Intelligent system for diagnosing rotating electric machines

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Abstract

The paper explores the characteristics of constructing a diagnostic system for rotary electric machines. The results of statistical research on the reasons for the failure of asynchronous motors, the most common class of rotary electric machines, are analyzed, and a principle of implementing and the architecture of a universal multifunctional intelligent system for their diagnosis are proposed. The feasibility of using a non-standard artificial neural network as a key element in forming a logical conclusion about the development of a defect is justified. The user interface of the proposed diagnostic system, its operating algorithm, and the construction of vibration measurement channels are developed.

Keywords

Electric machine, diagnosis, software, defect, measurement, vibration.

1. Introduction

The growing role of diagnostics of rotating electric machines, which has been observed during recent decades [1], necessitates the development of universal multifunctional digital systems intended for diagnostics of their technical state. At the same time, it is obvious that the structure of such digital information-and-measurement system will largely be determined by both input technological parameters and expected operating conditions.

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The results of statistical insights into the probability of arising defects' development, particularly during operation of asynchronous electric motors, make it possible to single out the following most probable defect types for the said type of equipment [2]:

1. Thermal damage of pole windings' insulation – 30%.
2. Interturn short circuit – 15%.
3. Bearing damage – 12%.
4. Mechanical damage to stator windings or insulation – 11%.
5. Mechanical deformation of rotor or stator structures – 9%.
6. Electric motor's two-phase operation – 8%.
7. Breakage or weakening of the rod mount in the white cage – 5%.
8. Weakening of stator winding braces – 4%.
9. Imbalance of the electric motor's rotor – 3%.
10. Misalignment of shafts – 2%.
11. Other defects – 1 %.

At the same time, detection and localization of the defects that lead to deformation of bearings' structural elements cause asymmetry of currents in the stator circuit or appearance of the rotor's mechanical asymmetry, which make up over 60% of total number of cases, should be performed exactly through analysis of the vibro-acoustic signal in subassemblies of investigated electric machine [3]. However, due to overlapping of vibro-acoustic signal's reactions in cases of various types of damage and in electric machine's regular operation modes, the use of only specified technological parameter is not sufficient for construction of an effective diagnostic system. Therefore, to implement the set task, it is advisable to use additional technical parameters, such as: stator current, clearance, rotor's angular speed, etc. [4, 5].

In addition, it is worth noting that such system's sensor units will inevitably be situated in close proximity to the electric machine, thus being subjected to mechanical and thermal impact, with the entire system as a whole, including the information processing unit and communication channels, being obviously subjected to a significant electromagnetic impact.

So, in view of the aforesaid, one can conclude that development of a universal multifunctional digital diagnostic system based on analysis of rotating electric machines' vibro-acoustic parameters, which would be characterized by a high efficiency and possibility of flexible software adaptation to the subject of research, is a crucial scientific-and-applied task.

2. Making up the Concept for Building the System of Defect Development-Related Decision Making

One of the basic trends in present-day science development is the increase in the specific weight of systems that can be classified as systems of exceptional complexity [6, 7]. The main specific feature of systems of this class consists in the presence of a large number of connections and (or) influencing factors, the classical mathematical description of which is impossible or inadvisable due to a significant increase in the model's complexity, which makes it unsuitable for practical use [7].

Considering the scale of public demand for scientific approaches that can be used to solve the problems of specified class, it would be quite logical to actively develop the approaches that go beyond classical mathematical modeling. And although the method of expert opinion [8] still remains the most common method of solving such problems today, it is obvious that current level of science and technology development requires other approaches being faster, automated and therefore less time-consuming, which approaches can be used to build technical systems of operational response. Such approaches include relatively new areas of machine learning and neural modeling [9].

An exceptional difficulty in generation of rotating electric machine's vibro-acoustic parameters is related to both the dynamics of disturbing influences caused by the variable load and rather complex design of its mechanical part, which includes a significant number of spatially distributed elements with elastic and viscous connections [10].

Since construction of a clear-cut mathematical model of rotating electric machine's mechanical connections is practically impossible, it would be advisable to consider the latter as the "black box". That is its external functioning, rather than its structure, should be modeled [11]. Therefore, to solve the given problem, the application of an artificial neural-like network (ANN) is proposed, which is characterized by its ability to adapt to virtually any diagnostic object, considering both its constructive features and the conditions of its operation during the training phase. This capability is determined by the settings embedded within the structure of the neural network. Thus, one can observe its development at all stages, providing targeted influence as needed. Since expert neural network systems are still not sufficiently integrated into technical diagnostic systems today, the development of approaches for their implementation to address the described scientific and technical task will undoubtedly have significant scientific and practical value.

In order to build an ANN, one should first determine what information should be supplied to its inputs and what should be obtained as a result of ANN's functioning.

Considering the foregoing arguments, it is proposed to construct the said diagnostic system on the basis of vibro-acoustic signal's measuring channels. It is also proposed that the system includes additional measuring channels that would supply real-time information on instantaneous power, angular velocity and other technical parameters required for setting the current mode of electric machine's operation.

Measurement-related information from the outputs of vibro-acoustic signal's measurement channels is sent to the current monitoring subsystem, which is implemented in hardware terms within one ANN-featured server, where highly informative criteria are formed based thereon. Additionally, it is advisable in the current monitoring subsystem to carry out analytical calculations of the rotor's angular acceleration based on instantaneous values of its rotation speed and selection of vibration displacement levels on each of the measuring channels that exceed the permissible standardized value. Therefore, it is proposed to supply the following input information to the ANN input:

- all vibration displacement values that exceed the permissible standard for each of the vibration sensors during particular time interval with these values' temporal fixation for time interval $\Delta\tau$;

- the value of highly informative criteria calculated on the basis of the vibro-acoustic signal;
- currents in stator phases;
- rotor's angular acceleration;
- other additional parameters of the machine's technical condition that can be used to establish the current mode of the electric machine's operation (depending on its features).

Considering the results of performed analysis, to implement a universal multifunctional digital diagnostic system, the ANN structure was proposed in the form shown in Fig. 1.

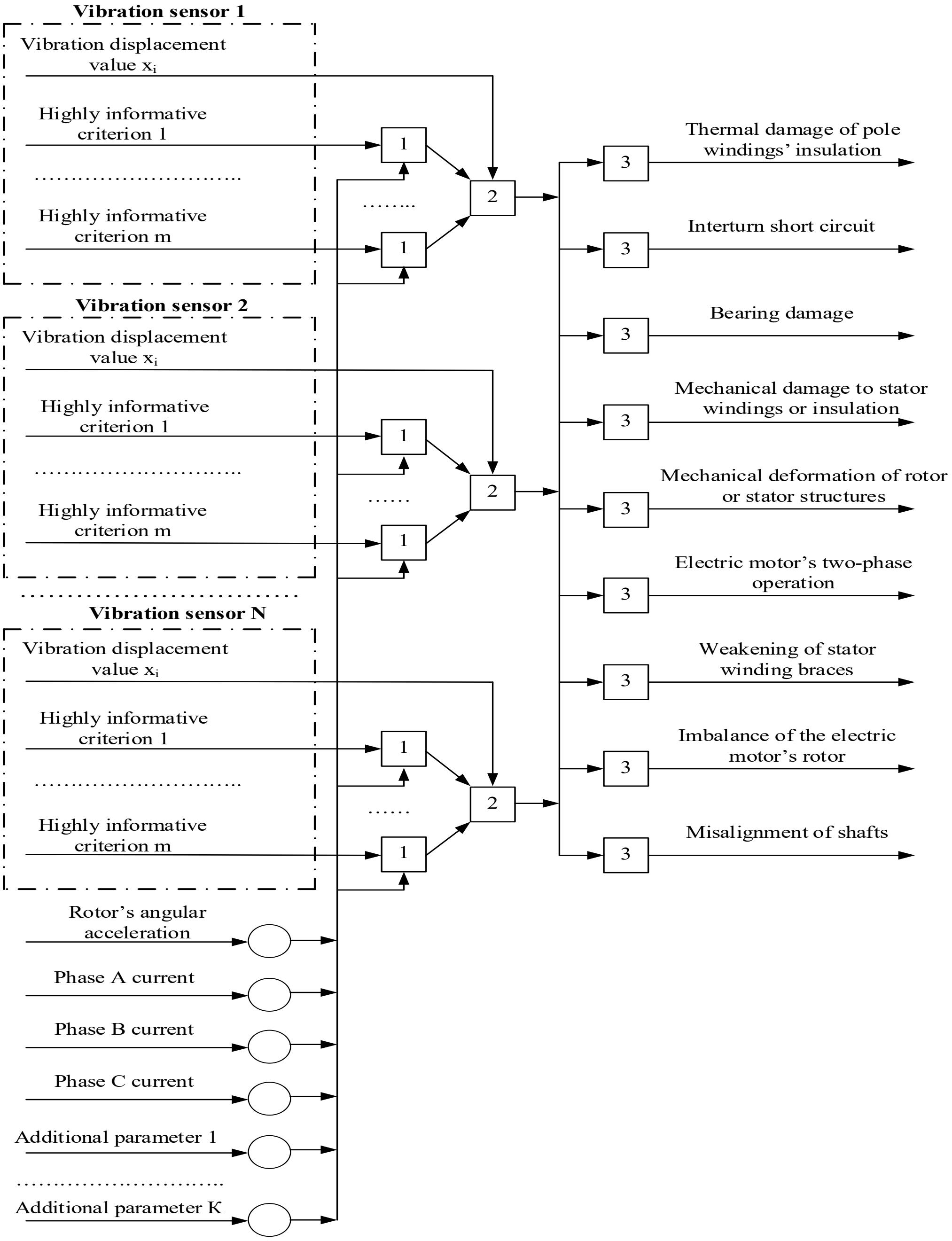


Figure 1: Artificial neural network structure

As can be seen in fig. 1, construction of a four-layered non-homogeneous and non-standard ANN is envisaged.

The number of zero-layer input neurons (they are depicted as circles in Fig. 1) corresponds to the number of additional parameters supplied to the ANN inputs. Input neurons perform the function of numerical data acceptance and sorting. The said neuron layer is an autonomous part of the ANN and is functionally responsible for determination of the current mode of electric machine's operation.

The first ANN layer (the neurons of which are marked by squares with digit 1) contains $N \cdot M$ neurons. Each of these neurons receives the value of a highly informative criterion calculated within the current monitoring subsystem, which is maximum sensitive to informative vibration factors. In addition, each of the first-layer neurons receives integral information about the current mode of the electric machine's operation. This approach is justified due to the fact that the electric machine is a system with complex mechanical connections. Therefore, in the event of local disturbances caused by non-informative factors, the resulting action of which has the characteristics similar to the effects caused by certain types of informative parameters, in the vast majority of cases the measurement information at the output of only a single sensor or a group of sensors located in some particular area will undergo significant distortion machines [3, 11].

The second layer of ANN neurons (designated by digit 2) contains N neurons, each of which receives generalized criterion information from each of the vibration acceleration sensors and performs integral processing thereof. At this stage, the preliminary task of probabilistic analysis of defects' presence is implemented and measurement redundancy is eliminated, considering the inevitable dependence of high-information criteria submitted to the ANN input on more than one significant state (defect presence, operating mode, etc.). Neurons of this layer, the conversion functions of which are also formed at the pre-operational training stage, additionally receive information on exceeding the level of vibration displacement. Activation of the second-layer and of the entire ANN at the same time, occurs only in the case when at least one of the vibration signals contains excessive vibration displacement. Such being the case, the activation function of the second-layer neurons will look like this:

$$\phi(a_i) = sign(x_i - x_0, \Delta\tau) \cdot \sum_{j=1}^{M} \psi(p_j), \tag{1}$$

where $\Delta\tau$ –the temporal delay for switching off,

x_i – the current value of vibration displacement received by respective neuron;

x_0 –the vibration displacement threshold value;

p_i – corrected j^{th} informative criterion;

$\psi(p_i)$ – the function of influence by corrected j^{th} informative criterion;

sing (a_i - a_0, $\Delta\tau$) – the relay function with a switch-on delay.

The third ANN layer (designated by digit 3) contains 9 neurons, each of which corresponds to one of the defects having the highest probability of development in accordance with statistical studies [2]. In the neurons of this layer, intermediate conclusions made by the second-layer neurons are averaged based on their integral analysis.

The transformation functions of each of the neurons of the proposed artificial neural network are formed as a result of pre-operational training based on statistical information about specific features of operation of electric machines of studied class.

It should be noted that such system's logical conclusion formed by the third-layer neurons will be probabilistic in nature. While the criterion for making the decision on the presence of respective defect will be the excess by particular established value of its presence probability generated by the third-layer neurons.

3. Development of the Diagnostic System's Hardware Structure

To solve the problem of building the hardware structure of a multifunctional digital monitoring system, proposed was the structural diagram shown in fig. 2.

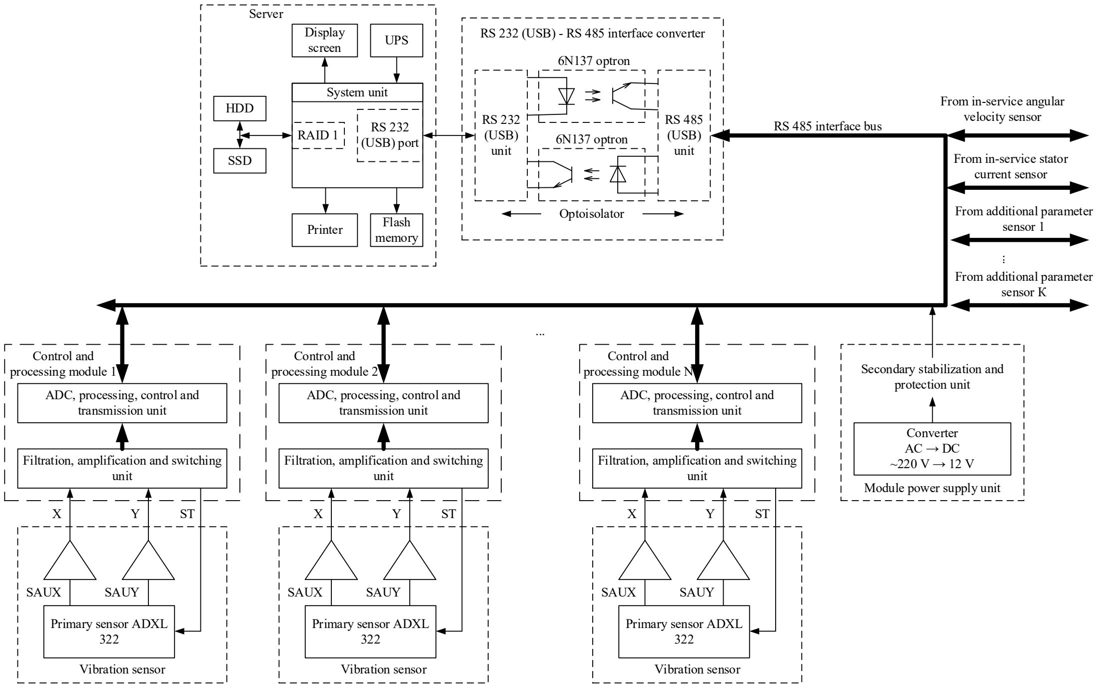


Figure 2: Block diagram of the diagnostics system

The proposed system is designed for continuous monitoring of vibration state of rotating electric machine's subassemblies and allows detecting the moments of defect origination based on an automated acquisition of measurement-related information, its transmission, storage, processing and presentation in the form convenient for the operator's perception. This system presents a complex of hardware and software tools. The hardware includes the following basic units and subassemblies: vibration measurement channels, RS 232 – RS 485 interface converter, RS 485 interface communication lines, auxiliary parameter measurement channels (including in-service ones), the server and the power supply unit.

With the help of vibration sensors, which are attached to the electric machine's selected subassemblies, as well as control and processing modules (CP), vibration measurement channels ensure the receipt of primary measurement-related information and its preliminary processing. After that, this information is transferred to RS -485 to RS -232 (USB) interface converter through RS-485 interface bus and, together with auxiliary parameter measurement-related information, enters the server.

The server software implements two autonomous units: current monitoring subsystems and the ANN. Measurement-related information is processed and the monitoring system is managed in the server using application-dependent software.

The system ensures constant monitoring of vibration parameters and signals when vibration parameters exceed maximum permissible values (sound and light alarming), as well as informs the operator on location of potential defects and the probability of such location's origination on the mnemonic diagram. During the monitoring process, the electric machine's mnemonic diagram displays information on current vibration values in numerical form from the subassemblies, on which the vibration sensors are mounted. All measurement results are stored in the server archives, which allows viewing the dynamics thereof. The appearance of the mnemonic diagram of application-dependent software is shown in fig. 3.

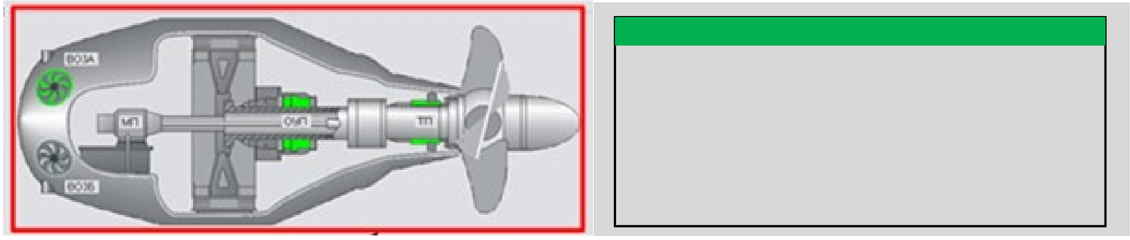
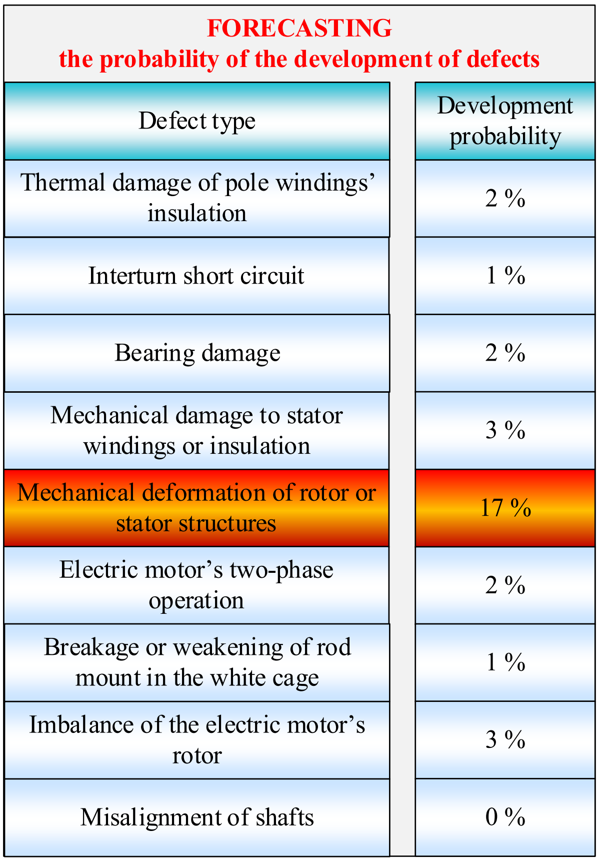


Figure 3: Mnemonic diagram of application-dependent software

In addition, the application-dependent software provides for a dialog box that, in the absence of the conclusion about the defect presence, can be called in a manual mode, being meant for the operator's real-time familiarization with the machine's current technical state by way of visualization of current probability of development of basic defect types. The appearance of the said dialog box is shown in fig. 4.



FORECASTING
the probability of the development of defects

Defect type	Development probability
Thermal damage of pole windings' insulation	2 %
Interturn short circuit	1 %
Bearing damage	2 %
Mechanical damage to stator windings or insulation	3 %
Mechanical deformation of rotor or stator structures	17 %
Electric motor's two-phase operation	2 %
Breakage or weakening of rod mount in the white cage	1 %
Imbalance of the electric motor's rotor	3 %
Misalignment of shafts	0 %

Figure 4: Dialog window intended for the operator's real-time familiarization with the electric machine's current technical state

When the system makes a defect presence-related decision (probability of its development that could reach a certain threshold value), the command to electric machine's emergency stop is sent from the server and the operator is informed thereabout by means of an emergency alarm.

The warning signal is displayed on the mnemonic diagram and in the dialog box to quickly familiarize the operator with the electric machine's current technical state when the defect development probability approaches its established threshold value (Fig. 4, "Mechanical deformation of rotor's or stator's structure" defect).

The diagnostics system starts its operation with an automatic self-testing. Having successfully passed the test, "System is normal" inscription will appear on the display screen.

In the course of its operation, the system periodically performs an automatic self-test by updating its results as described above on the display screen. It is also possible to perform prescheduled manual self-testing at the operator's command.

To ensure the measuring channel's operation as part of the system for diagnostics of rotating electrical machines, the converter of RS-485 network interface to RS-232 user interface was used, which is a standard device for the vast majority of digital measuring channels.

4. Structural Features of Vibration Measuring Channels

The vibration sensor board and control-and-processing (CP) unit make up the vibration measurement channel. The CP unit comprises the microcontroller, an analog switch, an active low-pass filter, an analog-to-digital converter (ADC) and the interface.

The principle of the measuring channel's operation is as follows. The sensor converts the vibration value into an analog (electrical) signal, which is supplied to a low-pass filter through one of the analog switch's inputs and scaled to the level required for a reliable operation of the ADC. Quantization and discretization of the measured quantity are performed in the ADC. The binary codes obtained in this way are pre-processed and transmitted through the serial interface to the server. The microcontroller ensures the scaling of the vibration sensor's output signal, analog-to-digital conversion of instantaneous vibration values, indirect determination of vibration acceleration, vibration speed and vibration displacement based on measurement information, transfer of the measured values' array to the diagnostics system server. The appearance of the vibration measuring channel is shown in Fig. 5.

Figure 5: Appearance of the vibration measurement channel

The vibration sensor and the buffer amplifier are located in a separate structurally finished cylindrical body mounted on the control object's fixed surface. The vibration sensor is connected to the CP unit using a cable and a connector placed on respective unit.

The CP unit and other subassemblies that ensure the measuring channel's functioning are placed inside the metal housing mounted with the help of two screw connections. There is a detachable connection for the system network interface cable on the CP unit's housing.

To measure vibrations in the proposed system, it is advisable to use accelerometers, which represent the sensors of linear accelerations, for example sensors of ADXLxxx series by Analog Devices. This type of sensors is characterized by a small inertial mass (0.1 μg), high overload capacity (some 10,000 g with no sensor failure) and a wide operating frequency range (from static acceleration to kilohertz units) [11]. A block diagram of one of such sensors is shown in fig. 6.

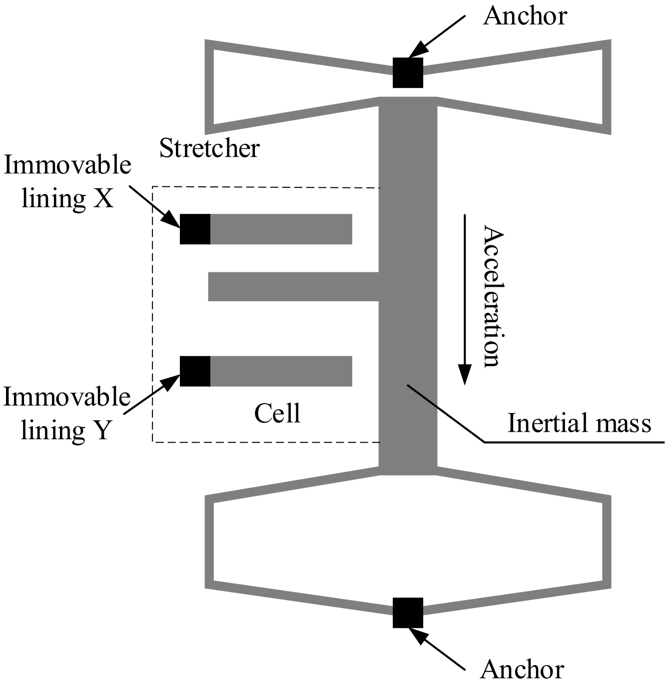


Figure 6: Structural diagram of the sensitive element of the vibration sensor

Fig. 6 only shows the sensor's main structural unit. In fact, the sensor comprises more than 50 such elementary cells. The inertial mass of the acceleration sensor is displaced relative to the crystal's other part during displacement velocity measurement. Its finger-like protrusions form the capacitor's moving electrode.

Under the action of acceleration, the inertia force can be determined on the basis of Newton's second law as follows [12]:

$$F_{ei} = m_e \cdot a, \tag{2}$$

where m_e – the mass of the elementary cell's moving part;

a – the acceleration of the elementary cell's moving part

The inertial force is balanced by the spring's resistance force

$$F_{np} = k \cdot X, \tag{3}$$

where X – mass displacement relative to the equilibrium position;

k – the elasticity coefficient of the unit cell stretches.

By equating the spring's inertia force and resistance force that occur in a static operation mode (uniform acceleration measurement), we obtain:

$$a = \frac{k}{m_e} X = S_e \cdot X, \tag{4}$$

where S_e – the sensitivity of the capacitive micromechanical accelerometer's elementary cell

As follows from (4), the sensitivity of the capacitive micromechanical accelerometer's elementary cell is a constant value, which depends on the sensor's structural parameters (k and m_e).

Since the inertial mass movement occurs in the plane of the polysilicon film, the axis of the sensor's sensitivity lies in the same plane being accordingly parallel to the plane of printed circuit board, on which the sensitive element is located.

At rest (movement at a constant speed), all the moving electrode's "fingers", thanks to the stretching action, are at the same distance from the pair of the stationary electrode's "fingers". At any acceleration, moving electrodes approach one of the sets of stationary electrodes and move away from the others. As a result, relative displacement becomes non-uniform, and the capacitance between the moving electrode and each of the moving electrodes varies in proportion to the vibration acceleration. That is:

$$\Delta C_e = \alpha \cdot X, \tag{5}$$

where ΔC_e is the change in the capacity of the sensor's elementary cell.

Since the capacitive micromechanical sensor contains n elementary cells being identical in their design, being located in the same plane, with their capacitances connected in parallel, we can write as follows:

$$\varepsilon = a_1 = a_2 = \ldots = a_n, \tag{6}$$

where ε – the acceleration measured by the sensor (input physical quantity).

$$\Delta C = \sum_{i=1}^{n} \Delta C_{ei}, \tag{7}$$

where ΔC – the change in the capacitive micromechanical accelerometer's capacitance.

$$m = \sum_{i=1}^{n} m_{ei}, \tag{8}$$

where m – the mass of the capacitive micromechanical accelerometer's moving part.

Such being the case, taking the average value of the elasticity coefficient of its elementary cells' stretches as the elasticity coefficient of the capacitive micromechanical accelerometer, we obtain:

$$\varepsilon = \frac{k}{m} X. \tag{9}$$

Given that, in accordance with declared technical characteristics of sensors of ADXLxxx series by Analog Devices, the technical characteristics of which will be used later, the temporal constant of measuring transducers of “capacitance to voltage” type is significantly less than the temporal constant of the inertial mass, and the change in the value of the output voltage is proportional to the change of the sensitive element’s capacity [13, 14], we obtain:

$$U = \beta \cdot \Delta C = \beta \cdot \gamma \cdot X = \frac{\beta \cdot \gamma \cdot m}{k} \varepsilon, \tag{10}$$

where β – the coefficient of proportionality of capacity transformation into increase in the sensor’s output voltage; γ – the coefficient of proportionality of transformation of the sensor’s moving part displacement relative to the stationary part into capacity increase.

Such being the case, the sensor’s sensitivity may be determined as follows:

$$S = \frac{dU}{d\varepsilon} = \frac{\beta \cdot \gamma \cdot m}{k}. \tag{11}$$

The sensor’s static characteristics for the sensitivity of 0.1 V·s^2/m, which is typical for sensors of ADXL320 series by Analog Devices [13], is shown in Fig. 7

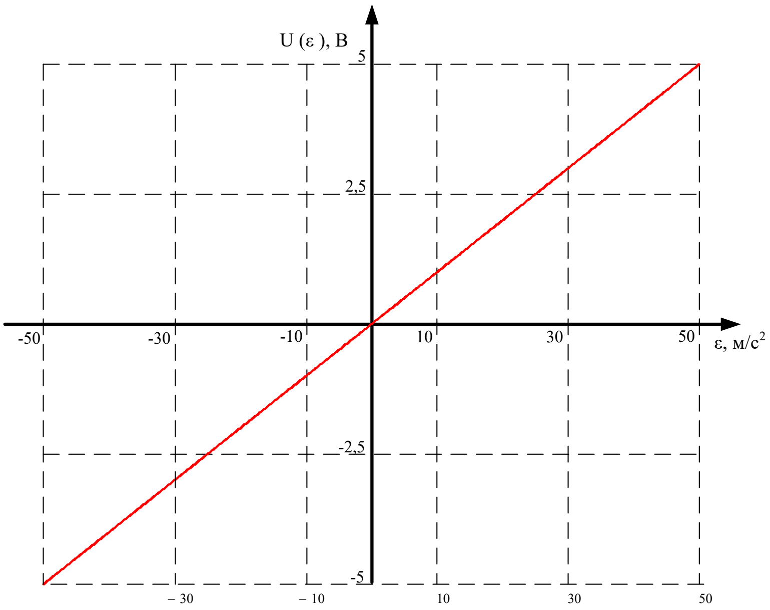


Figure 7: Static characteristics of ADXL320 capacitive micromechanical accelerometer

The vibration sensor board filters the vibration signals converted into electrical ones and scales them to a level sufficient for analog-to-digital conversion.

Filtering, amplification and analog-to-digital conversion of analog electric vibration signals received from the sensors' output, pre-processing, storage and transmission of measurement-related information are carried out in the CP unit of each measuring channel. As a result, temporal implementations of vibrations' digital values distributed in time with a given discretization step are generated to be transmitted via communication lines of RS 485 interface to the server for further processing and presentation.

5. Conclusions

The article analyzes the results of statistical research on the causes of failure of asynchronous motors, the most common class of rotary electric machines. According to the analysis results, the feasibility of diagnosing such equipment through the analysis of vibro-acoustic signals and auxiliary technical parameters, which allow determining the current operating mode of the electric machine, is demonstrated.

A principle of implementation and architecture of a universal multifunctional digital diagnostic system for rotary electric machines is proposed. This system comprises hardware and software components, including vibration measurement channels, RS 232 - RS 485 interface converter, RS 485 communication interface lines, measurement channels for auxiliary parameters, a server hosting subsystems for real-time monitoring and an artificial neural network, and a power supply unit. The system's software algorithms include analytical calculation of highly informative criteria characterized by increased sensitivity and expressiveness to the most probable defects of rotary electric machines.

The use of a non-standard artificial neural network is proposed as a key element in forming a logical conclusion about the development of a defect. The structure of the artificial neural network and the methodology for forming transformation functions for each of its neurons as a result of overexploitation training are proposed and justified. The implementation of the proposed structure of the ANN will allow for effective solving of the expert assessment task regarding the technical condition of electrical machines, provided that highly informative criteria with strong expressiveness and selectivity are promptly delivered to its inputs.

To ensure adequate speed of updating and accuracy of the input parameters for the ANN, most of which are proposed to be obtained through preliminary digital processing of vibro-acoustic signal parameters, a design for a vibration measurement channel and the mathematical model of capacitive micromechanical accelerometer ADXL320 have been developed.

The user interface of the proposed diagnostic system, its operating algorithm, and the construction of vibration measurement channels are developed. It is shown that the architecture and operating algorithm of the diagnostic system provide the possibility of hardware expansion of the number of measurement channels and flexible software reconfiguration of the system depending on the characteristics of the diagnostic object.

Currently, metrological research and experimental operation of the diagnostic system are being carried out in conjunction with rotary electric machines of various types. The developed diagnostic system will significantly increase the reliability of electric machine operation and reduce operational costs by reducing equipment downtime and the number of scheduled preventive maintenance inspections in perspective.

References

[1] N. Saad, M. Irfan, R. Ibrahim, Condition Monitoring and Faults Diagnosis of Induction Motors. Electrical Signature Analysis, CRC Press, London, 2019.

[2] S. Nandi; H. A. Toliyat; X. Li, Condition monitoring and fault diagnosis of electrical motors, IEEE Transactions on Energy Conversion 20 (2005) 719–729.

[3] V. Hraniak, Using discrete wavelet analysis of vibration signal for detection of electrical machines' defects, Revue Roumaine des Sciences Techniques. Série Électrotechnique et Énergétique, 68 (2023), 357–362. doi:10.59277/RRST-EE.2023.4.6

[4] G. Zhao, L. Sun, N. Niu, X. Wang, Z. Xing, Analysis of vibration characteristics of stators of electrical machines under actual boundary, Mechanical Systems and Signal Processing, 185 (2023), 118-129. doi:10.1016/j.ymssp.2022.109778

[5] V. F. Hraniak, V. V. Kukharchuk, Y. G. Vedmitskyi, I. V. Vishtak, P. Popiel, G. Yerkeldessova, Phase noncontact method and procedure for measurement of axial displacement of electric machine's rotor. Proc. SPIE 10808, Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments (2018). doi:10.1117/12.2501611

[6] I. Savchenko, A. Shapova, I. Kuziev, Modeling of high module power sources systems safety processes, Materials Science Forum, 1052 (2022), 399-404.

[7] T. O. Prokopenko, Systems theory and system analysis. Tutorial, Cherkasy State Technical University, Cherkasy, 2019.

[8] A. A. Nersisyan, L. G. Mishura, Study of the implementation of information technologies in investment activities, Scientific journal of NRU ITMO. Series Economics and Environmental Management, 2 (2019), 145-153.

[9] T. S. Klebanova, L. O. Chagovets, O. V. Panasenko, Fuzzy logic and neural networks in enterprise management. Monograph, Publishing house "INZHEK", Kharkiv, 2011.

[10] I. Honcharuk, I. Kupchuk, V. Yaropud, R. Kravets, S. Burlaka, V. Hraniak, J. Poberezhets, V. Rutkevych, Mathematical modeling and creation of algorithms for analyzing the ranges of the amplitude-frequency response of a vibrating rotary crusher in the software Mathcad, Przeglad Elektrotechniczny, 98 (2022), 14-20.

[11] V. V. Kukharchuk, S. Sh. Katsiv, V. F. Hraniak, S. O. Bykovsky, Discrete wavelet transforms in the diagnosis of hydraulic units, monograph, Vinnytsia National Technical University, Vinnytsia, 2019.

[12] S. S. Rao, Vibration of continuous systems, Jon Wiley & Sons, New York, 2007.

[13] Analog Devices. Small and Thin ±5 g Accelerometer ADXL320. Datasheet, 2007. URL: https://www.analog.com/media/en/technical-documentation/data-sheets/ADXL320.pdf

[14] S. Sysoeva, Car accelerometers. Part 5. The prospective elemental base of surface silicon capacitive MEMS accelerometers, 4 (2006), 28-39.