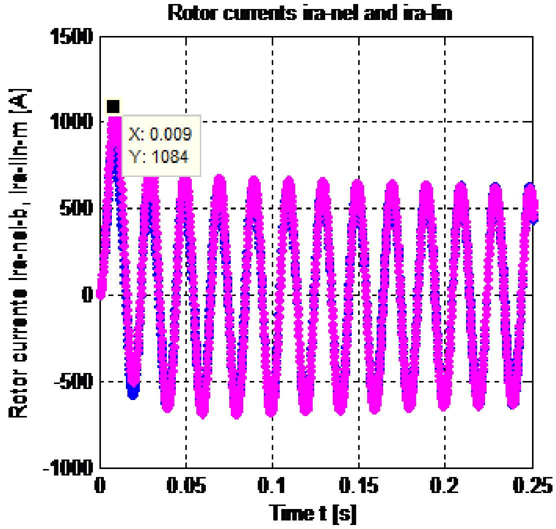
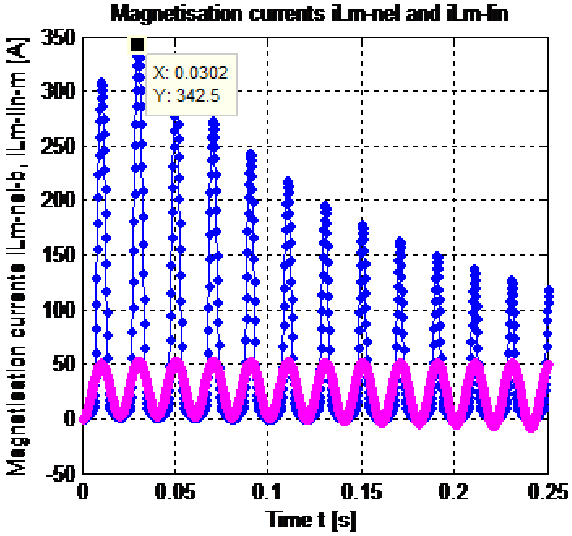


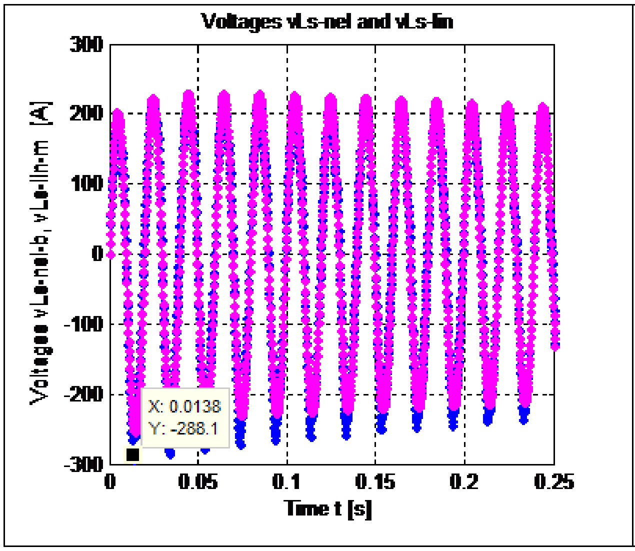
(a) (b)

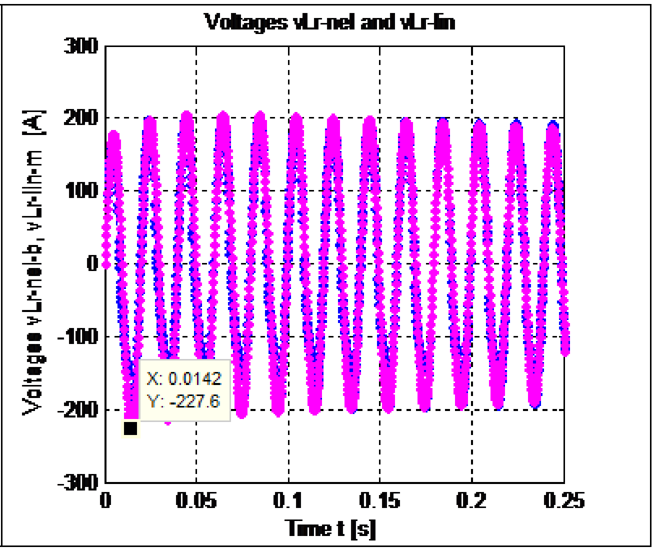
FIG. 4. 37. a) Characteristic $_{Lm}$(iLm) = $_{IT6}$(iL6) and b) Characteristic R2 (t).

The time variations of the characteristic dimensions of the asynchronous motor in the transient regime from the start (the first moments of time) are given in Table 4.3.

Table 4.3. Time variations of the characteristic dimensions of the asynchronous motor in the transient mode from the start





4.7. Observations and conclusions

The results obtained by simulating the asynchronous motor in transient mode, using the state equations for the circuit in figure 4.1, the magnetization characteristic F_{iLm} - i_{Lm}, the characteristic R4 + R5 = R'_r / s - time (in fact, R'_r / s as a function of s, s = a) and the Matlab program, presented in Tables 4.3 and 4.4, lead to the following conclusions:

- The purpose of simulating the asynchronous motor in dynamic regime is to obtain, after a sufficiently long integration time, the permanent (sinusoidal) regime - the brute force method [30]. The dimensions corresponding to the dynamic regime are marked in the figures shown in Table 4.3;
- Considering the magnetization characteristic F_{iLm} - $iL_{m,}$ the characteristic R4 + R5 = R'_r / s - time (in fact, R'r / s as a function of s) and the Matlab program, with the Pacen program it was managed to highlight the presence of harmonics (using the routine fft - fast Fpurier transforms from the Matlab programming environment) into the variation of the currents and voltages of the circuit sides from figure 4.1;
- The voltages at the terminals of the three inductors uLs, uLr and uLm are much more distorted than the corresponding currents, this is due to the fact that in the expression of these densities appear the current derivatives (by derivation increases the degree of distortion);
- The amplitudes of the upper harmonics at currents are below 5% of the fundamental harmonic, while the harmonics of the voltages at the terminals of the three coils reach 38%;
- Approximating the nonlinear magnetization characteristic Fi_{Lm} - i_{Lm} and the characteristic R4 + R5 = R'r / s - time (in fact, R'r / s as a function of s, s = a) - parametric circuit element (variable in time) through points (which are usually obtained experimentally) allows the Pacen program to analyze such circuits and highlight unwanted phenomena caused by the saturation phenomenon - Joulle losses and especially additional iron losses. These lead to a reduction in the power factor and efficiency.

CHAPTER 5

ESTIMATING ASYNCHRONOUS MOTOR PARAMETERS USING OUTPUT SIZE ERROR SQUARE METHOD (TRANSFER FUNCTION)

5.1. Introduction

Classical methods for estimating parameters differ from one application to another. For example, for induction motors, conventional methods are based on the results of tests performed on asynchronous motors with the rotor locked or idle (no load). Such a method of determining (estimating) the parameters is sometimes unsuitable for the initialization of an asynchronous motor used in electric drives. To simplify the initialization process, the engine parameters can be estimated from the manufacturing (catalog) data by a drive processor. In one of these methods, the engine parameters are identified from the catalog data by a numerical method [36]. This method of estimating offline parameters requires a computer and software to perform these calculations. In this method, the initial values of the engine parameters are calculated with certain approximations (hypotheses). After that, each parameter is changed from its initial value to zero in small steps. The size of the step determines the accuracy of the procedure. For each possible combination of parameters, the exact equivalent circuit of the induction machine is used and the mechanical power and reactive power at rated load and at sudden torque are calculated. The results obtained by these calculations are compared with those provided by the manufacturer and certain differences (errors) are noted. Thereafter, each error is weighted according to the importance of the method user's calculations. Calculate the total weight of errors for each possible combination. The method is completed by selecting the engine parameters,*minimum error weight*.

5.2. Description of the transfer function method

Considering a linear circuit (a linear system) that operates in the frequency range. In this case, any transfer function that describes the operation of the considered circuit can be generated. The selected circuit model contains only concentrated circuit elements and possible independent voltage and / or current sources (input signals). This type of circuit is described, in transient mode, by a system of linear differential equations. Using the Laplace transform or the Fourier transform these differential equations can be plotted into linear algebraic equations in the frequency domain.

Any passive linear diode circuit, operating in permanent mode (in the frequency range), can be described by two algebraic equations in which two of the four variables associated with the two gates are considered as independent variables, and the other variables are considered dependent variables, after as follows:

$$\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \end{bmatrix} \cdot \begin{bmatrix} X_1 \\ X_2 \end{bmatrix}. \tag{5.1}$$

The coefficients of equations (4.8) are transfer functions (circuit) that depend on the circuit parameters and the complex frequency s or j. Depending on the nature of the input quantities and the output quantities, different circuit functions can be defined in relation to the two gates, as follows: Z, Y, H, S, fundamental parameters A, B, C and D etc.

Starting from the equivalent diagram of an analog circuit in sinusoidal mode, any complex transfer function can be generated. $\underline{H}$(j) in a completely symbolic form, partially - symbolic or numerical. The modulus and phase of the complex transfer function can be measured by supplying the circuit (system) with a variable frequency voltage source.

Considering $\underline{H}$(f) the transfer function (an output measure or a certain measure of system performance - useful power, efficiency, etc.) generated, in complete symbolic form, using the Asinom program or the Gsimft program [58, 59]. I assume that the parameters of the circuit (system, asynchronous motor) to be identified (estimated) are: x1, x2, ..., xp (p being the number of unknown parameters), the other n - p parameters are assigned the nominal values (of catalog). Consider k samples of frequency at which the considered circuit function is measured (simulated).

The following objective function is formulated:

$$f_j(x_1, x_2, \ldots, x_p, f_j) = \left(\left|\underline{H}(f_j)\right| - \left|\underline{H}(f_j, x_1, x_2, \ldots, x_p)\right|\right)^2,\ j = \overline{1, k}, \tag{5.2}$$

wherein the objective function is a vector with k components, or

$$f(x_1, x_2, \ldots, x_p) = \sum_{j=1}^{k}\left(\left|\underline{H}(f_j)\right| - \left|\underline{H}(f_j, x_1, x_2, \ldots, x_p)\right|\right)^2 \tag{5.3}$$

when the objective function is a scalar, in this case k can be equal to one.

Usually the size $\underline{H}$(f) is a rational frequency function. The coefficients of the polynomials at the numerator and denominator of the transfer function (output quantity) are complex, consisting of products of the parameters of the circuit (system). In these products each parameter of the circuit (system) appears only once at power one, when the circuit is linear, and at powers greater than one, when the analyzed system is nonlinear.

5.3. Estimation of the parameters of an asynchronous motor based on transfer functions

To determine the complex input impedance $\underline{Z}_{ii}$= Z$_{1\_5\_1\_5}$ use the equivalent scheme on one phase of an asynchronous motor represented in figure 5.1.

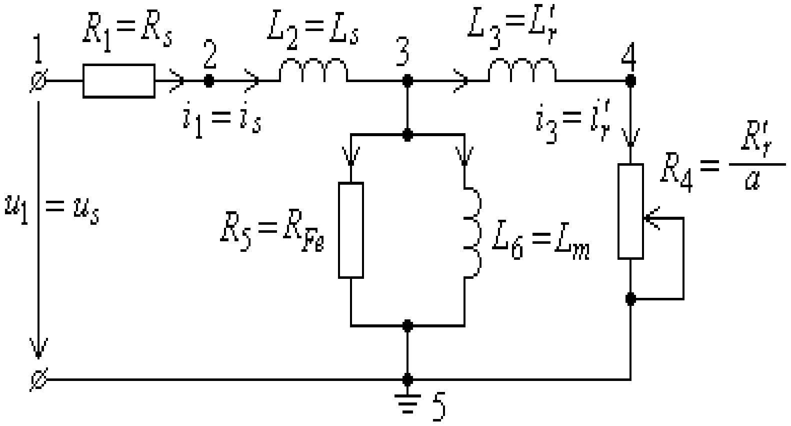


FIG. 5.1. Equivalent scheme of single-phase asynchronous motor

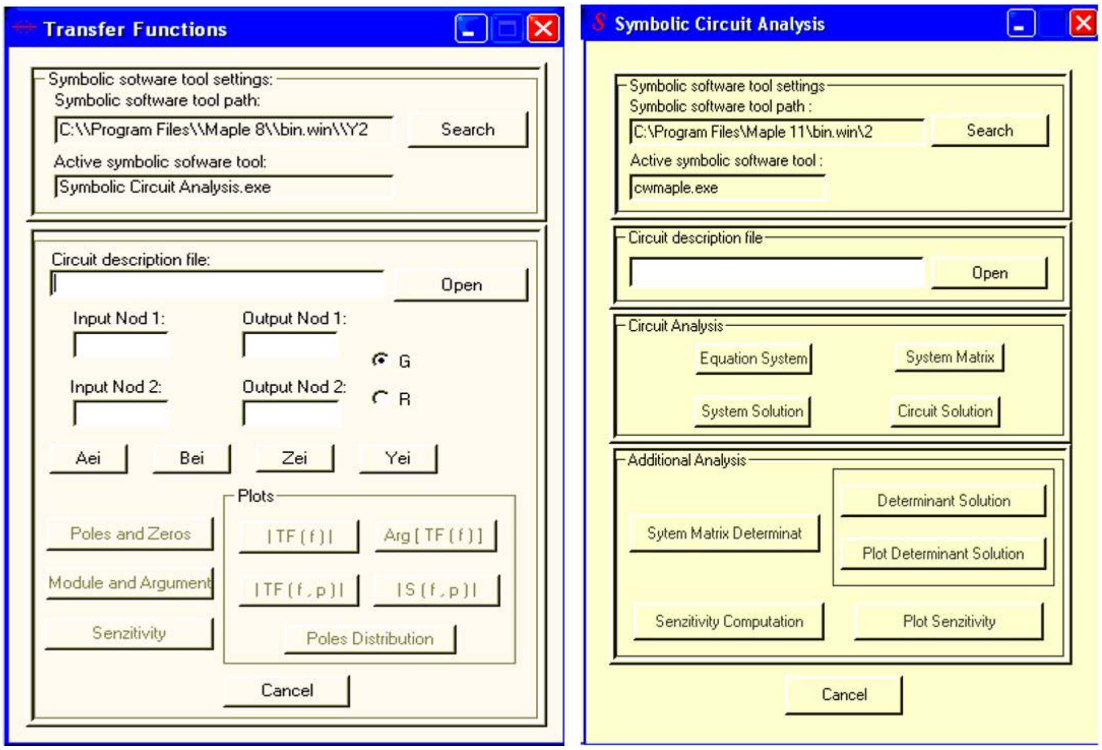
Considering, as an example, the asynchronous motor with the following nominal data: Pn = 5.5 kW; Un = 230 V / 400 V; In = 22.5 A / 13.2 A; fn = 50 Hz; n1 = 750 r / m; an = 9.6%; mp = 1; 1 m_n = 1.8; $cosfi_n$ = 0.74; R_s = 1.07131 ohms - obtained by direct measurement, = 1.2951 ohms; Ls = 0.00835 H; L'_r = 0.04543 H; Lm = 0.1070573 H, R_{Fe} = 250.0 ohms. Structure The asynchronous motor parameter identification program has the following structure:

```
> restart; Digits: = 8; with (linalg);
```

The input file, Senz_motor_as.crt, has the structure:

```
7
5
1 2 R1
2 3 L2
3 4 L3
4 5 R4
3 5 R5
3 5 L6
```

Figure 5.2 shows photographs of the windows used in GESIFT and ASINOM programs.



Symbolic software tool path: C:\\Program Files\\Maple 8\\bin.win\\Y2

Active symbolic sofware tool: Symbolic Circuit Analysis.exe

● G ○ R

Symbolic software tool path : C:\Program Files\Maple 11\bin.win\2

Active symbolic software tool : cwmaple.exe

FIG. 5.2. GESIFT (left) and ASINOM (right) program user window

Calculation of sensitivities in relation to asynchronous motor parameters

The input impedance Zii = Z1_5_1_5 is considered as a transfer function. To identify the parameters of a system it is very important to know the frequency variations of the sensitivities of the transfer functions used, because the parameter values that determine very small values of the sensitivities lead to the very weak convergence of the algorithms used in solving systems of nonlinear algebraic equations.

Normalized sensitivity of a transfer function *H* in relation to any parameter x of the analyzed system is calculated with formula 5.10.

$$S_x^H = S_s(H,x) = \frac{\partial H}{\partial x} \cdot \frac{x}{H}. \tag{5.10}$$

When the input signals are sinusoidal, the circuit function of a linear circuit can be expressed as follows:

$$H(j\omega) = |H(j\omega)|e^{j\phi} \text{ sau } \ln H(j\omega) = \ln|H(j\omega)| + j\phi, \tag{5.11}$$

Where: is the amplitude function and represents the phase function. if x is a given circuit parameter, then the amplitude sensitivity can be defined (5.12):

$$S_s(A(\omega),x) = x\frac{\partial A(\omega)}{\partial x} \tag{5.12}$$

and phase sensitivity (5.13):

$$S_s(\phi(\omega),x) = x\frac{\partial \phi(\omega)}{\partial x}. \tag{5.13}$$

The normalized sensitivity of the circuit function,, satisfies the relation (5.14).

$$S(H(j\omega),x) = \frac{\partial(\ln H(j\omega))}{\partial(\ln x)} = \frac{\partial(A(\omega)+j\phi(\omega))}{\partial x/x} = \frac{\partial A(\omega)}{\partial x/x} + j\frac{\partial \phi(\omega)}{\partial x/x} \tag{5.14}$$

Consequently, the sensitivity of the amplitude and the sensitivity of the phase can be expressed as a function of the sensitivity as a function of the circuit (5.15):

and .

$$S_s(A(\omega),x) = Re\{S(H(j\omega),x)\} \text{ și } S_s(\phi(\omega),x) = \mathrm{Im}\{S(H(j\omega),x)\}. \tag{5.15}$$

```
> restart: Digits: = 8: with (linalg):% For the calculation of the normalized relative sensitivities the expression of the input impedance Z1_5_1_5_f and formulas (5.8) and (5.13) were used. Examples are the calculation of normalized relative sensitivities with respect to parameters R1 and L2.
> SZ_R1: = collect (simplify (diff (Z1_5_1_5_f, R1) * R1 / Z1_5_1_5), f):
> SZA_R1: = simplify (subs (R1 = 1.07131, R2 = 1.2951, L2 = 0.008354, L3 = 0.04543, L6 = 0.1070573, R5 = 250, a = 0.098, evalc (Re (SZ_R1)))):
> SZPh_R1: = simplify (subs (R1 = 1.07131, R2 = 1.2951, L2 = 0.008354, L3 = 0.04543, L6 = 0.1070573, R5 = 250, a = 0.098, evalc (Im (SZ_R1)))):
> SZ_L2: = collect (simplify (diff (Z1_5_1_5, L2) * L2 / Z1_5_1_5), f):
> SZA_L2: = simplify (subs (R1 = 1.07131, R2 = 1.2951, L2 = 0.008354, L3 = 0.04543, L6 = 0.1070573, R5 = 250, a = 0.098, evalc (Re (SZ_L2)))):
> SZPh_L2: = simplify (subs (R1 = 1.07131, R2 = 1.2951, L2 = 0.008354, L3 = 0.04543, L6 = 0.1070573, R5 = 250, a = 0.098, evalc (Im (SZ_L2)))):
> with (plots):
Fs: = plot (SZA_R1, f = 0.0..120.0, style = line, color = blue):
Gs: = plot (SZA_L2, f = 0.0..120.0, style = line, color = red): Hs: = plot (SZA_L3, f = 0.0..120.0, style = line, style = line, color = green): Fs1: = plot (SZA_R2, f = 0.0..120.0, style = line, style = line, color = cyan): Gs1: = plot (SZA_R5, f = 0.0..120.0, style = line, style = line, color = black): Hs1: = plot (SZA_L6, f = 0.0..120.0, style = line, style = line, color =
```

```
brown): Hs2: = plot (SZA_a, f = 0.0..120.0, style = line, style = point, color = purple):
display ({Fs, Gs, Hs, Fs1, Gs1, Hs1, Hs2}, axes = boxed, title = `SZA_R1-blue, SZA_Ls1-red,
SZA_Ls2-green, SZA_R2-cyan, SZA_RFe -black, SZA_Lm-brown, SZA_a-violetp`);
        with (plots):
        Fs: = plot (SZPh_R1, f = 0.0..120.0, style = line, color = blue):
        Gs: = plot (SZPh_L2, f = 0.0..120.0, style = line, color = red): Hs: = plot (SZPh_L3, f =
0.0..120.0, style = line, style = line, color = green): Fs1: = plot (SZPh_R2, f = 0.0..120.0, style
= line, style = line, color = cyan): Gs1: = plot (SZPh_R5, f = 0.0..120.0, style = line, style =
line, color = black): Hs1: = plot (SZPh_L6, f = 0.0..120.0, style = line, style = line, color =
brown): Hs2: = plot (SZPh_a, f = 0.0..120.0, style = line, style = point, color = purple):
display ({Fs, Gs, Hs, Fs1, Gs1, Hs1, Hs2}, axes = boxed, title = `SZPh_R1-blue, SZPh_Ls1-
red, SZPh_Ls2-green, SZPh_R2-cyan, SZPh_RF -black, SZPh_Lm-brown, SZA_a-
violetp`);
```

Figure 5.3 shows the variations of the sensitivity modules and in figure 5.4 the variations of the sensitivity phases in relation to the frequency.

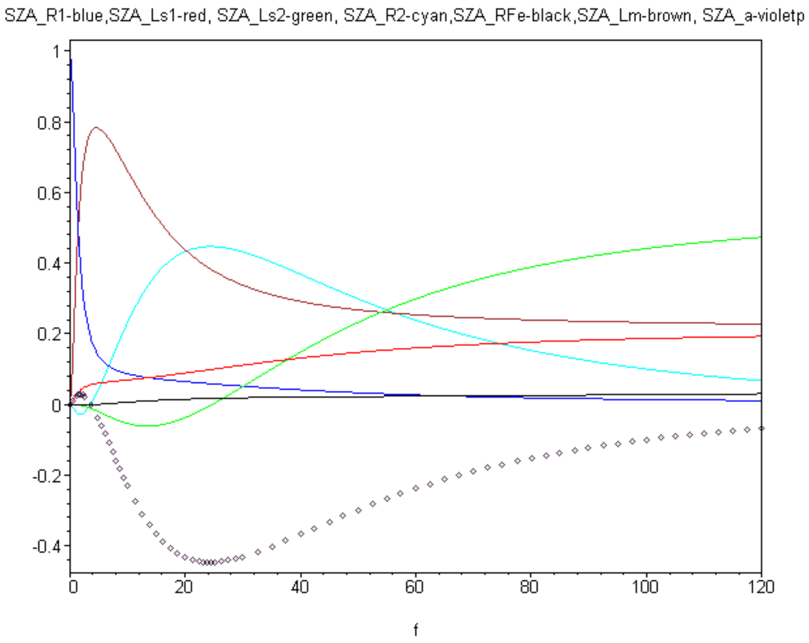


FIG. 5.3. Variations of sensitivity modules in relation to frequency

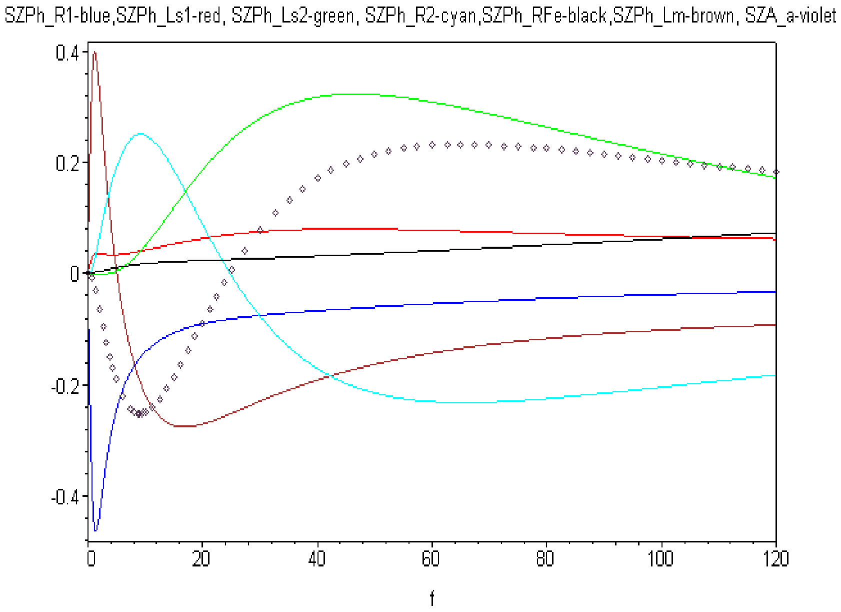


FIG. 5.4. Variations in the phases of sensitivities in relation to frequency

5.4. Observations and conclusions

- In order to apply the method of identifying the parameters of a system, based on the transfer functions, their symbolic full generation is required. The ASINOM and GESIFT programs, [19, 20] allow the generation of any transfer function in relation to any two gates selected by the user;
- The procedures for identifying the parameters, set out in this paragraph, require the measurement or calculation of the transfer functions used for a reasonable number of frequency samples, [22 - 56];
- The selection of the frequency range (frequency samples) must be done very carefully so that the values of the circuit functions are not very close. The more different the values of the circuit functions, at the selected frequency samples, the better the convergence of the four procedures, [65-72];
- To identify parameters that are difficult to estimate, the sensitivities of the transfer functions used must be calculated in relation to all the parameters to be identified, because the system parameters that have low sensitivity values are difficult to identify. For example, in relation to the resistance of the R_{Fe} resistor, the sensitivity of the input impedance has the lowest values in the considered frequency range, this is the reason that leads to the biggest error in estimating this parameter, regardless of the initial values considered;

- From the analyzed examples it was deduced that the most efficient procedure for identifying the parameters is the one that calls the routine *fminunc* from the Matlab programming environment. This routine allows the identification of a large number of parameters;
- The procedures for identifying the parameters based on solving the systems of nonlinear equations (5.10) and (5.11) converge only if the number of estimated parameters is less than or equal to three;
- The convergence of the *fminimax* routine depends on the initial (initial) values of the parameters to be estimated, and the convergence of the *fminunc* routine depends on the initial (initial) intervals of the parameters to be identified;
- The *fminimax* and *fminunc* routines have a number of optimization options that increase the convergence rate;

All four procedures for identifying asynchronous motor parameters based on transfer functions were tested on other examples that led to the same observations and conclusions presented above.

CHAPTER 6

ORIGINAL CONTRIBUTIONS AND CONCLUSIONS

C1. General conclusions

Nuclear safety is one of the most important requirements for the operation of a nuclear power plant. The purpose of this doctoral thesis is to present in detail two directions of interest for ensuring nuclear safety, respectively by modifying the control console architecture for the TRIGA SSR 14MW reactor and simulating the asynchronous motor operation of the primary reactor cooling circuit pumps using computer programs. in the Matlab operating environment.

The first objective of the thesis was achieved by describing the control system of the TRIGA SSR 14 MW reactor, the functions of the main console and the circuits of the control-command system. Personal contributions come from the nature of the workplace, main reactor control room operator, and through direct involvement in meeting the requirements and design criteria, choosing the supplier, implementing new systems and operating them within ICN Mioveni for the TRIGA SSR 14MW reactor.

The second objective of the thesis was to analyze and computer simulate the operation of the asynchronous motor used for the pumps of the primary cooling circuit of nuclear reactors. I used the Matlab working environment and some programs developed in Romania to determine engine performance in both permanent and dynamic, transitional mode. The results of these simulations help in choosing the type of engine used, to understand its behavior. By identifying the parameters with the method of the square error of the output quantities (or circuit functions) the optimal values of the parameters that lead to the highest performance of the asynchronous motors used can be determined, thus greatly increasing the operating safety of cooling circuit pumps.

Following the studies carried out during the elaboration of the doctoral thesis, I was able to draw the following general conclusions:

- Nuclear safety is achieved by using he highest standards in the design, choice of materials, choice of production methods for materials and equipment, production, construction, installation and operation techniques;

- Increasing nuclear safety is a permanent process, carried out both for the construction of new nuclear power plants or for research and also for those already in operation;
- Introducing new nuclear safety systems, improving those in use and updating with new technologies is a permanent concern for the specialists in the nuclear field;
- Increasing the reliability of security systems and methods of improvement are achieved through redundancy, fault tolerance, self-testing and self-configuration;
- The use of complex calculations, operational simulations in critical situations, as well as finding the appropriate solutions are part of the strategy for the development of safe nuclear reactors and the effort to increase the safety of facilities already in operation;
- The functions of the reactor control console allow the realization of the two purposes for which it was designed: operation of the reactor and ensuring nuclear safety;
- All procedures for identifying asynchronous motor parameters based on transfer functions were tested on other examples that led to the same observations related to their usefulness for asynchronous motor simulation;
- Nuclear safety ensures the proper functioning of nuclear reactors but also stimulates scientific research in all technical fields to obtain high performance materials, construction technologies and the introduction of new operating systems, monitoring and control of nuclear reactors;
- The application of the principles of nuclear safety within the TRIGA SSR 14MW reactor from ICN Mioveni was also achieved by introducing the new command control console, with a state-of-the-art man-machine interface;
- Computer simulations of asynchronous motor operation allow the development of powerful, economical and reliable cooling systems at the same time, with a great plus for the nuclear safety of power plants;
- Ongoing research into the design, materials, construction, assembly and operation of nuclear power plants will greatly reduce the risk associated with the nuclear field and meet the increasingly stringent requirements of modern nuclear safety.

C2. Original contributions

- I contributed to the design of a control-command system that ensures the monitoring of the three important parameters for nuclear safety: *neutron power* (neutron flux), measured with the help of 4 fission chambers placed in the 4 corners of the active area, *fuel temperature*, measured using the thermocouples existing in the instrumented fuel elements and the *positions of the control rods*;

- The designed control system circuits include both nuclear and non-nuclear channels that provide the information necessary for operational safety;
- Through the permanent analysis, performed, of the reactor power and of the parameters with implication in the nuclear safety and the comparison with the preset values, the automatic operation of the reactor represents a high safety facility that allows its safe operation;
- The proposed reactor protection system (RPS) ensures high reliability, minimizes personnel exposure to radiation during reactor operation, causes unique failure, minimizes common defects through physical separation, functional independence and diversity of equipment used, uses certified, qualified technologies of experience and testing, implements intrinsic and engineering nuclear safety functions;
- The developed Reactor Control and Monitoring System (CMS) is physically and functionally independent of (RPS), cannot cancel an action initiated by the reactor protection system, implements automatic and manual functions, limitations and conditions of interlock;
- The interface of this system with the reactor protection system is unidirectional (from the protection system to the reactor control and monitoring system) and galvanically isolated (optical isolators or relays);
- I have identified that the criteria underlying the design of the reactor control and monitoring system are simplicity, reliability, availability, the possibility of easy repair of components, specific computer programs, modularity and the possibility of permanent development;
- Ensuring efficient, reliable, powerful engines with known characteristics contribute to reducing the risk of reactor cooling loss (LOCA) and increasing nuclear safety;
- Through the simulations performed, with adequate programs, the operation of asynchronous motors both in permanently and transiently (dynamically) regime, their electrical performance can be known.
- The Matlab working environment, that I used, allows complex simulations of asynchronous motor operation;

- The ASINOM program allowed me to study the asynchronous motor in permanent sinusoidal mode, when using the equivalent scheme, which works on the electromagnetic torque – slip characteristic corresponding to the case when it is considered that the electrical parameters of the rotor vary with rotor frequency, from start (s = 1 , fr = 0 Hz) until slip $s1$ = 0.215 ($r = {}_{rx}$= 81.0 rad / s, fr = 12.9 Hz), then switch to the electromagnetic torque - slip characteristic when the electrical parameters of the rotor are constant. In this way, an active torque higher than the rated torque is ensured at start-up and the motor can start at rated load;
- I approximated the nonlinear magnetization characteristic FiLm - iLm and the characteristic R4 + R5 = R'_r / s - time (in fact, R'_r / s as a function of s) - parametric circuit element (variable in time) through points (which usually are obtained experimentally) allows the PACEN program to analyze such circuits and to highlight the undesirable phenomena produced by the saturation phenomenon - Joulle losses and especially additional iron losses. These lead to a reduction in the power factor and efficiency;
- I applied the method of identifying the parameters of a system, based on the transfer functions, requires their completely symbolic generation with the help of ASINOM and GESIFT programs, which generate any transfer function in relation to any two gates selected by the user;
- In order to identify the parameters that are difficult to estimate, I had to calculate the sensitivities of the transfer functions used, in relation to all the parameters to be identified, because the system parameters that have low values of the sensitivities are difficult to identify;

C3. Prospects for further development

The implementation of digital control and safety systems in nuclear installations, control methods and structures with controlled reliability, leads to a significant increase in operational safety, with the following immediate benefits:

- replacement of conventional components with computerized terminals (PLCs, LCD displays, etc.);
- simplified intuitive presentation of process data packets on color LCD panels;

- increasing the ability of systems to perform security functions through intelligent information processing; the possibility of running self-assessment and fault tolerance programs;
- flexible structures with possibilities for expansion and modernization;
- significant reduction of maintenance activities;

Modern digital systems offer opportunities to achieve ergonomically optimized human-machine interfaces for the selective access of various categories of personnel: process operators, service personnel , system engineers, managers.

These systems allow the acquisition and protection of data for immediate and long-term use, the rapid assessment of potential risk situations, as well as post-event analysis.

Fast local processing and taking critical protection actions are essential in the safety of installations, dedicated distributed control systems being recommended in this case.

The general trend in addressing future nuclear objectives is the unitary treatment and integration of the entire security structure into industrial IT systems with connections to high-speed digital networks and skills for unit assessment and emergency management.The execution of modern control cameras with large LCD display panels gives operators an overview of the processes and specific information on the operating status of the equipment involved.

I list the additional facilities expected for safety systems and control rooms:

- Online diagnosis and alarm with methods for automatic resolution and reconfiguration of systems and reallocation of resources.
- Online evaluation of system reserves; the number of active measuring systems and lines, the estimated measuring accuracy on each channel, the degree of dispersion and the level of disturbances, the degree of aging and anticipated wear for translators and equipment.
- Hierarchical treatment of concurrent events.
- Automatic validation of information, location and indication of significance.
- Display with ergonomic display systems, graphics and time magnifier.
- Introduction of additional security and diagnostic consoles, as well as for reconfiguration and service operations.
- Introduction of accident and crisis handling console with remote operation possibilities.
- Functions of simulation and prediction of the evolution of processes.

Intelligent processing of risk areas and alarm situations by classification, ranking and filtering can avoid operator overloading and situations of instability and indecision. Increasing the measurement accuracy of the process parameters by local digital processing leads to improved plant stability and increased efficiency by optimizing the reactor power for monitoring the network load.

The introduction of expert real-time evaluation and diagnosis systems, as well as multifunctional sensors with distributed intelligence, increases the degree of real-time information for system operators leading to faster decision-making. A very topical issue is the modernization of the current control and security systems in nuclear power plants, in order to achieve some objectives of prolonging their economic life.

Asynchronous electric power motors are some of the most important components in terms of safety of nuclear installations and not only, so this study can be continued based on the technical diagnosis and forecast of faults of these motors.

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