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DOCTORAL THESIS
(SUMMARY)

RESEARCH ON DECISION SUPPORT IN MAINTENANCE ACTIVITIES FOR EQUIPMENT

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ABSTRACT

The doctoral thesis titled „Research on decision support in maintenance activities for equipment" has as main objective *the substantiation of the decision for maintenance intervention by monitoring the industrial equipment operation*, and as working hypothesis that *any disturbance in a kinematic chain (KC) caused by the malfunction of a mechanism influences the parameters of the drive electric motor.* The changes that occur to the components of the technical system are continuous and caused by the wear and tear of the moving parts as a result of the fatigue and aging phenomenon, of the possible modifications of the physical-mechanical properties or due to thermal stresses above the values prescribed by the manufacturer in the Instructions Book.

A device containing a kinematic chain is modeled. This chain is formed of minimal elements (which simulate the operation of a real technical system) and the changes resulted from the load with disturbance factors lead to obtaining information that can be used for real electromechanical systems managed by means of ***maintenance markers***.

One mentions the steps for making an acquisition system using the LabVIEW software application.

We show the steps of the research leading to the moment of maintenance decision support**.**

The research carried out within this thesis led to an effective system of interpretation of the kinematic chain components status in a technological system by monitoring the drive electric motor. Thus, for the first time a connection was established between the dynamic characteristics of the motion transmission mechanisms and the electromagnetic system of the drive motor, by monitoring and analyzing the electrical parameters that characterize the motor condition. The name given by the author to these parameters is "***maintenance markers"***.

Key words**:** virtual system, maintenance markers, equipment modeling, technical parameters monitoring, virtual instrument, maintenance decision.

INTRODUCTION

Given the industrial globalization, the diminution of the material resources and the economic crises more and more present, a new approach has emerged in the use of production technical systems, emphasizing the new role that the maintenance activity may have in the production of goods with lower costs.

Although raw materials used in the manufacturing process are experiencing year-on-year increases, significant reductions in the cost of some products manufacture have been reported on the global market, as a result of a new approach to maintenance activity. This new framework for organizing the production has been taken into consideration by researchers from prestigious universities but also by members of the management board of many industrial companies.

The doctoral thesis includes an introduction, seven chapters, annexes and bibliography.

Chapter 1, entitled *„Current stage of the research on decision support in maintenance activities for technological equipment"* reviews the maintenance current issues. The methods used in maintenance highlight the effectiveness of observing the equipment and demonstrate that the continuous or timely collection of relevant data by means of complex systems, by monitoring the mechanical, electric etc state, allows the maintenance department to intervene efficiently for maintaining the technical systems in normal operation parameters and to effectively control the unplanned downtime.

The problems concerning the analysis of the technical equipment structure are developed in Chapter 2, called *„Analysis, identification and coding of the components of the technological equipment"*. This chapter points out that the equipment consists of interconnected running elements which form the technical system. But it has to be said that the special connections make the difference: the system thus constituted by a set of elements depends generally on the purpose and role of their design for the functionality of the technical equipment.

Chapter 3 called *„Monitoring of the technical systems, basis of preventive maintenance strategy"* highlights the evolution of the operating technical equipment and the permanent changes of a certain amplitude undergone over time. These changes that occur in the component elements are continuous and due to the wear and tear of the moving parts following up the fatigue and aging phenomenon, to the possible changes of the physical-mechanical properties or to a thermal stress over the values prescribed by the manufacturer in the Instructions Book.

Figure 3.1 shows the basic diagram of information acquisition during the monitoring of the technical system/equipment.

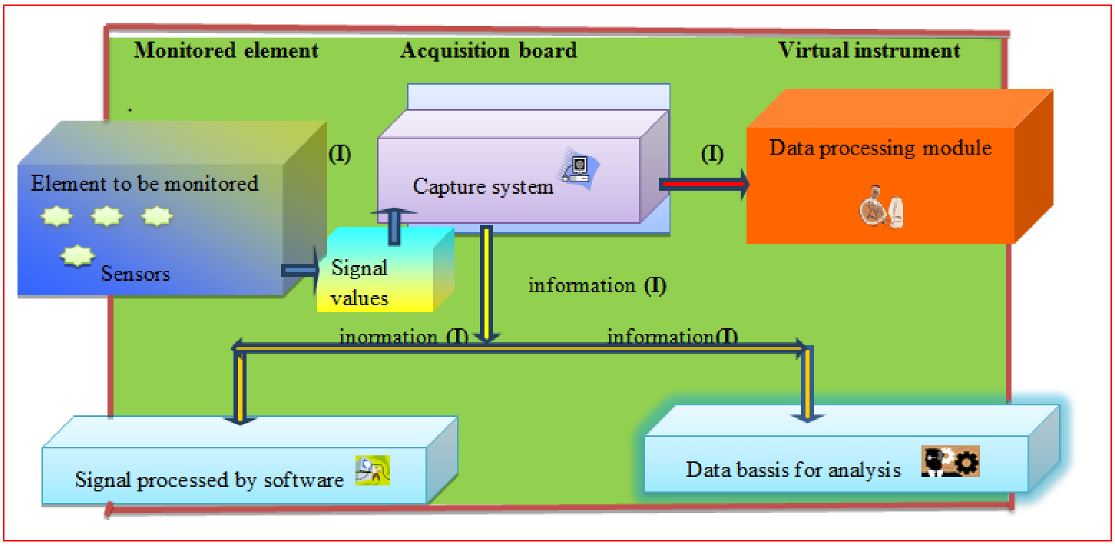


Fig.3.1. Basic diagram of information acquisition.

The monitoring screen of equipment behavior will also display the written information but only when the predetermined threshold of the recorded signal value is reached.

3.3 Components of the monitoring screen

The information collected must be managed and registered in conformity with the chosen strategy of action. The impact of the system monitoring on the key decision must be also monitored. Only the proper management of the information provided by the system and its adequate interpretation will lead the maintenance department to effective decisions.

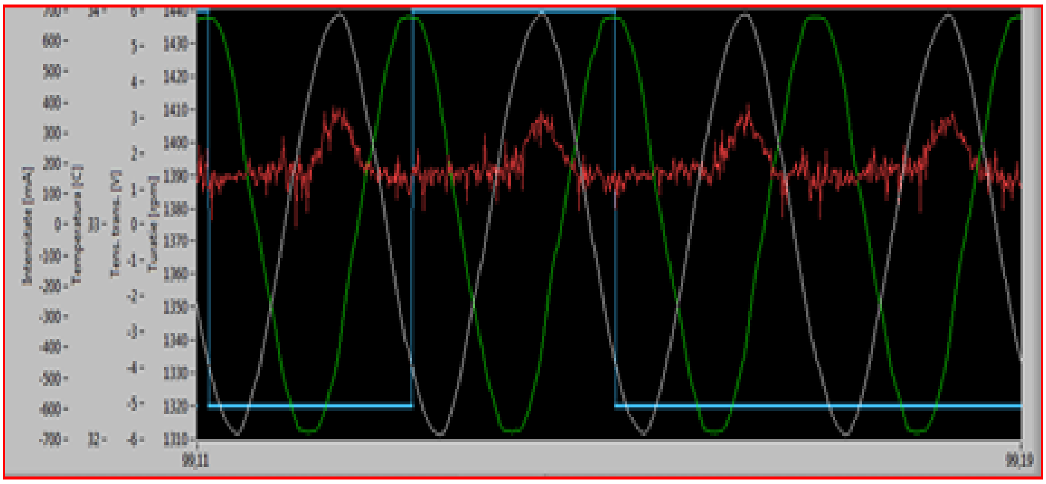


Fig.3.3. LabVIEW-based monitoring equipment

It should be noted that the displayed data bring relevant information regarding the operation of the monitored technical system (figure 3.3). In the case of exceeding the normal values of the measured parameters (for which normal values and operation limit are set) these data warn us optically on the system state at that time, figure 3.4.

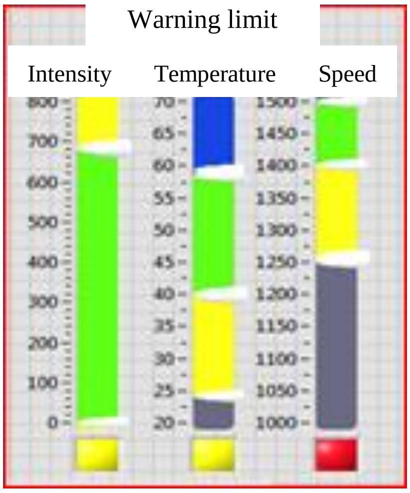


Fig.3.4. Monitoring equipment with optical warning

Changes in some parameters of the component elements of a technical system may also occur because of the operating conditions or as a result of some manufacturing defects presented in Chapter 4 of the thesis : *„Contributions on the simulation of a kinematic chain operation in MATLAB SIMULINK”*.

4.2. Modeling of the kinematic chain in MatLab Simulink

The concept used in the research work is based on the simulation of a technical system operation by means of Matlab software. Figure 4.3 shows the equipment model that contains a kinematic chain formed of minimal elements, used to simulate the operation of the technical system; the changes resulted from disturbance factors loading lead to obtaining information that can be used in the case of real electro-mechanical systems controlled by means of maintenance factors.

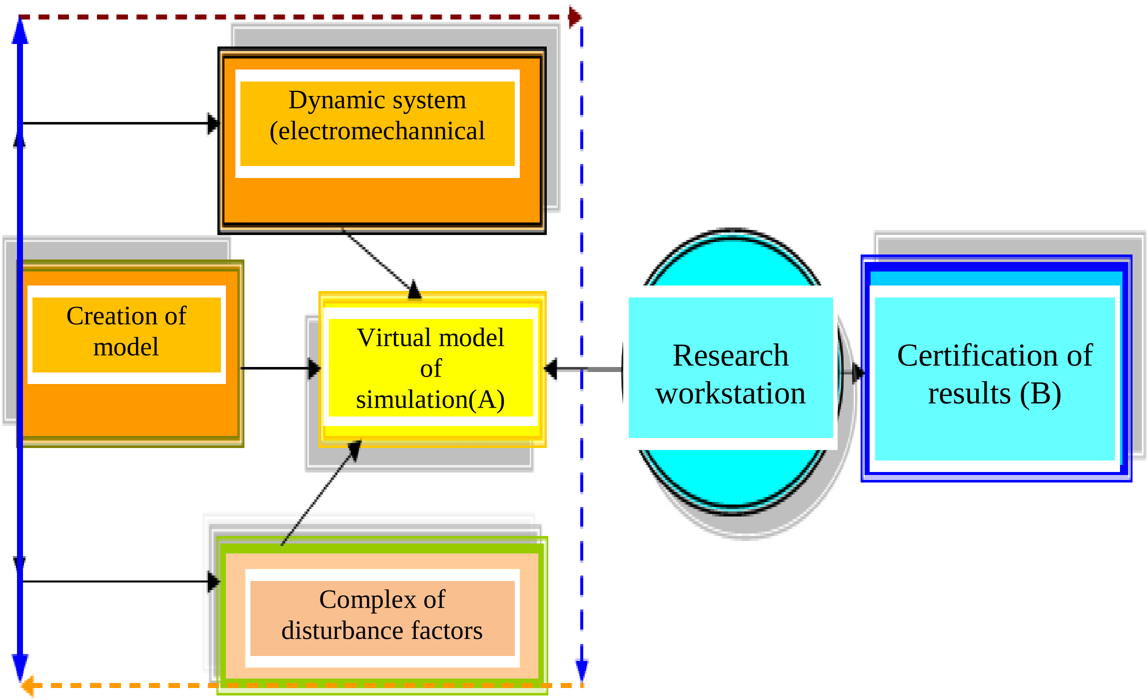


Fig. 4.3. Modeling of blocks to simulate the operation of the technical equipment

The use of the algorithm proposed by this model will simulate the control of a technical system formed of bearing assemblies with shafts, bearings, gears, couplings driven by an AC asynchronous electric motor. The purpose is to analyze the angular speed, motor rotational speed, electric parameters of the drive electric motor and the values imposed by the changes that occur during the equipment operation over time.

Figure 4.4 illustrates the model of the kinematic chain (KC) made in Matlab-Simulink.

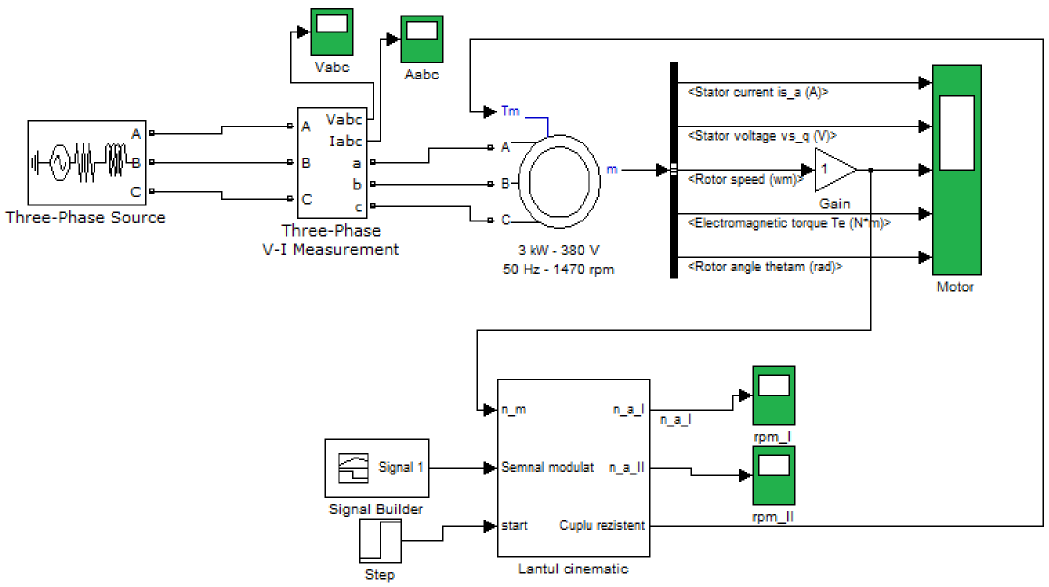


Fig. 4.4. Model of kinematic chain in Matlab-Simulink

The model of simulation technical system for the operating equipment is made on the basis of the data mentioned above, figure 4.5.

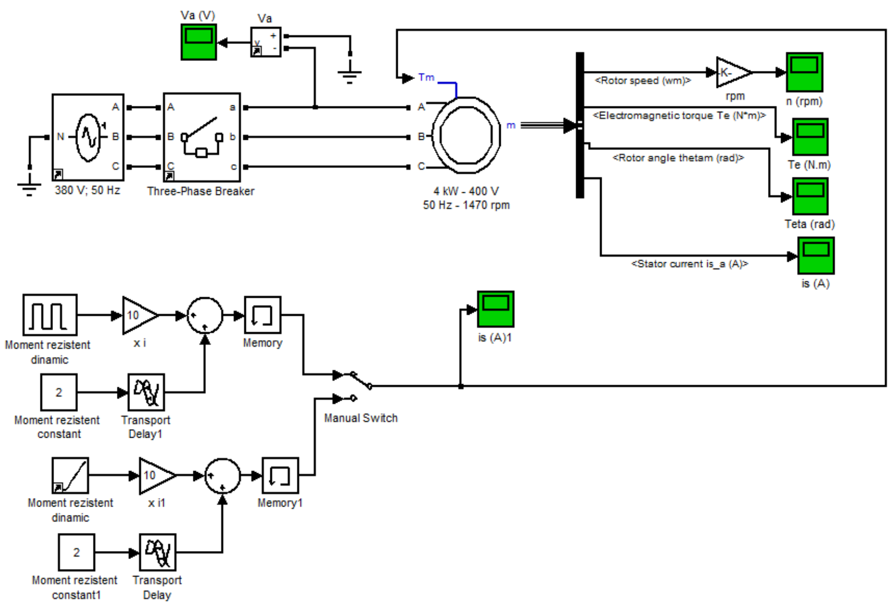


Fig.4.5 Structure of the analysis technical system (**A**)

4.3. Simulation of technical system operation

4.3.2. Simulation of technical system with load

Complex information and data which can be interpreted as establishing a disturbance area or a worn element of the technical system appear at a **supplementary load** (occurrence of a disturbance component, case 2) represented in figure 4.7, exemplified by:

- dynamic resisting moment (c)
- constant resisting moment (d)

In this case, the switch for disturbance components alternation is set in position 2 as in figure 4.8. It can be noticed that various information occur at a full rotation of the shaft, giving us the possibility to analyze the state of the technical system, figure 4.15.

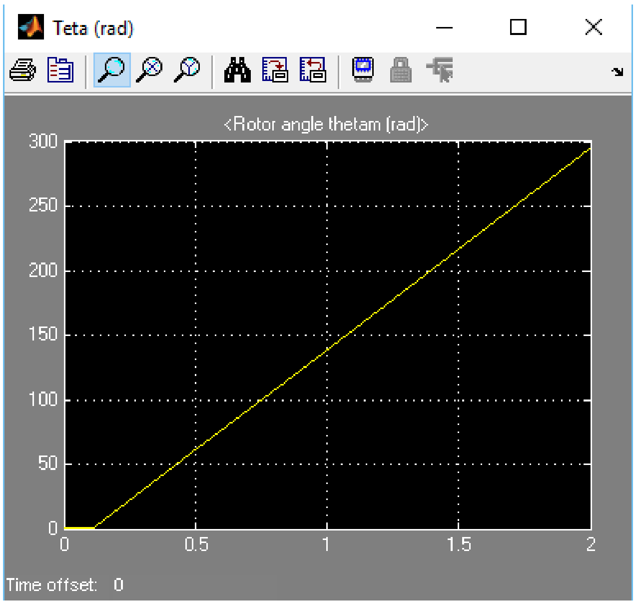


Fig.4.15. Signal recording during a shaft rotation

The system imbalance shown in figure 4.16 is analyzed when a component / phenomenon (**F**) disturbance occurs in an angular range. In this simulation we considered a force that appears in a certain area, namely in the angular range 0 - 90°. This range can be related to a period of time and can give much information with which to perform analyses for each spindle.

The information obtained helps to determine the angular position and the spindle where an imbalance occurs, in our case (spindle 3) in figure 4.2.

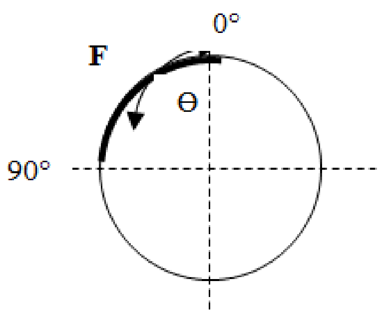


Fig.4.16 Simulation of the disturbance period of time

The engine rotational speed is known, namely: n_m= 1470 rpm.

Thus we can determine the speed of the spindle no.3 using the formula:

$$n_m=1470*i_1*i_2*i_3 \quad (4.23)$$

in which: i_1, i_2, i_3 are the ratios of transmission to the gears.

In this case, it is possible to identify the value of the torque that increases over the time interval: 0.1-0.11s (on the 0-90° range), after which it decreases up to the minimum (normal) constant value, shown in figure 4.17.

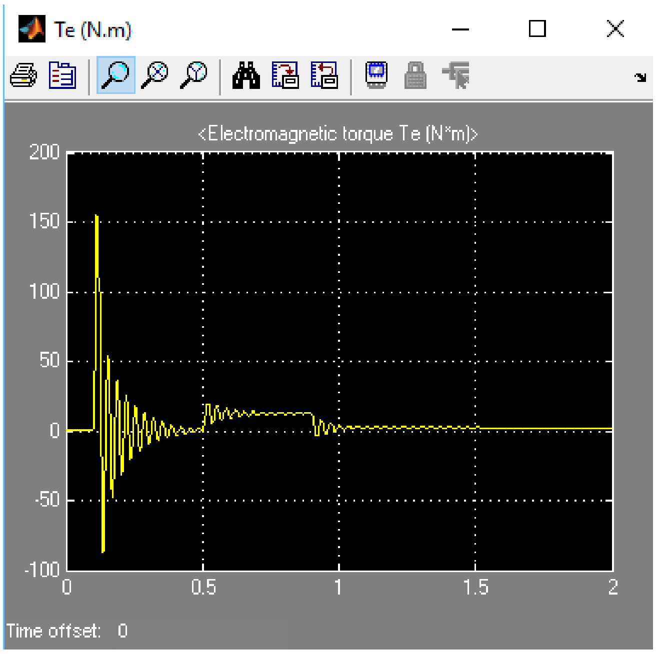


Fig.4.17. Marking the maximum torque at the electric motor

The time interval is associated with the angular interval where we have the maximum moment of system disturbance, value reflected in figure 4.2, value Θ (time interval, associated with the angular interval).

Following up the occurrence of the disturbance phenomenon, highlighted /simulated in the first interval of the rotation movement of the rotor of the electric motor, figure 4.16, a fluctuation of the electric current quantity can be observed. It increases in a short period of time, as seen in figure 4.22.

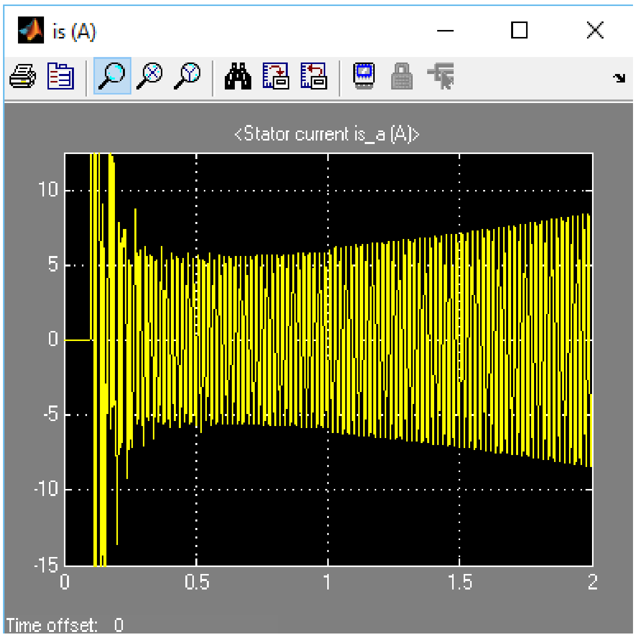


Fig.4.22. Monitoring of electric current intensity

The value of current remains constant until the disturbance element occurs in the time range (1.5-2)s, when the value increases up to the acceptable maximum limit, as seen in figure 4.16 (0-90° range).

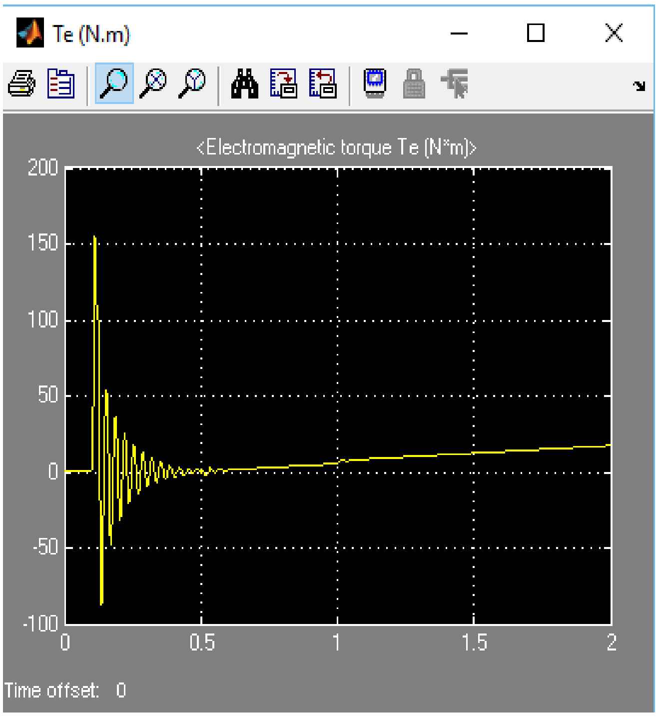


Fig.4.23. Monitoring of disturbance component

In figure 4.23 it can be observed a steady increase of force as a result of passing through the disturbance area. The time interval is short but the data obtained lead us to a result similar to the one studied and to the conclusion that the simulation approaches the real part of the research.

The simulation method is relatively simple in the context of the structure of the technical system under study, shown in figure 4.24.

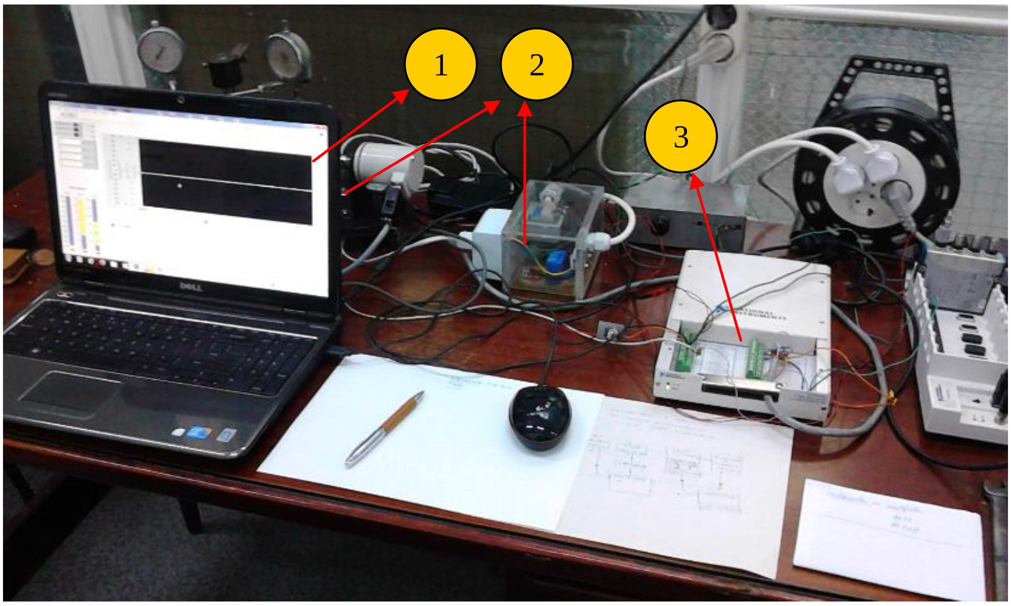


Fig.4.24. Technical system under study (1-system, 2-sensors, 3-acquisition board)

From all matters presented above it results a behavior similar to the one of the real system studied. Information reveals that similar data appear in both situations after a period of proper operation of the technical system (the monitored critical elements): increase of stator current intensity, increase of motor housing temperature, diminution of the electric motor speed. It has to be said that, in the real case of the research, the software module enable us to mark some minimum/maximum thresholds by optical or acoustic signal. In the real case, the system can be turned off automatically if this function is programmed.

In Chapter 5, *„Contributions on the creation of a virtual system for maintenance markers acquisition in a kinematic chain”* the stages for making of an acquisition system are mentioned. In order to create this system it is absolutely necessary an analysis of the information for setting up an application.

5.1. Stages of creation of a virtual system of data acquisition

The route of information is based on the necessary data that must be captured from the equipment submitted to analysis.

The specialist of maintenance should select and customize out of LabVIEW software application variants the type of application needed to extract the information reflecting the study basis.

The composition is as follows:

- monitoring the temperature of a part of the electric motor housing;
- saving the data at a required time interval;
- process control loops;
- dynamic signals acquisitions;
- connection bridges (A,B)

Defining the signal for the analogue input allows the use of thermocouples, current and voltage sensors while the outputs are current signals.

Electrical signals from an incremental encoder are used for the digital signal. This encoder makes possible the counting of the rotations of an element belonging to the equipment, the counting of events and the generation of pulses.

It must be taken into consideration that the scanning ratio should be > 10 samples/s and the resolution of 16 bit. The monitoring system is formed of a central unit (laptop) and the operating system is Windows 7.

5.2. Virtual system for measuring the maintenance markers in a kinematic chain

The front panel of the virtual instrument is shown in figure 5.3 (for speed, temperature and current intensity).

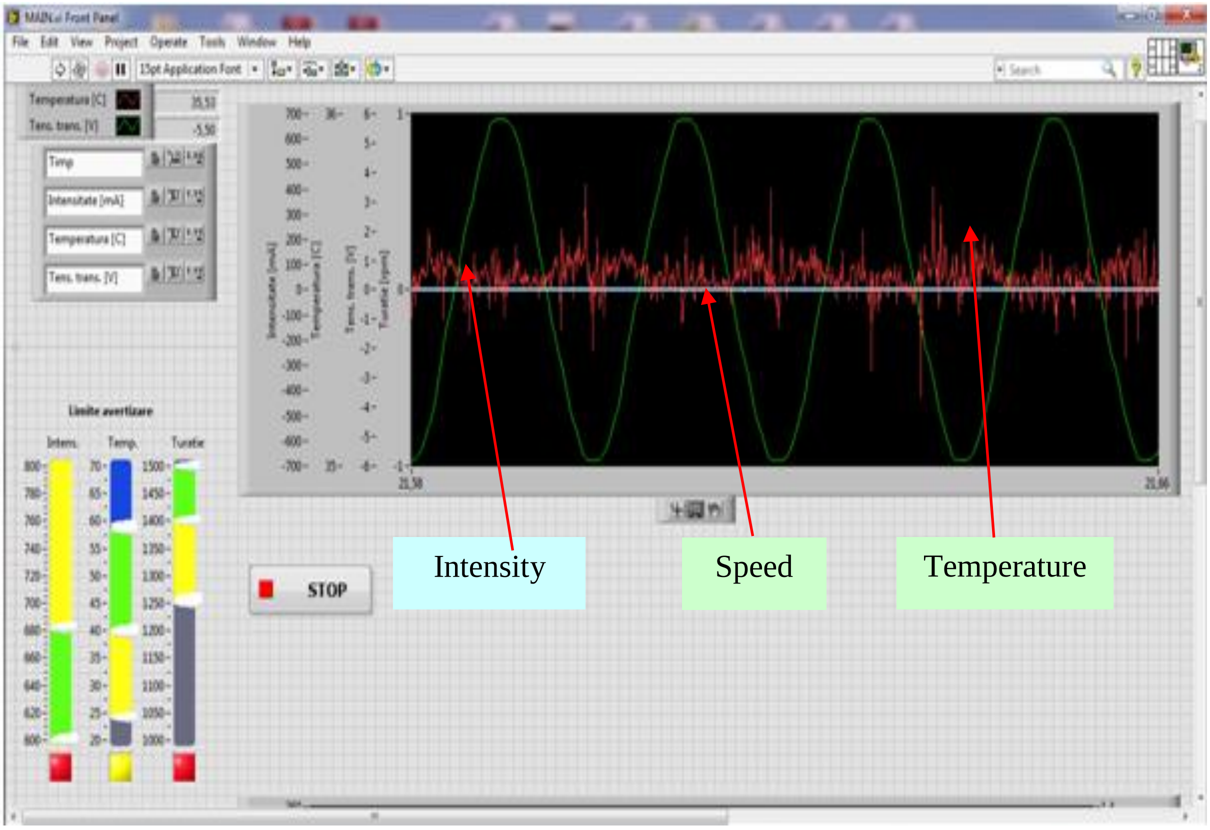


Fig. 5.3. Front panel for monitoring the speed, temperature and current intensity

When the working tools are set on the front panel (that means when the connection between the maintenance operator and the working unit is established) the block diagram of the virtual measuring equipment must be defined depending on the working tools, with the help of the executable nodes. In fact, this even means the implementation of the software program that will trigger the acquisition of information at the virtual equipment and it must be created for each analysis of captured signal.

A part of the block diagram is shown in figure 5.5.

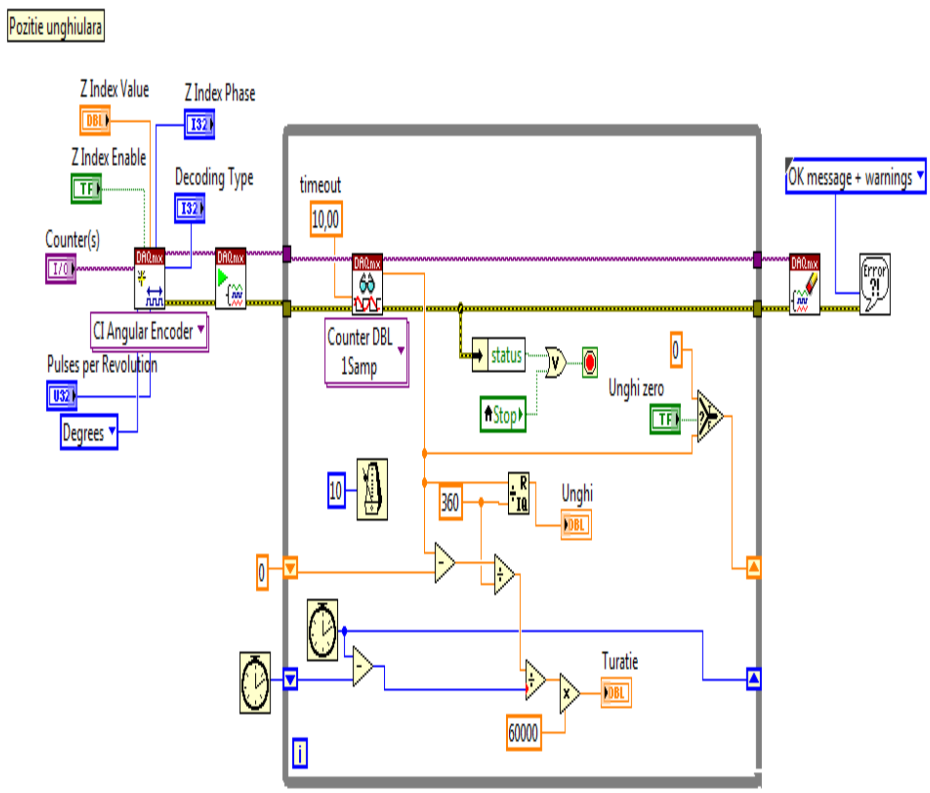


Fig. 5.5 Block diagram of a virtual instrument

The LabVIEW environment provides the maintenance specialist with a very simple and highly oriented graphical interface, which supplies relevant information on the electrical signals studied (temperature measurement, for example), figure 5.8.

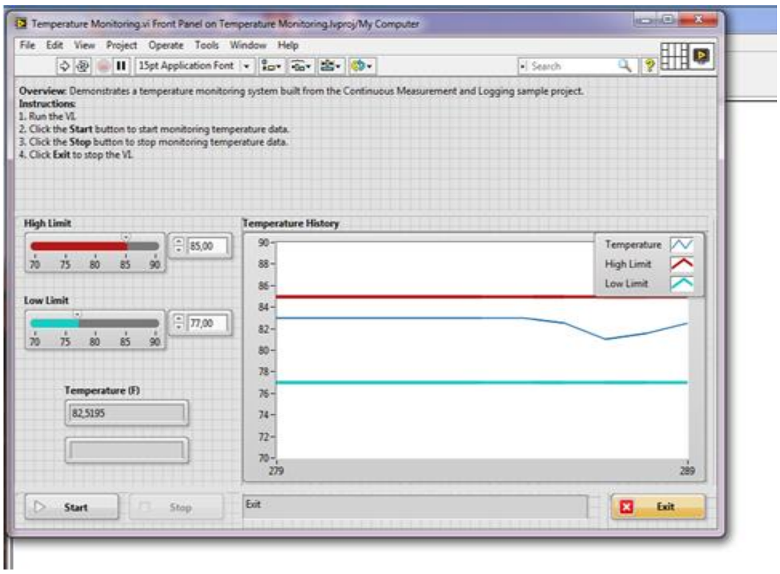
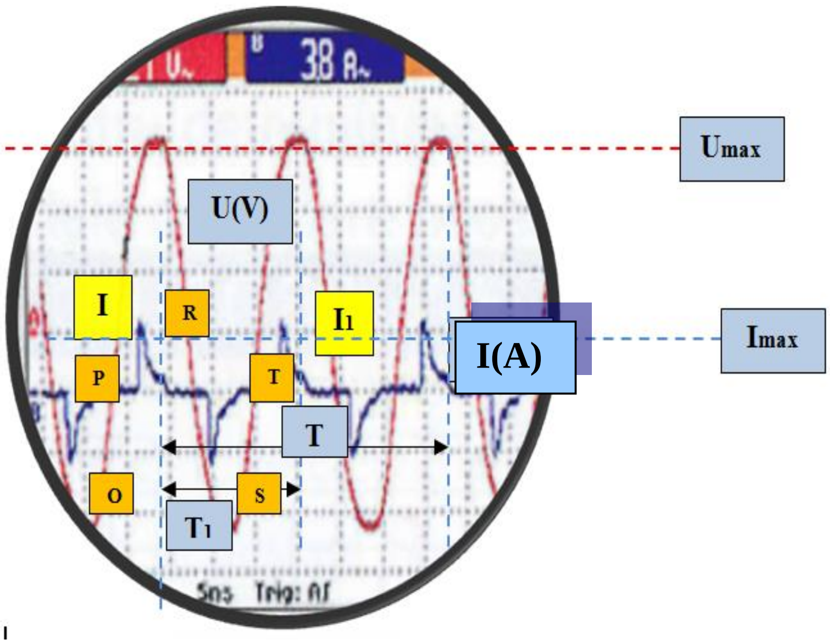


Fig. 5.8. Virtual instrument for temperature monitoring

5.4. Analysis of the monitored signal

The wear and the misadjustment that may occur in a production technical system lead to the alteration of normal operating signals and consequently give us the forefront of issues that affect performance and smooth-running. The process of direct analysis of the received information allows the comparison with the data specific to good operation, according to the documentation of the manufacturer. In this way it can be understood how operates a technical system which is monitored by dedicated markers, enabling the collection of important data and the analysis of its state, therefore letting us to be prepared to make the right decision.

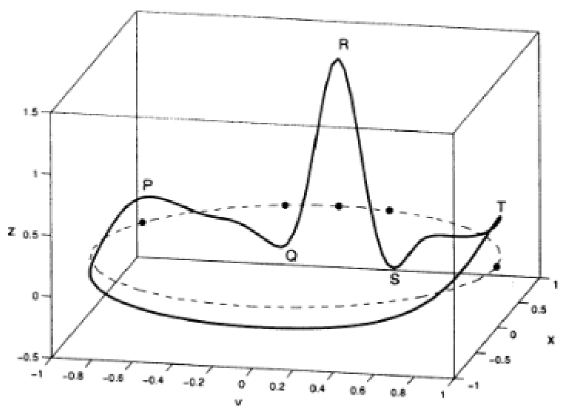
The method proposed in this paper discusses the use of the Hilbert transform to study the shape, periodicity/rhythm of an electrical signal.



- I = intensity of motor current;
- U = motor voltage;
- points on z axis (P, Q, R, S, T)

Fig. 5.9. Measurement of T_1-T intervals in order to determine the state of the technical system

Thus, for a current signal of normally running equipment (electric motor), the vectogram (the Hilbert transform for the shape of the electrical signal) performs a well-defined, accurate and rhythmic path with a trajectory restricted in three-dimensional plane. This vectogram is shown in the figure below.



$\dot{x} = \alpha \mathbf{x} - \omega \mathbf{y}$

$\dot{y} = \alpha \mathbf{y} + \omega \mathbf{x}$

$\Sigma{\downarrow}P_i(\ i \in \{P,Q,R,S,T\})$

a b

Fig.5.10. Equations (b) that generate a trajectory in three-dimensional space (a)

The positions of the points (P, Q, R, S and T) from the shape of the current signal are highlighted by the torques that register a maximum and a minimum in z direction. These torques are placed at fixed angles on an imaginary unit circle representing the angles *θP, θQ, θR, θS and θT.*

The solution of the equations leads to the results used in LabVIEW software application. In the first phase, the values of the samples of an ideal signal were obtained (normal operation of the electric motor), after which the Hilbert transform[7] was applied.

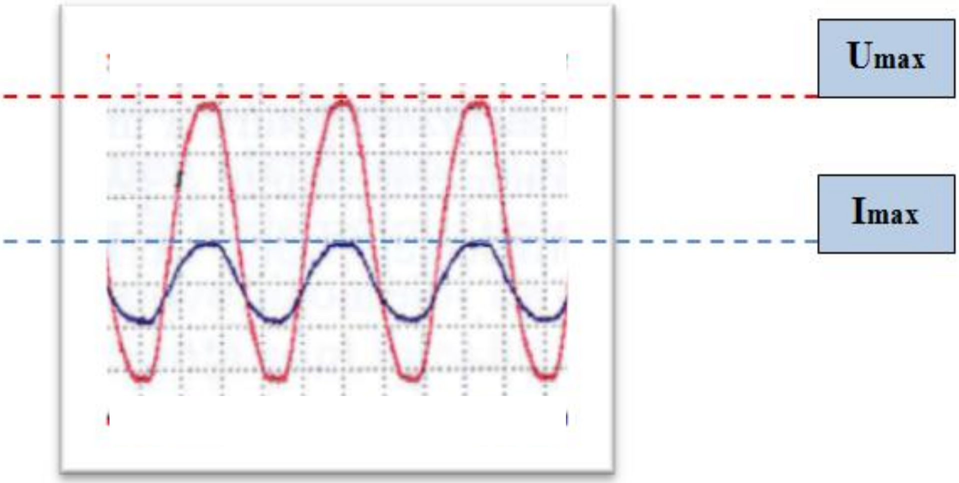


Fig.5.11. "Good" signal associated to a normally-running motor

Figure 5.11 reveals that the value of current (the normal signal at the commissioning of the technical system) is constant and tends to a limit-trajectory. This monitoring was also used to analyze the signals of the electric current at certain time intervals in the range of normal operation of the machine tool until reaching the intervention threshold for restoring the normal operating state (using the monitoring maintenance strategy).

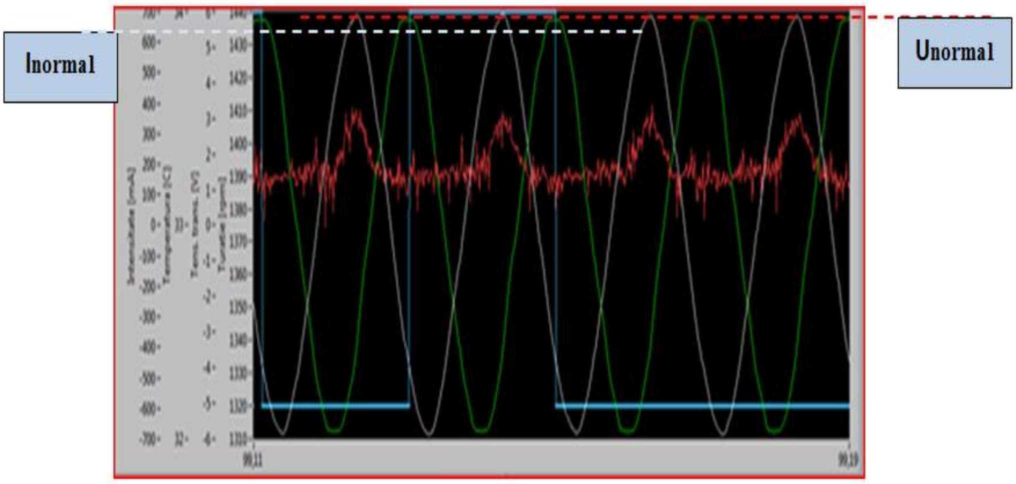


Fig.5.12. Signal associated to a motor with parameters at the threshold limit of proper operation

Regarding the current of the electric drive motor of the equipment, we find out that it has a value above a certain threshold of normal operation, figure 5.12. In this context we must make the decision to intervene.

Figure 5.13 shows the operation of a technical system.

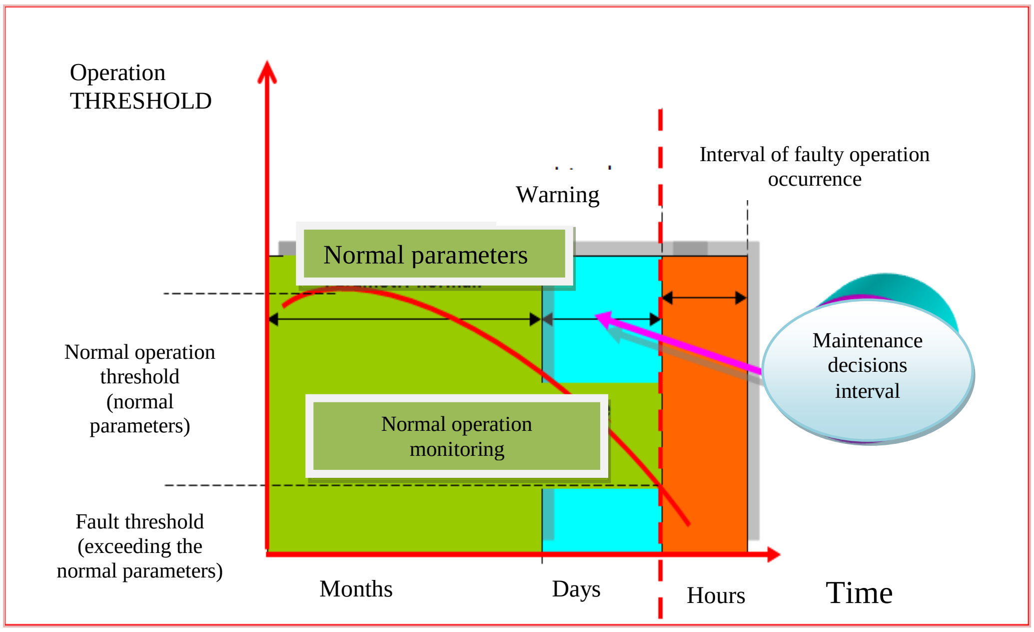


Fig.5.13. Operation of the technical system

5.5. Maintenance markers

The maintenance markers represent a number of technical parameters that can be monitored (e.g.: temperature, speed, intensity, current, angle, vibrations etc) specific to a technical system (electric motor, kinematic chain) with values within well-defined intervals.

A maintenance marker must provide the maintenance operator with information about:

- specific of a certain technical system/assembly/element;
- diagnostic mode of the system;
- possibility of monitoring and recording;
- predictivity of parameter value.

After the establishment of the number of markers, depending on the analyzed technical system, the monitoring of their evolution can be started along with the implementation of some maintenance operations as follows:

- if their value is within the good operation range determined by the specialist, it is considered that the maintenance operation was well done and the system runs normally;
- if this value is at the maximum level of good operation, it is considered that there are also other elements that do not allow normal operation and a new intervention on a system component shall be decided;
- the rapid increase of the value towards the warning field entails the decision to stop the technical system and to make a complex analysis of system critical components (established).

5.5.1. Motor speed

The motor speed, main component in communicating information on the technical equipment state, is given by the instantaneous rotational speed of the motor spindle. Combined with motor torque, the motor speed provides an overview of the mechanical performance of the rotary equipment.

By using algorithms, depending on LabVIEW software maintenance markers along with the specialized acquisition board, the operator is provided with information about the quality of the electric power of the drive motor by means of the shape and values of the single phase/three phase voltage and current required to calculate the speed and the intensity of the current absorbed by the motor, with an update frequency of 1 second. The analysis of the air gap field of this motor shows that the wave sizes/shapes of voltage/current represent the basis for analysis.

5.5.2. Electric analysis of the motor

Before we start the analysis of motor parameters, we must make reference measurements of energy quality to eventually find out the state of harmonics and the imbalance at the electric equipment output, so as not to have a major negative impact on the motor.

When we start the measurements, the results are summarized for the electric performance, mechanical performance etc. The proposed analysis scale has four color levels easy to understand and indicate the motor performance depending on the recommended levels of the electric parameters. The monitoring system allows seeing instantly the motor speed, current rating, motor housing temperature and voltage normal signal. The motor normal speed is instantly compared to the speed at time t_n and it puts at our disposal real-time technical information to help us make the right decision in due time. By analyzing these values at defined time intervals we can easily measure the equipment condition during each operating cycle, figure 5.14.

The monitoring screen is updated in the same time with the change of the charge and electric conditions and each new measurement is plotted with a specific color. In this example the motor has a normal speed value (such as the one shown on the nameplate). This fact indicates that there is no need to ameliorate the power quality, to make motor maintenance or other adjustment to improve motor performance. By frequently performing these tests over time, it is possible to create familiar references and good operating trends. The analysis of the current is very valuable information in any maintenance system that uses a continuous monitoring program of the running state of the motor.

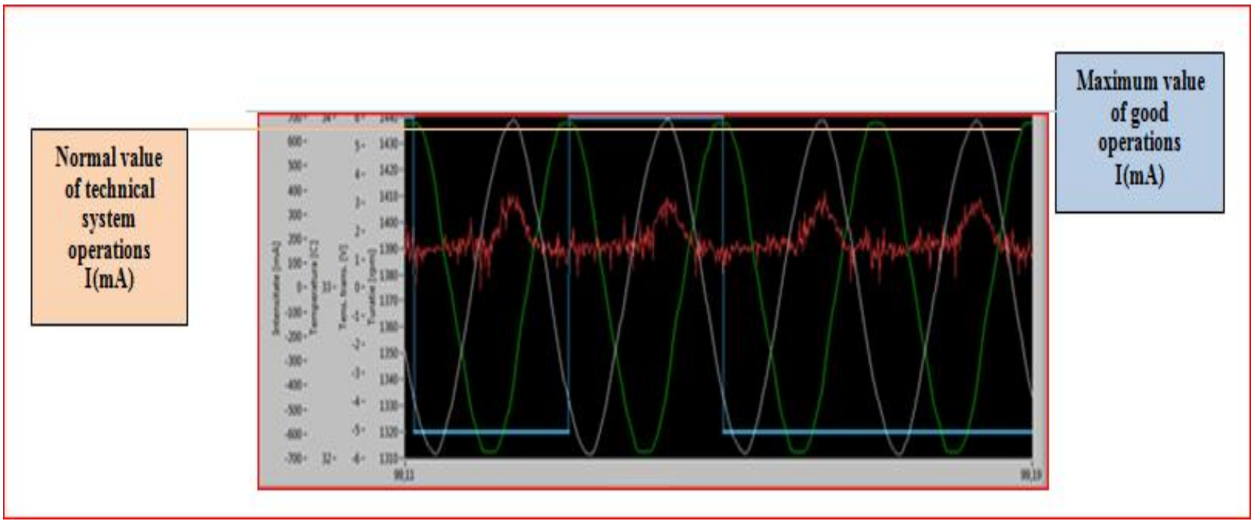


Fig. 5.14. Monitoring of electrical signals

This instrumentation can be used by the maintenance department of a company to analyze in real time the behavior of production equipment [99].

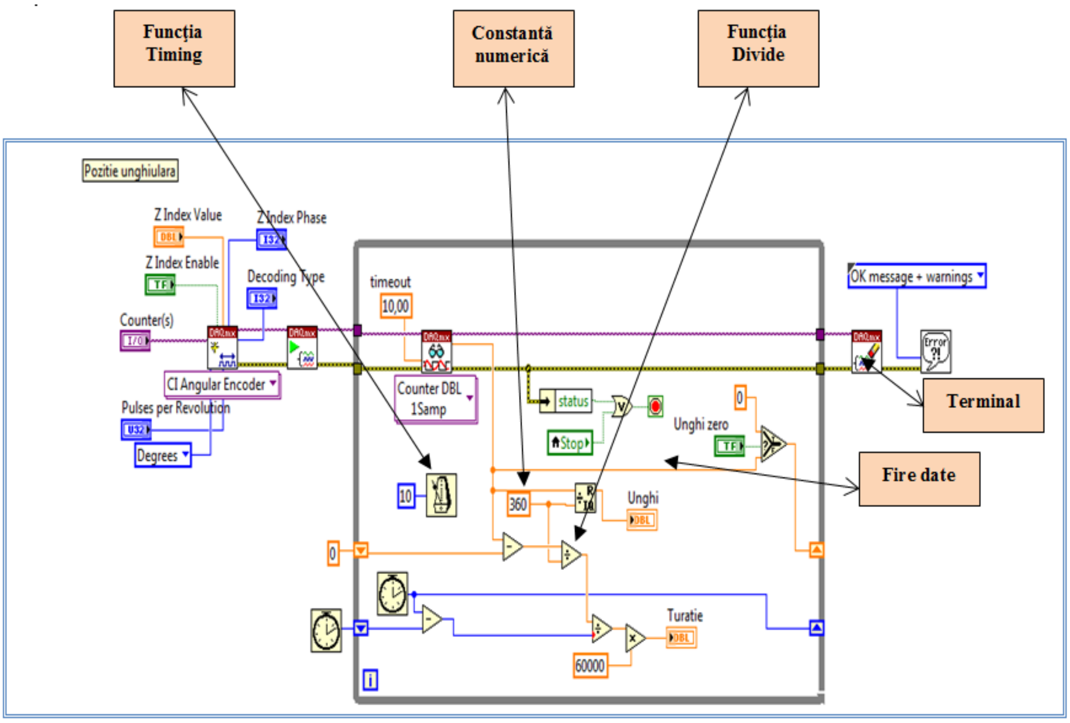


Fig.5.16 Block diagram 1(measuring device for angle and vibrations)

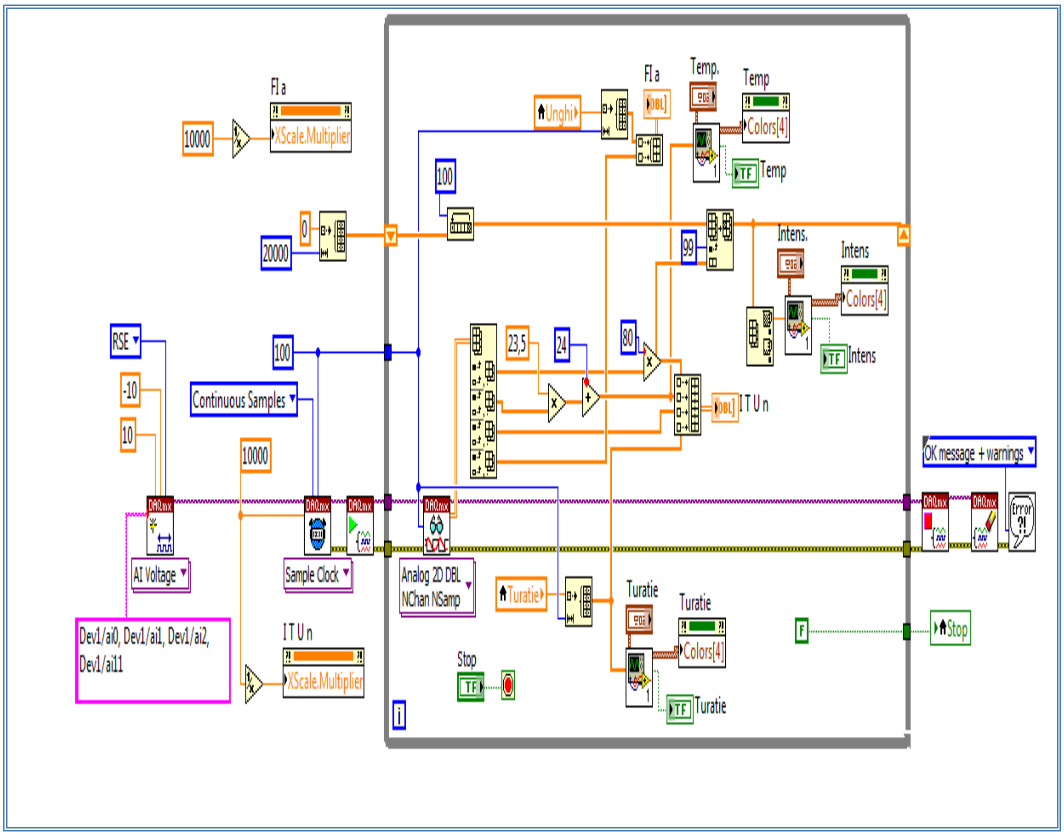


Fig.5.18 Block diagram 2 (measuring device for speed, temperature, current intensity)

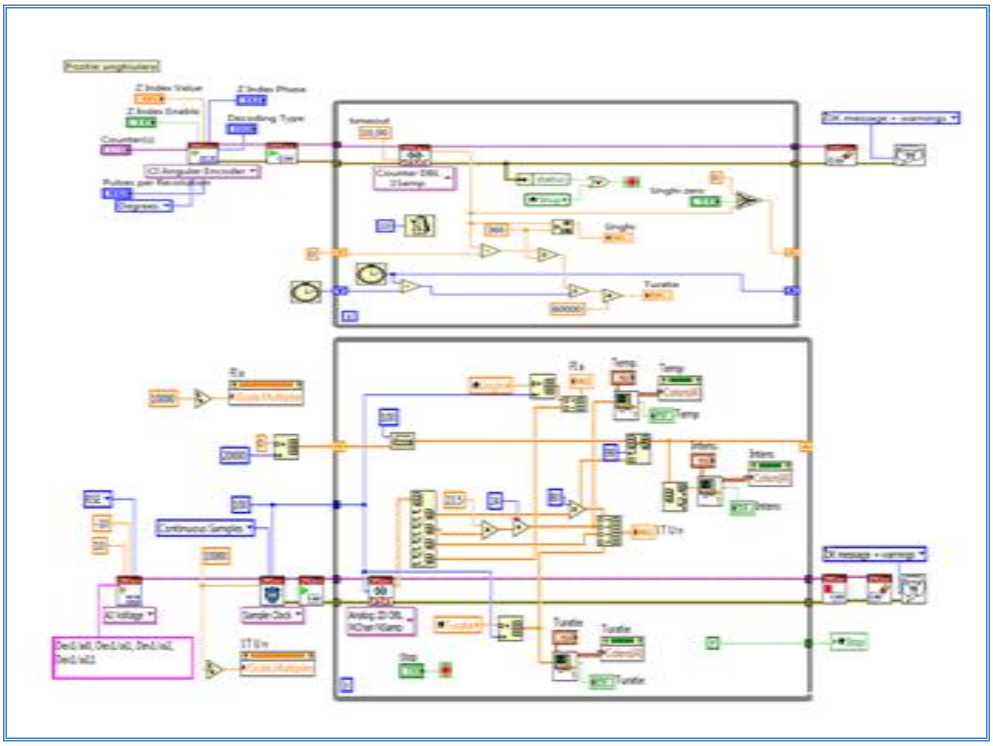


Fig.5.20. Block diagram of virtual equipment for electric motor monitoring

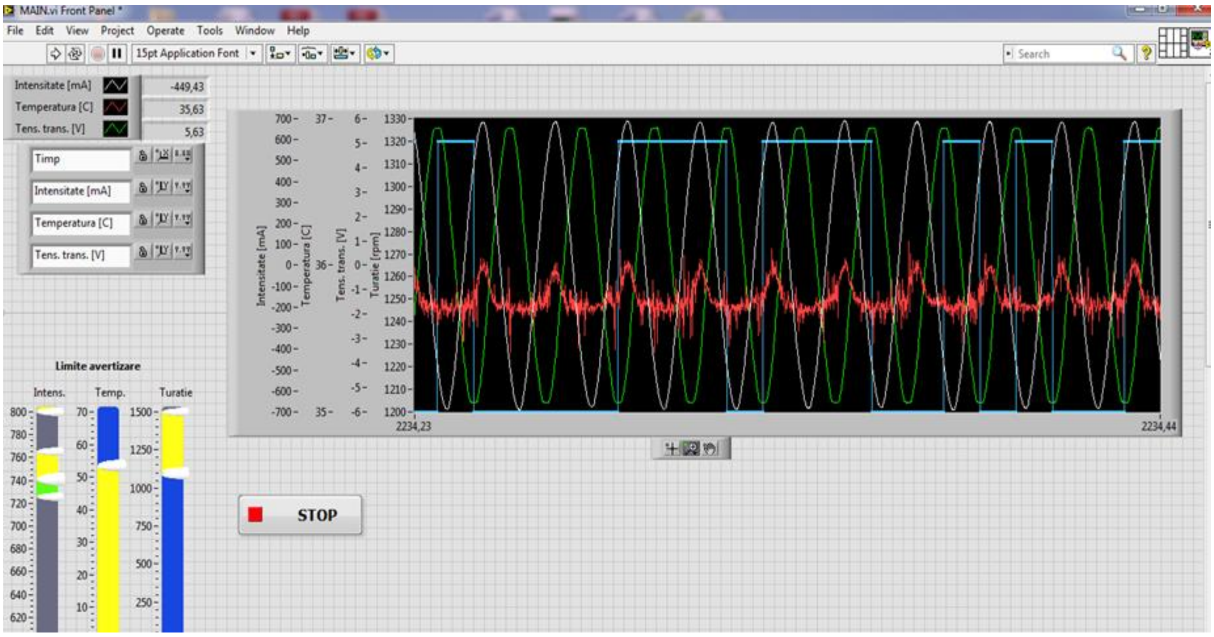


Fig.5.21 Frontal panel of virtual instrument l (block diagram 1(a), 2(b))

Chapter 6 named „ *Experimental research for diagnosing a kinematic chain by maintenance markers monitoring and decision support"* shows the research stages that lead to the moment of maintenance decision support.

The current analysis is based on the fact that the electric motor can be seen essentially as a transducer. Thus, the motors of equipment can be remotely tested from the maintenance department of the production hall, eliminating the risks of making measurements in dangerous or inaccessible zones.

The monitoring of the electric motor operation over time reveals that the harmonics of the current flows, visible in the equipment under study, appear when there is a high resisting moment (for example due to the malfunctioning of a kinematic chain component). These flows induce current components in the stator winding which causes the modulation of the input current. Knowing these signals help to identify the improper operation of a component of the technical system and to assess how severe is the improper running of the kinematic chain of the machine tool.

6.2. Making of the workstation

The workstation brings together a multitude of characteristic elements of a technical system that participates in the production process.

The component parts (figure 6.3) are classified as follows:

- working parts (specific to the technical system –bearing assemblies, shaft, bearings, motor, coupling etc);
- monitoring parts for the maintenance markers (signal captors: encoder, transducers of: current, voltage, temperature, vibrations)

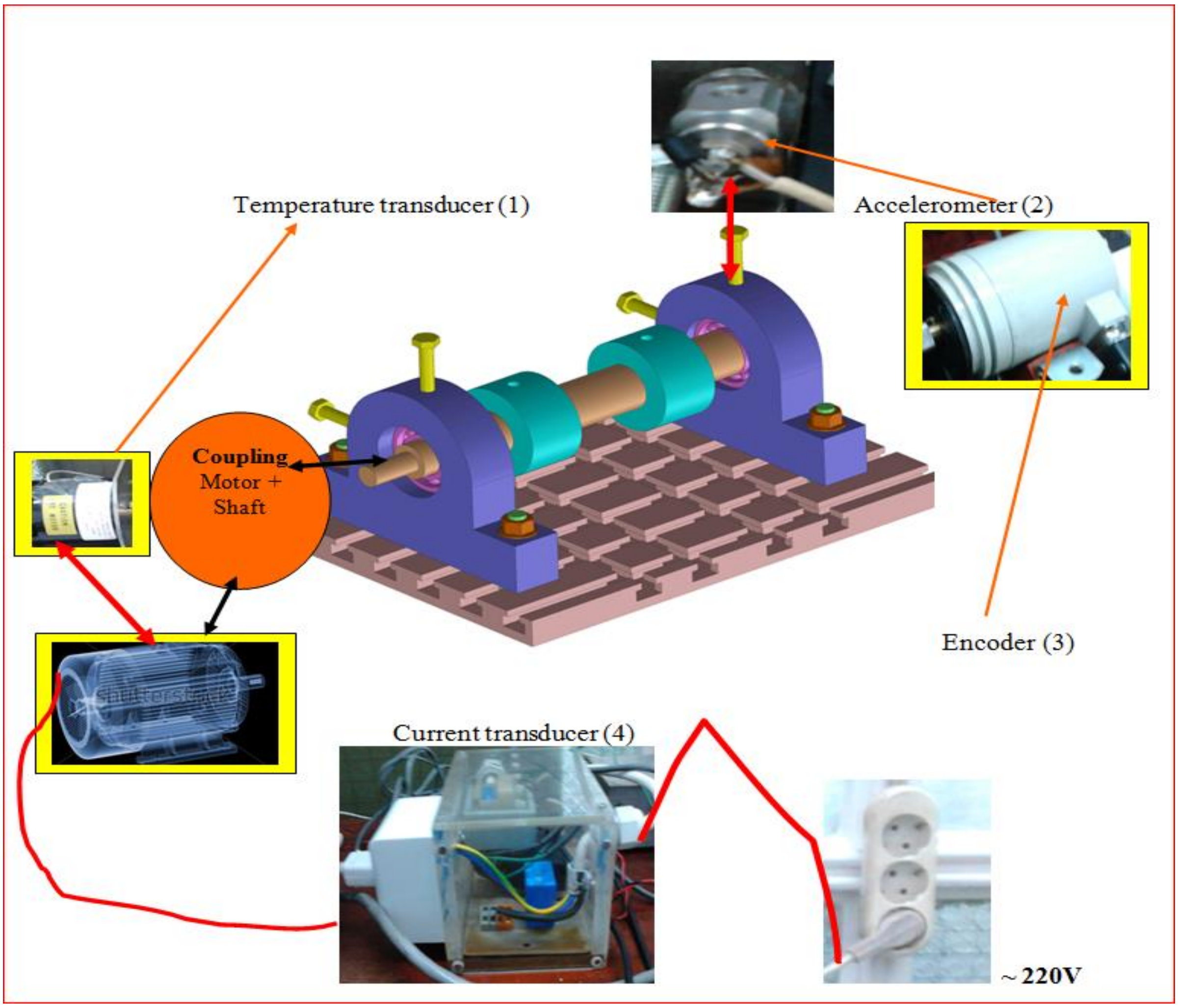


Fig.6.3. Workstation

Figure 6.4 shows the research workstation formed of sub-assemblies and components for the simulation of specific phenomena that may occur during the operation of a kinematic chain.

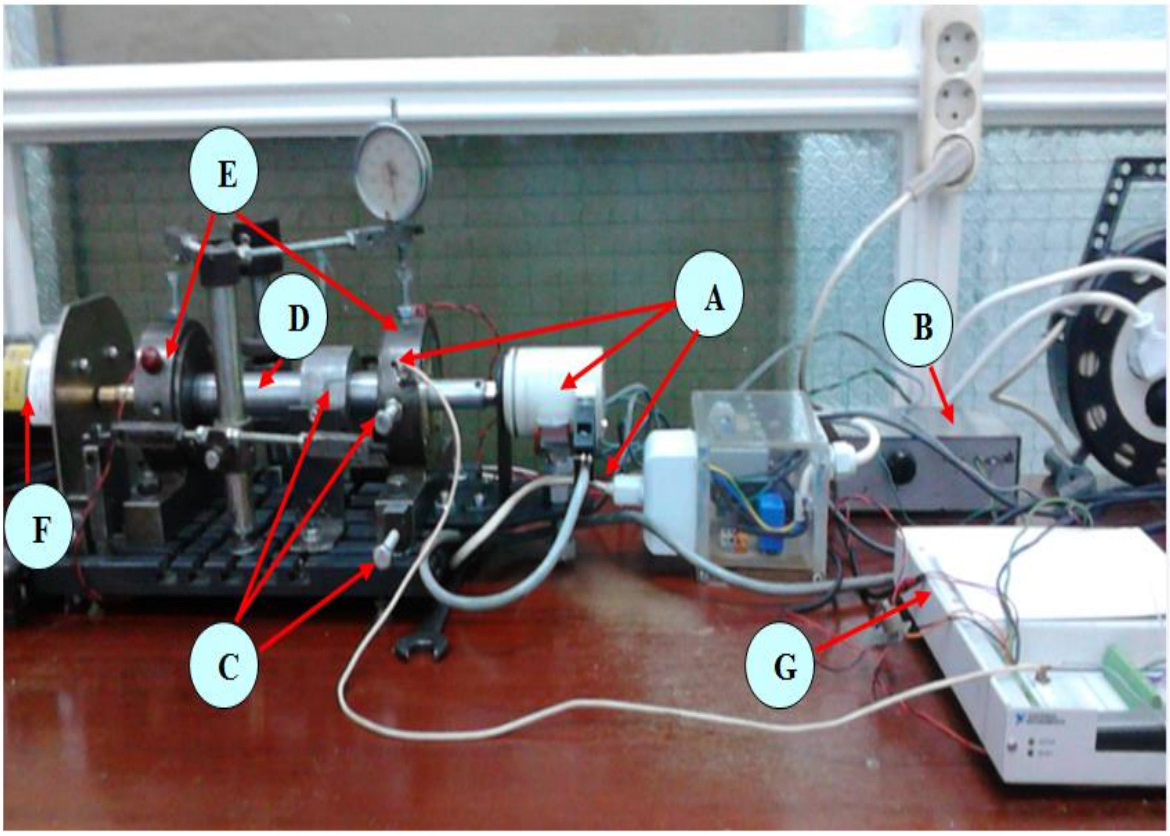


Fig.6.4 Work equipment under research

The research workstation includes the main elements of the work equipment, a complex of stimuli for imbalance, captors for the acquisition of possible information, system of analysis and monitoring, namely:

- transducers block assembly (voltage, current, rotational speed, angle, vibration) - **A**;
- compact system for amplification of the temperature transducer signal - **B**;
- constraint simulation elements (screws, magnet) - **C**;
- main shaft - **D**;
- main support bearings for the main shaft - **E**;
- single phase electric motor for main shaft drive – **F**;
- acquisition board, specialized software, monitor - **G**.

6.3.2. System for imbalance/simulation of operating hours

As it can be seen in figure 6.6, several elements were used to introduce simulations of possible phenomena that arise during the operation of the technical equipment. These elements are the following: screws (**A)**, sliding element (**B)** that has the possibility to be fixed in a certain position on the shaft. The screws allow introducing some simulations intended to reflect the state of the technical system depending on the number of operating hours. The starting point was to equal the screws movement to hours of operation. This was necessary for diminishing the operating time of the technical system. Thus, the maximum movement of 0.3 mm of the screws was equivalent to about 2500 hours of operation. At the same time, the sliding element was implemented to highlight the phenomena that may occur in the elements for rotational movement transmission (gears, sprockets etc).

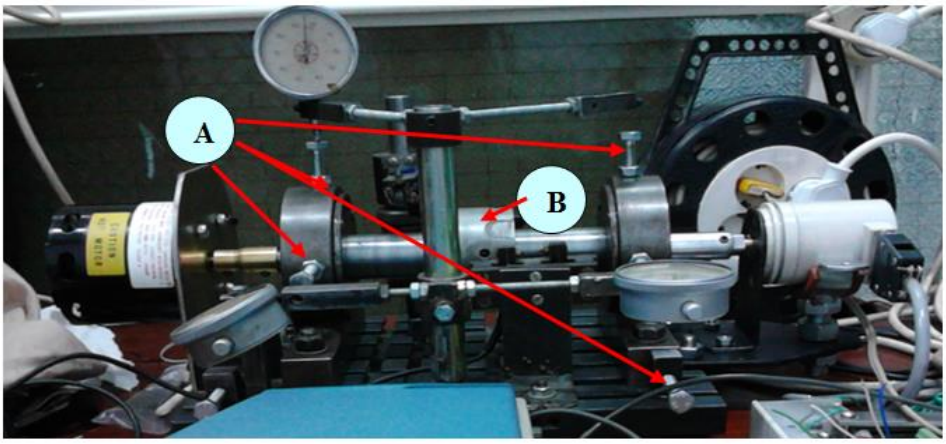


Fig.6.6. Imbalance system

6.3.2.2. Simulation of the operating time of a technical system

According to the specialized literature [113,157], by analogy, we start from *the average time of faultless operation* of the equipment which is taken into consideration by the manufacturer and the customer during the acceptance of a system (time that is estimated, however, on the basis of manufacturer's own experience) and which ranges between the limits T_i (lower) and T_m (upper).
In the specialized literature mentioned above, the values of the operational risks were noted by α and β. For declared reliability we have α = β, and the values used by the specialized literature are as follows: 0.1; 0.15; 0.2; 0.25.

In [113,157] it is mentioned that the long duration of a reliability acceptance test is uneconomical. In this situation, other elements (variants) of calculation can be considered.

Thus, the admissible limits of the technical system accuracy reserve can be taken into account. According to[113,157] it is possible to determine the operating time within the accuracy limit T, figure 6.8.

In the resulted triangle Δ ABC, see figure, the straight line CB represents the precision of the machine tool in the time interval Δt.

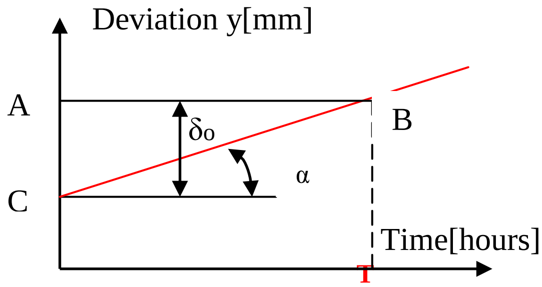


Fig. 6.8 Deviation variance y(t)

There is the relation:

$$tg\ \alpha = \delta_o / T \qquad (6.1)$$

but,

$$b = tg\ \alpha \qquad (6.2)$$

where: T = time of good operation (hours)

δ_o = precision of the machine tool (Instructions Book) (mm)

b = speed with which the accuracy reserve decreases (mm/hour)

We assumed that the wear and tear of the system (accuracy) is within the maximum range of 0.03mm when the intensity of the current is less than 0.8A. If we consider that in a precision lathe [113,157] the value b = 0.000012 mm/hour, we have the good operating period at the value:

$$T = \delta_0 \cdot 1 / b. \qquad (6.3)$$

where:

0.03 (mm)/0.000012 (mm/hours) = 2500(hours) maximum value

In this context, we took into account the maximum good operating period of 2500 hours for a simplified system. The intermediate values of 1000 and 2000 hours were also analyzed.

6.3.5. Optical warning system for making the maintenance decision

The optical warning system shown in figure 6.11 is a configuration of a LabVIEW software in which the components used for signals acquisition and the type of signal were taken into account. At the same time, monitoring devices adapted to the research needs were configured, respectively a platform for monitoring the values of the electric quantities (voltage, intensity), temperature, rotational speed, vibrations and angle where the phenomenon is manifested.

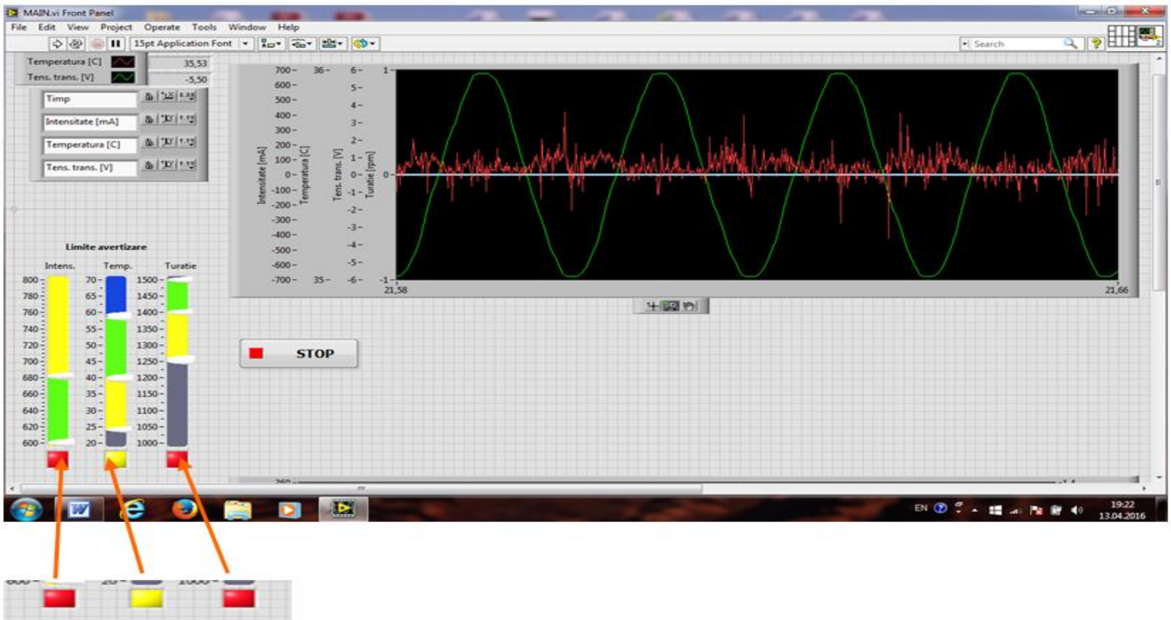


Fig.6.11. Optical warning system

On the left side it can be seen the warning specialized system which provides us with an optical signal (- abnormal,  - normal) when the maximal/minimal values of normal operation of the studied equipment elements are reached.

The capture shown in the figure above (e.g.: power supply = 220V alternative current, intensity = 0 A, temperature of motor housing = 34.5 ºC, speed = 0 RPM) highlights the power supply from the power outlet; the equipment is cut off after one hour of operation approximately. It can be noticed that we have marked in red  the values of speed and current intensity (***extreme case***, set in the system for the equipment operating period), which are not relevant at the present moment because the equipment is turned off.

This optical warning system, along with the recording of electrical signals size, makes effective the work of the maintenance operator as a result of the alert received when the maximum threshold of normal operation is reached (threshold set in the technical/research documentation).

6.4. Block diagram of the workstation for studying the kinematic chain maintenance

Figure 6.12 illustrates the main component elements of the block diagram used in the paper to study the maintenance of the kinematic chain of a mechanical system.

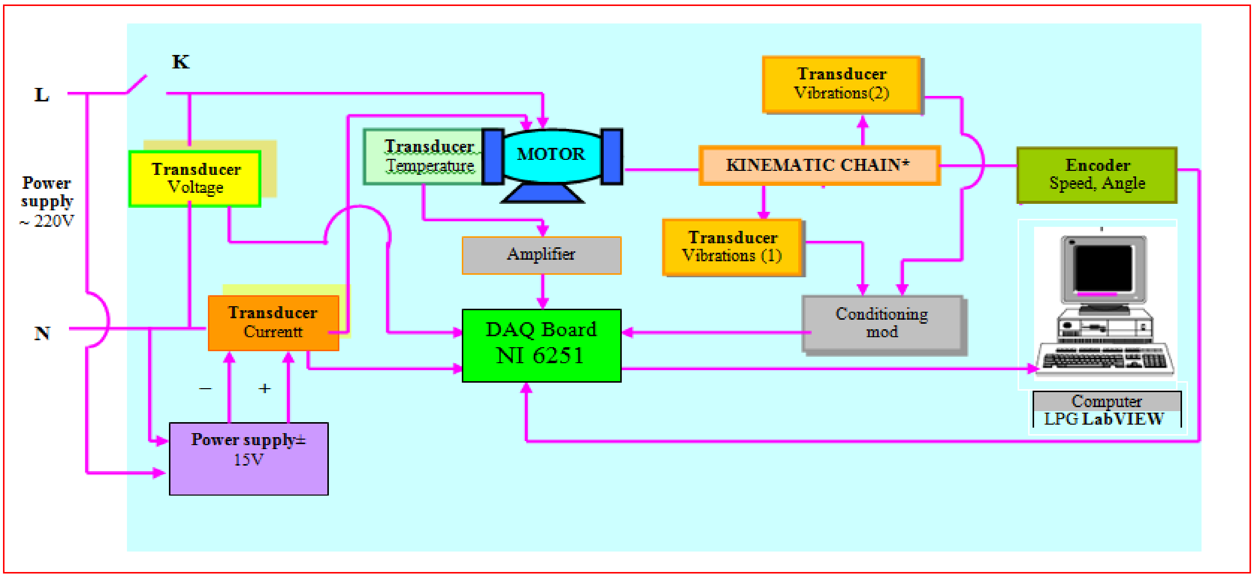


Fig.6.12. Component elements of the block diagram

A simplified kinematic chain was studied in this paper. This chain is supposed to fully meet the work hypotheses taken into account in order to make a maintenance decision and a complex monitoring.

6.5. Stages of the research on a simplified kinematic chain

In the studied system, shown in figure 6.14, it is possible to simulate operating periods (hours of operation) by moving the components (screws) 1, 2, 3 and 4. Tensions are induced in the housings of the bearings I, II by the controlled movement of the screws (feelers with dial gauges, which have an accuracy of 0.02 mm, are assembled on the screws head).

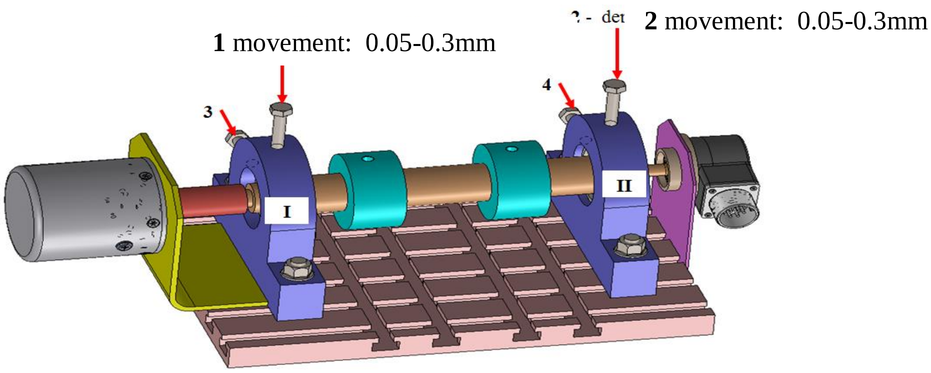


Fig.6.14. Research workstation (simplified model)

The movements take place in a certain order that tries to reveal the establishment of signals/information occurrence in the monitoring systems connected to the system under research.

In **step (k)** the screws S1 and S2 are moved by 0.3 mm while the screws S3 and S4 are also moved by 0.3 mm, figure 6.42; the values displayed on the virtual instrument are read (values of maintenance markers: current intensity, temperature, speed), figure 6.43. At the end of this operation, the technical system is let to function for about 20 minutes .The values recorded are read. One can observe that the maintenance markers value increases/decreases to a value included in the area of maximum warning (possible defect); the motor speed decreases momentarily up to 1250 rpm, the current intensity increases towards the value of 0.8A, figure 6.44. The system of information capture is continuously recording the values of the maintenance markers.

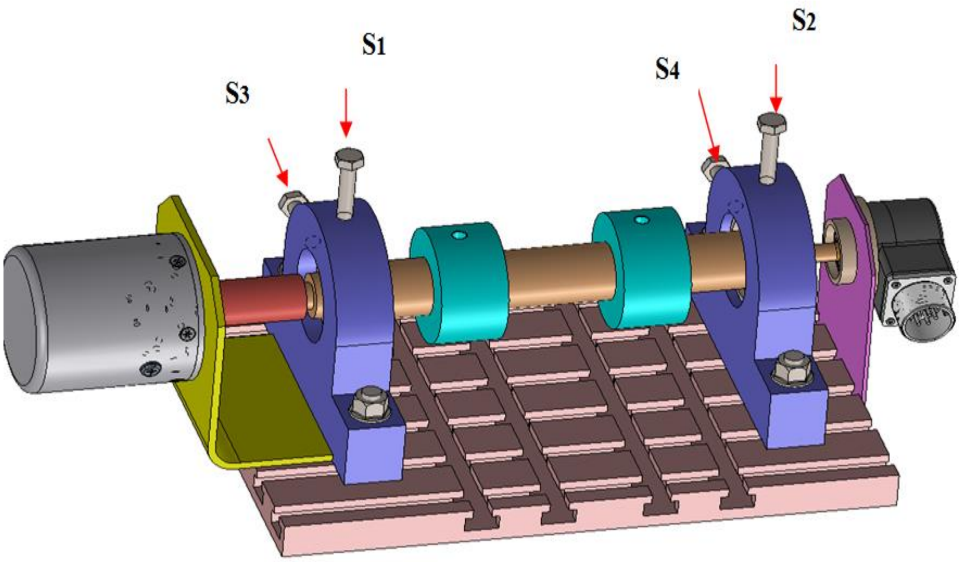


Fig.6.42. Technical system submitted to imbalance - state (k)

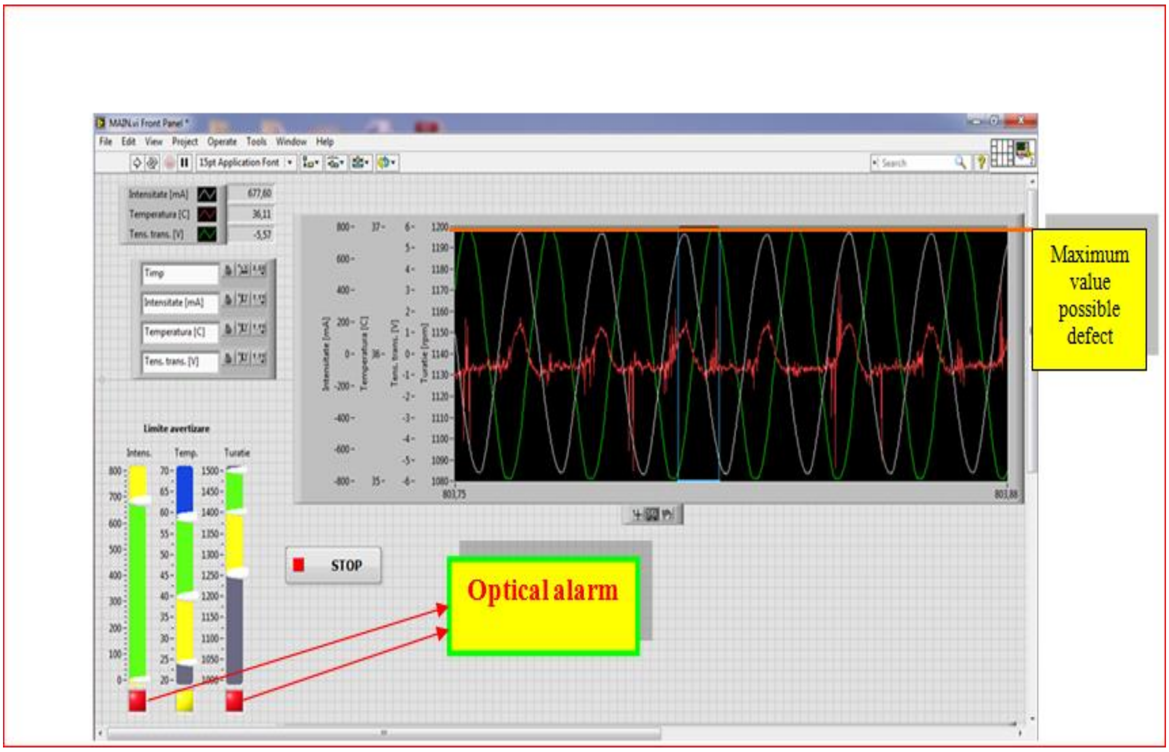


Fig.6.43. LabVIEW –based monitoring equipment - state (k)

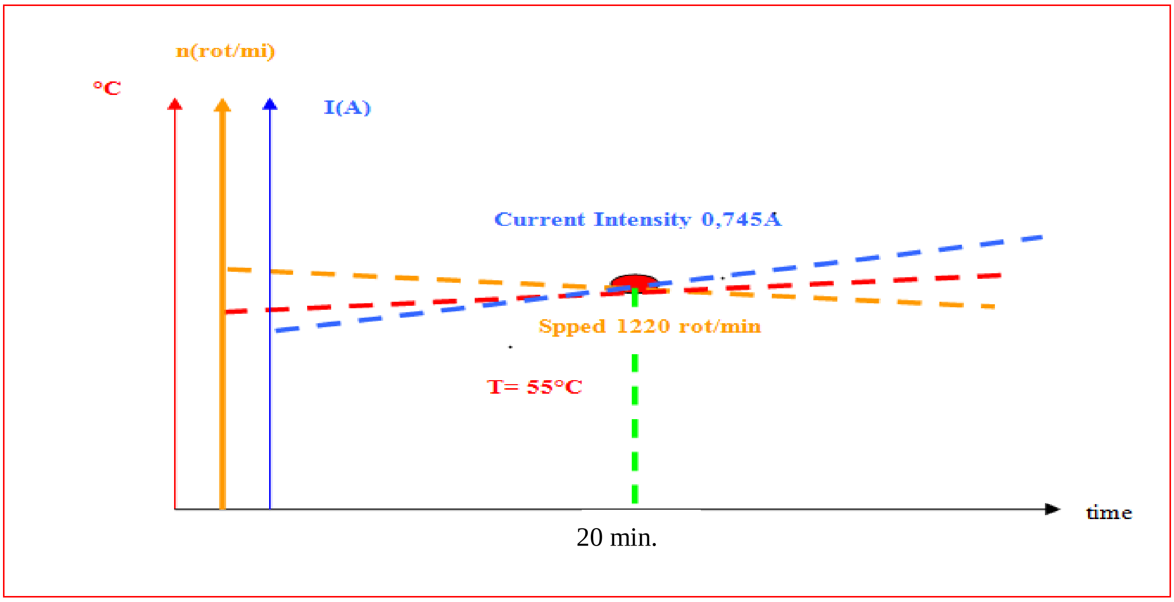


Fig. 6.44. Values of maintenance markers - state (k)

The measured values are captured and recorded. Part of these records is shown in table 6.6

During the **step (J),** the screws S1 and S2 are moved by 0.3 mm and the screws S3 and S4 are also moved by 0.3 mm, figure 6.45; the values displayed on the virtual instrument are read (values of the maintenance markers: intensity of current, temperature, speed), figure 6.46. At the end of this operation the technical system runs for 20 minutes approximately and then the values recorded are read.

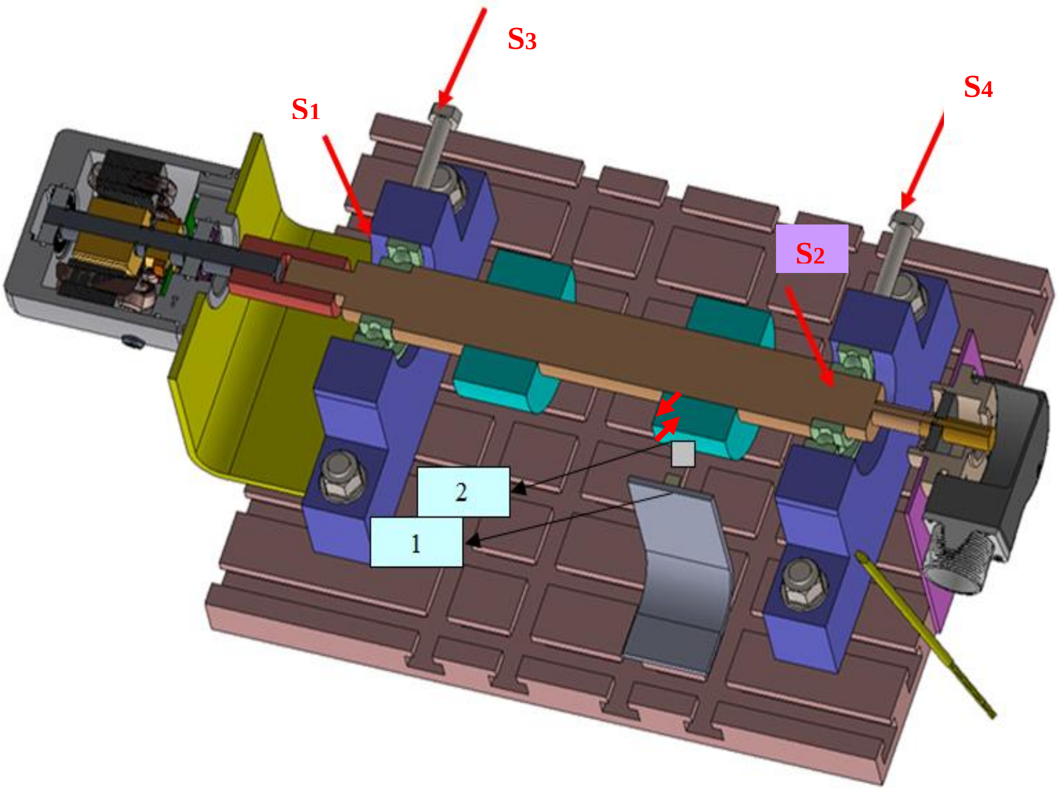


Fig.6.45. Technical system subject to imbalance – state (j)

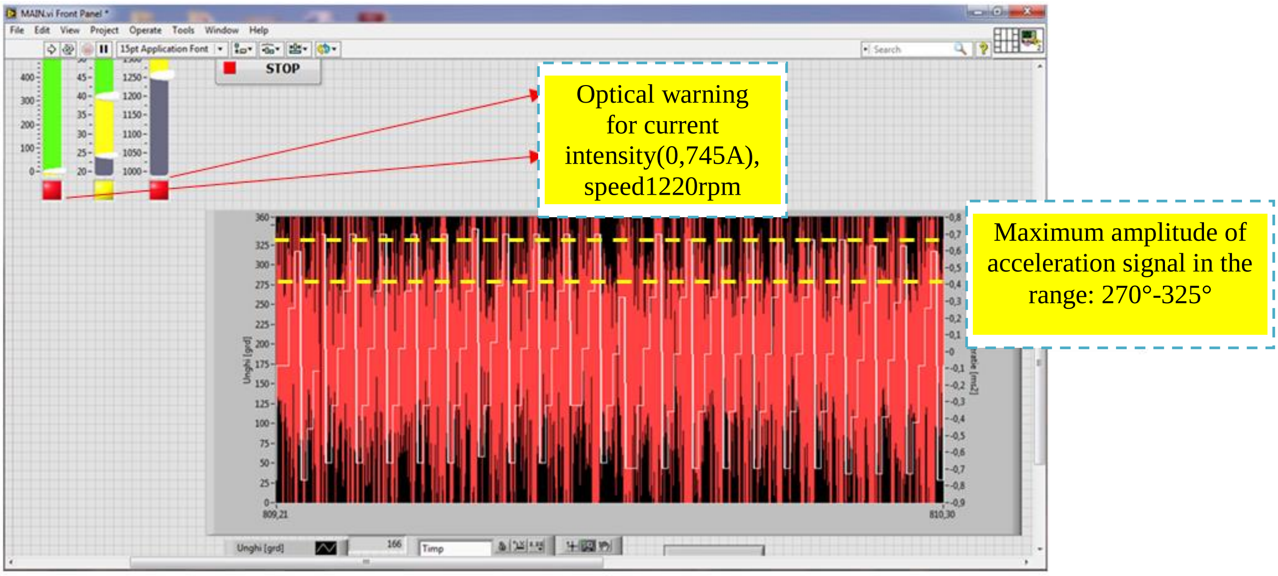


Fig.6.46. LabVIEW – based monitoring equipment for state (l)

The signals from 2 permanent magnets, one (1) located on the fixed support and the other one (2) on the main shaft, are also recorded in order to simulate a possible wear (improper operation). It is noted that the values of maintenance markers are increasing / decreasing to a value found in the maximum warning area (possible defect), the motor speed drops to 1220 rpm, the intensity of the current increases towards the value of 0.8 A, figure 6.43. The virtual instrument - figure 6.46 - shows that the maximum intensity of system vibrations is in the range: 270°-325° for a certain angle. The system of information capture is continuously recording the values of maintenance markers. The measured values are captured and recorded.

Part of these records is listed in table 6.7.

Table 6.7. Values measured

No	Speed [rpm]	Acceleration [ms²]	Angle [°]	No.	Speed [rpm]	Acceleration [ms²]	Angle [°]
1	1350	0.282160	352.8	**27**	1350	0.420501	72
2	1350	0.282185	352.8	**28**	1350	0.422346	72
3	1350	0.283014	352.8	**29**	1350	0.423784	72
4	1350	0.285898	352.8	----	-------	----	----
5	1350	0.287971	352.8	**50**	1320	0.671013	288
6	1350	0.288375	352.8	**51**	1320	0.669244	288
7	1350	0.288876	352.8	**52**	1320	0.669468	288
8	1350	0.395468	352.8	**53**	1320	0.651057	288
9	1350	0.397797	352.8	**54**	1320	0.642372	288
10	1350	0.397886	352.8	**55**	1320	0.653208	288
11	1350	0.397396	352.8	**56**	1320	0.659302	288
12	1350	0.399906	352.8	**57**	1320	0.651164	288
13	1350	0.414565	352.8	**58**	1320	0.600731	288
14	1350	0.421226	352.8	**59**	1320	0.629087	288
15	150	0.377018	352.8	-------	-------	-------	------
16	160	0.433621	72	**65**	1320	0.638197	316
17	170	0.458593	72	**66**	1320	0.618676	316
18	180	0.410068	72	-------	-------	-------	-------
19	190	0.355617	72	-------	-------	-------	-------

20	200	0.375961	72	-------	-------	-------	-------
21	210	0.425503	72	-------	-------	-------	-------
22	220	0.399452	72	-------	-------	-------	-------
23	230	0.394797	72	-------	-------	-------	-------
24	240	0.394430	72	**118**	1220	0.359483	64
25	250	0.395255	72	**119**	1220	0.346932	64
26	260	0.416126	72	**120**	1220	0.353002	64

In the **step (m)** we analyze the results obtained. There are a number of changes in the parameters of the drive electric motor of the studied technical system.

After analyzing the values of the monitored quantities, we notice changes in the values of the electric parameters and the temperature of the electric motor housing as a result of the normal wear and tear process during the technical system operation. In this context we can also control, in addition to the performances of the drive electric motor of the technical system, the condition of some critical elements of the equipment which must meet the technical requirements specified by the manufacturer for the good operating period.

Two monitoring situations necessary for the moment of maintenance decision should be considered, namely:

- monitoring, at long intervals of time after the period of intervention, for current repairs recommended by the manufacturer;
- monitoring, at very short time intervals/continuously, the moment when the values of the monitored maintenance markers reach the thresholds closed to the *maximum limit of the good operation zone* (critical zone).

The interpreted data are based on the value of the maintenance markers sizes and the relationship of these ones with the equipment state in several moments of the monitoring. These data are clearly shown in figure 6.47

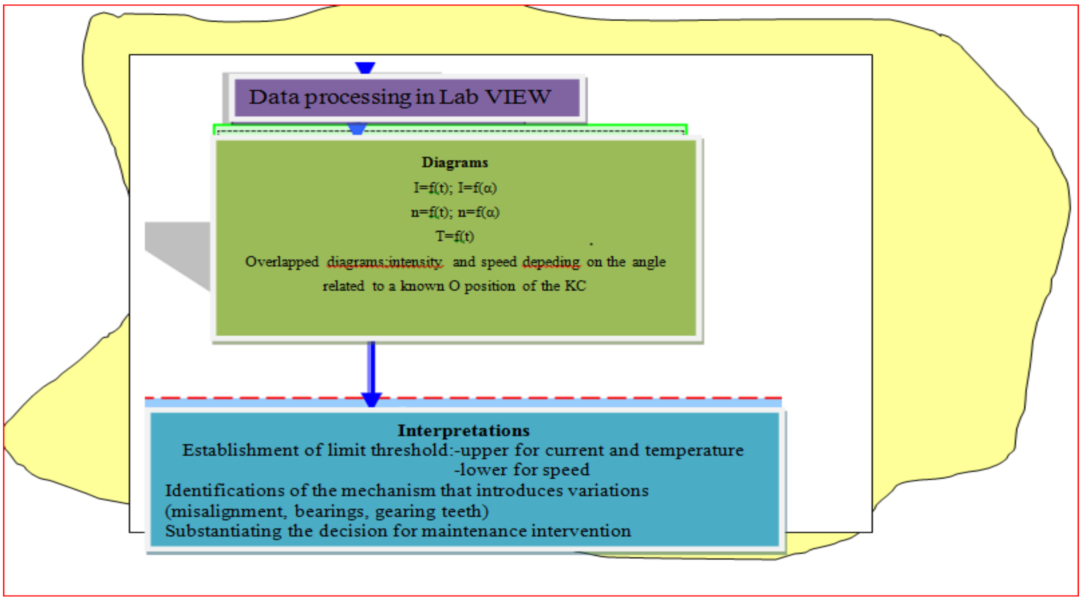


Fig.6.47. Interpretation of the research results

The assessment of the value of the recorded maintenance markers sizes aims at:

1. analyzing the magnitude of electric current intensity during the normal operation of the technical system;
2. analyzing the values of electric motor speed depending on the state of the technical system;

3. analyzing the electric current intensity depending on the angle when maximum vibrations are captured in the kinematic chain;
4. analyzing the electric motor speed depending on the angle when maximum vibrations are captured in the kinematic chain;
5. analyzing the temperature of motor housing depending on the values of current intensity and motor speed.

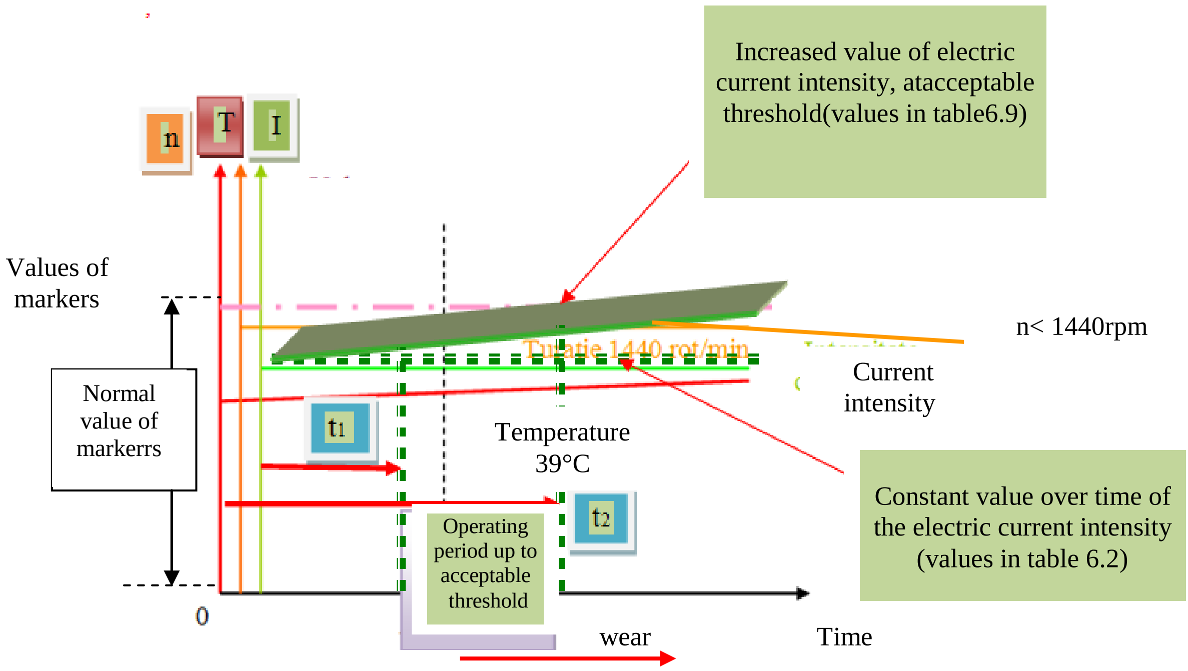


Fig. 6.48. Assessment of electric current intensity at t_1 and t_2 torques

6.6 Conclusions

The research carried out using the maintenance markers and the motor electricity footprint which defines the state of the technical equipment (elements, kinematic chain) clearly indicates that when the disturbance component increases (in the studied case, by moving the screws) the current intensity and the temperature increase too, while the motor speed decreases. This new method, exemplified in this paper for the analysis of the technical equipment by monitoring the electricity footprint, the temperature and the angle of disruption of the normal operation state, can be easily used in maintenance. This paper proves that the parameters of the drive motor of the technical equipment are a relevant indicator of its operating state. The markers indicated in the research paper are important indicators used to assist the maintenance decision.

The advantages of the virtual instrumentation derive from its features. Once the warning thresholds have been set by the specialized department, the VI can be signaled optically, acoustically or can send alerts on the phone or via internet.

Even more, in the absence of human intervention, the technical system can be turned off when the thresholds programmed by the maintenance department are reached, in order to avoid damage to components or possible accidents.

Chapter 7. *„Final conclusions and personal contributions”* exemplifies the final conclusions, research findings and prospects for future development.

7.1. General conclusions

Knowing and controlling the moment of maintenance decision helps to keep within the optimal parameters of the risk factors when using the system and has a positive influence on the benefit of the company.

The research carried out within the thesis led to the creation of an effective system of interpretation of the state of the kinematic chain components in a technological system by monitoring the drive electric motor. Thus, for the first time it was established a connection between the dynamic characteristics of the mechanisms for motion transmission and the electromagnetic system of the drive motor by monitoring and analyzing some electrical parameters of the motor, that the author named *maintenance markers*. The study of the influence of the electric motor electromagnetic field upon the deformations of the elastic system of a technological system was the subject of many specialized papers but the reverse action, much more complex, was not studied.

Using the monitoring system of the maintenance markers we can continuously view and determine the following:

- magnitude of the electrical signals falling within the normal operation thresholds, including an optical warning for the maximum limit of the signal;
- identification of the mechanism of the kinematic chain that alters the dynamic characteristics of the system by correlating the frequencies;
- creation of a data base of the recorded signals;
- assessment of the system state and establishment of its evolution;
- determining the maximum level of the signal by analyzing the history of system operation;
- possibility to make a signal report for the state of the technical system.

The monitoring system used by means of the virtual instrument developed in this research paper is formed of:

- sensors for the capture of markers;
- LabVIEW software for the virtual instrument of monitoring and processing;
- analysis virtual components and control thresholds of the processed signals.

The presented method based on this virtual instrument of analysis of the maintenance markers value gives the possibility of controlling and keeping safely the production technical system with the following advantages:

- making decisions at the most appropriate time;
- increase of the good operating period;
- possibility of developing the maintenance strategy and the accountability of the personnel;
- maintaining the reliability of the technical system in conformity with the recommendations of the manufacturer of the technical system;
- effective use of the system throughout the entire lifetime communicated by the manufacturer;
- acceptable risk-taking in the operation of the system;
- minimizing the down-time;
- possibility of remote control of the system and diminution of risks up to controllable values during the use of the technological system.

7.2. Personal contributions

Theoretical contributions

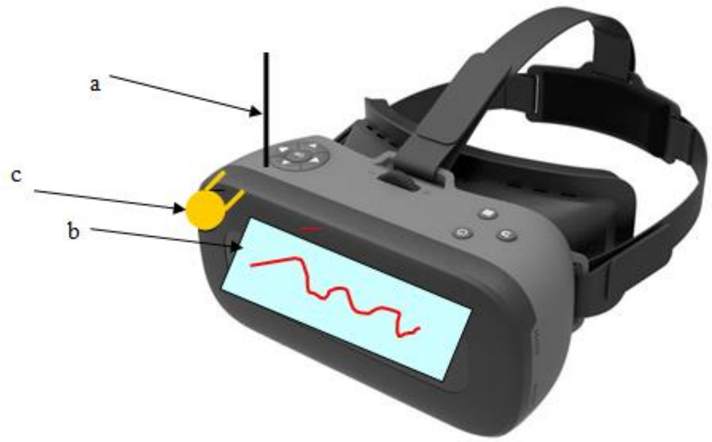
- Creation of a comprehensive documentary study by consulting a bibliography that interwove with the rich experience(over 25 years)of the author in maintenance field.
- Implementation of the notion of *Maintenance Marker* for the assessment of the state of a technological system.
- Development of a mathematical model for defining the dynamic characteristics of a kinematic chain. The mathematical model established the dependency between the dynamic characteristics of the mechanisms for motion transmission in a kinematic chain and the electromagnetic system of the drive motor.
- Making of the kinematic chain (KC) model in Matlab-Simulink.
- Study by *simulation* of the behavior and influence of the various defects of the motion transmission mechanisms in a kinematic chain upon the maintenance markers: electric current absorbed by the motor; speed and torque of the motor shaft. The simulation was performed in different cases of static and dynamic charge.
- Use of virtual devices of LabVIEW software to monitor a technical system.

Experimental contributions

- Design and construction of a workstation.
- Design of a virtual instrument in LabVIEW to monitor the maintenance markers established for the drive electric motor of the kinematic chain that performs the following functions:
  - Identification of the values resulting from the technical system operation;
  - Possibility to establish the angular range where there is an increased value of the operational state to the limit of the need for maintenance works;
  - Possibility to determine the optimum moment for making the maintenance decision and turning off the technical system;
  - Possibility to determine the intervention time and to make an efficient supply of spare parts.
- Preparation of a working procedure for monitoring the state of the technical system;
- Passing through a number of stages of calibration, testing and operation with the working technical system;
- Elaboration of the procedure of assessment of the technical system condition by data processing.
- Simulation of different defects of the kinematic chain components and acquisition of the maintenance markers.

7.3. Subsequent directions of research

The intervention in a production hall from anywhere in the world can be effectively managed by means of a portable technology using special glasses provided with maintenance software and a mobile communication system. This system is equipped with specialized software that has or can take over a file with the history of the equipment behavior over time if a satellite/mobile data network is available. The smart glasses for maintenance will be equipped with specialized software that can create virtual images with the technical systems.



7.1 Maintenance glasses with communications mobile system (a-aerial, b-protection screen, c- video camera with projector

With these maintenance glasses, various systems of audio-video streaming can be developed, enabling the companies that have maintenance contracts and must send operators for various interventions to different locations around the world to make an effective control of the equipment.

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