The problem of the reliability of measurements of rotational parameters of electric motors was solved, which was focused on the development of an algorithm for evaluating measurements under conditions of additional noise. An analysis of methodological approaches and mathematical tools used to process and interpret the uncertainty of measurement results was carried out. Cases where they may not be effective due to high noise levels were considered. To detect anomalies in the signal, an algorithm for assessing the reliability of measurements using fuzzy logic was proposed. A structural diagram of the model for measuring the torque of an electric motor under the conditions of a noisy signal was developed, where transfer functions were used to model the angular velocity and torque parameters. A method for detecting anomalies in noisy signals is presented, which identifies the amplitude and time characteristics of spiking pulses. The method includes the application of a wide range of analytical tools for deep analysis of signals and is particularly effective for detecting anomalies that may be hidden in background noise. A prototype of a measuring bench was developed, which uses neural networks to detect anomalies when measuring the rotational parameters of electric motors, which made it possible to obtain a training sample using a sample electric motor and apply it to evaluate the parameters of another electric motor. In a practical aspect, the developed methods and technological solutions for improving the reliability of measurements of rotational parameters of electric motors could be used to make corrections in existing systems. In particular, they could be used in industry, electric transport, as well as in the aerospace and military sectors where the reliability of measuring systems is important

Keywords: assessment procedure, torque, electric motor parameters, neural network, fuzzy logic

UDC 621.317
DOI: 10.15587/1729-4061.2023.292187

DESIGNING TOOLS FOR ASSESSING THE RELIABILITY OF ELECTRIC MOTOR TORQUE MEASUREMENTS BY USING IDENTIFIERS OF ANOMALOUS DEVIATIONS IN A NOISY SIGNAL SYSTEM

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Received date 11.09.2023
Accepted date 17.11.2023
Published date 29.12.2023

How to Cite: *Kvasnikov, V., Kvashuk, D., Prygara, M., Legeta, J. (2023). Designing tools for assessing the reliability of electric motor torque measurements by using identifiers of anomalous deviations in a noisy signal system. Eastern-European Journal of Enterprise Technologies, 6 (5 (126)), 15–25. doi: https://doi.org/10.15587/1729-4061.2023.292187*

1. Introduction

Requirements for measuring the reliability of rotational parameters of electric motors are constantly increasing, which is a consequence of the optimization of technological processes in various industrial sectors. In particular, in the field of material processing, greater precision of processing is required, in transport, the emphasis is on the precision of electric vehicle control, and in robotics, the requirements for precision are also increasing.

In parallel with this, the number of destabilizing factors also increases, especially in the context of attempts to optimize the operational resource of electric motors by increasing various types of loads on them, which increases additional noise during measurement. In general, this creates additional challenges for diagnostic and control systems, requiring them to be highly adaptable, flexible, and ensure reliable and stable operation.

Therefore, the results of scientific research in the field of measurement of rotational parameters of electric motors can have a number of specific practical values. Thus, more accurate measurement systems will allow improving the control and regulation of technological processes, which can lead to a reduction in resource costs and an increase in product quality. In turn, studies that consider the assessment of the reliability of measurements of torques of electric motors in systems with a high level of noise are relevant and could make a significant contribution to improving their efficiency and safety.

2. Literature review and problem statement

Research related to the assessment of error tolerance of measurement systems has recently focused on the question of how well a system could operate without errors, and how this could be measured or quantified. Special attention is focused on measurements of parameters of dynamic systems where the length of modeling sequences (N>1000) can affect the quality of measurements. At the same time, under conditions of uncertainty, scientists are looking for optimal solutions for filtering anomalies, correcting nonlinearities, and identifying deviations caused by noise or impulses in the system. The biggest area that needs such solutions is the control of electric motors, where noise parameters are present in many elements of the system. This especially applies to the measurements of the loads imposed on the shaft since it is necessary to take into account both the electromagnetic moment and the mechanical moment, as well as the angular velocity and angular acceleration, which depend not only on the noise parameters but also on their intensity. Therefore, attempts are constantly being made to improve measurement systems by improving methods and means of processing measurement information. Thus, work [1] reports improved methods of high-precision measurement of rotational parameters using spherical probes and specialized algorithms. These methods make it possible to accurately estimate not only the eccentricity itself but also its angular parameters. At the same time, the issue of universality of such algorithms and their integration with various measurement systems remains unresolved. In addition, this algorithm requires modifications because in addition to the standard noise characteristics of the signal, there are also random errors, the processing of which requires significant computing resources.

When considering the process of measuring the torques of electric motors, it is necessary to emphasize the importance of increasing the sampling frequency of the signal since instantaneous jump-like changes significantly distort the measurement result. This especially applies to vibrational parameters. Solving measurement problems under vibration conditions by diagnosing vibration sources and determining its general impact is presented in work [2], where an integral method of its assessment is proposed.

Thus, in the work, torsional fluctuations in wells were investigated, where the characteristics of both static and dynamic torque characteristics were revealed. Models of friction and sensitivity effects are taken into account. However, it would be possible to improve them by indicating possible caveats. The cited work used analytical expressions for the description of rotational parameters but there are no practical experimental confirmations under real conditions. It would be possible to characterize the proposed stability of the algorithm for identifying anomalous phenomena during the measurement of moments of drilling rigs from the point of view of preventing economic losses.

Testing of vibration characteristics and other destabilizing factors that affect the process of measuring the torques of electric motors made it possible to obtain the characteristics of static and time-dependent effects in work [3]. Thus, it was established that the static components are mainly determined by the forces of constant friction. To take them into account, an algorithm has been developed that allows detection of measurement anomalies at certain time intervals with the possibility of correcting its sensitivity.

Taking into account the complexity of the problem of measuring the torques of electric motors, the developed algorithm for the detection of anomalies definitely represents a significant progress in this area. However, for a comprehensive analysis of the effectiveness of this method, it is necessary to conduct complex experimental studies. In particular, it is important to evaluate the sensitivity of the algorithm in the context of different types of electric motors whose dynamic characteristics can significantly affect the accuracy of measurements.

This is related not only to vibration characteristics but also to other characteristics, such as voltage instability and non-linearity of the measuring channel, which can be considered as abnormal deviations from the standard operating mode due to noisy signals.

Classical means of working with a noisy signal during measurements describe interference at the input of the signal receiver, taking into account various types of noise. For example, the method of total variation and the method of median filtering of one-dimensional signals demonstrate the effectiveness of eliminating these types of noises, as shown in study [4], which presents a filter-based frequency prediction (PF-FE) algorithm used to estimate several sinusoids under conditions of additive white Gaussian noise. At the same time, if the filtering of additive noise can be implemented by classical filters, then in the event of anomalous noise effects or individual random impulses, it is necessary to apply more flexible filtering methods. To do this, they are trying to determine the criteria for such noise. However, the problem of identifying such noise is not only in determining the criteria for its occurrence, which can be used in identification algorithms, but also in the speed of information processing. Although the cited study focuses on algorithmic aspects, for its expansion it would be possible to present ways of practical application, or limitations in practice.

Work in this direction is ongoing but the speed of measuring devices also depends on the structure of noise-like signals. Thus, in [5], a high-speed method for determining changes in dynamic parameters of electric motors is proposed, which is based on the use of powerful computing devices. However, taking into account the cost of the means of achieving such a result, it can be concluded that there are cheaper and promising solutions since the main problem is not only to detect such changes but also to be able to respond to further changes as soon as possible. A quality detector for this task should have high detection rates of response speed and measurement accuracy. Therefore, in most practical situations, it is extremely important to avoid a significant number of false alarms since an effective detector must be insensitive to noise and quickly detect signal changes. An attempt was made to implement such a system for identifying jump-like phenomena during the measurement of mechanical quantities in [6], where a method for recognizing a reference signal to which random additive noise is added was proposed, depending on the types of pulses, a method for recognizing a reference signal under conditions of additive interference is used. However, such a method could be greatly improved by presenting the details of such a methodology. In particular, it would be better to expand the information on how the experiments were conducted and the data processing in relation to their results. Considering that the method has sufficient efficiency, it would be appropriate to present the results of specific comparisons to confirm the efficiency. Given that the method can work in real time and is invariant to the amplitudes of the signal pulses, the periodicity of such signals that may overlap should also be taken into account. At the same time, to expand the capabilities of the proposed method, it would be better to specify limitations within the frequency ranges, which in turn may affect the overlap of individual noise parameters. Given that the noise overlay makes it almost impossible to calculate the derivatives of the signal change at some time points, the proposed method makes it possible to determine which fragment of certain reference signal characteristics is contained in the analyzed spectrum at a certain time point. However, taking into account the periodicity of the signal, it is necessary to specify the limits of the frequency characteristics. But despite this, in the cited work, the problem was solved, in which, based on the values of the output signal and its first derivative, it is determined which of the reference functions is present in the analyzed signal at a given time.

In [7], solutions for this are described using the disproportionality function with respect to the derivative of the first order for numerical functions. However, its application under the conditions of obstacles is not sufficiently described. In more detail, the corresponding problem is covered in [8], with multiplicative error, where disproportionality is described in a special way when there is a shift in time. So, at the moment when the derivative of the impedance becomes zero, the disproportionality also becomes zero. This means that the recognition of the reference signal occurs even in the presence of interference. However, the proposed method cannot be used when the reference functions are not smooth. For reference signals, which are rectangular, sawtooth and other pulses, the first derivative does not always exist. As a result, the disproportionality of the signal cannot always be calculated. For these conditions, it is proposed to use integral disproportionality with respect to the first-order derivative for parametric functions.

The solution to this problem was implemented in work [9], by recognizing a fragment of one of the given sets of reference signals, which is included in the analyzed spectrum at the current time. The main advantage of this method is efficiency and the ability to work with signals for which it is impossible to calculate the first derivative. At the same time, the recognition system is invariant to signal amplitudes and individual obstacles. At the same time, the speed of this method requires an increase in the sampling frequency due to the characteristics of the measuring device, the presence of additional additive noise filters and additional methods of signal amplification. Therefore, this method needs more detailed characteristics for use under different measurement conditions.

Based on the research, the optimization of torque measurements of electric motors requires the identification of errors under noisy and non-linear conditions caused by vibrations and temperature factors. Therefore, there is a need to create universal identifiers that can be adapted to a particular type of electric motor.

3. The aim and objectives of the study

The purpose of this study is to devise a procedure for identifying instrumental errors, which are caused by random noise-like phenomena that occur during the measurement of torques of electric motors. This will make it possible to increase the accuracy of measurement under the influence of destabilizing factors that create additional noise.

To achieve the goal, the following tasks were set:

– to build a channel model for measuring the angular velocity and torque of a direct current electric motor under conditions of a noisy signal;

– to propose a procedure for assessing the reliability of measurements of torques of electric motors based on fuzzy logic and discrete wavelet analysis;

– to design an experimental prototype for identifying abnormal signal deviations based on neural networks.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our research is a technique for ensuring the reliability of measuring the rotational parameters of electric motors by identifying additional destabilizing noise-like influence factors.

The research hypothesis assumes that there are criteria for short-term anomalous noise-like effects on the accuracy of the torque measurement, which are difficult to fix, which is associated with a small time of manifestation. However, they can be identified by additional informative parameters. The developed algorithm for recognizing such anomalies under conditions of noisy signals will make it possible to increase the accuracy of the measurement by filtering individual anomalous noises and detect hidden changes in the operation of the electric motor.

Modeling of the measurement of the torque of the electric motor under conditions of noisy signals and implementation of the measurement algorithm was carried out using separate open software libraries. Methods for identifying abnormal signal changes are based on fuzzy logic and neural networks of the Autoencoder type.

Experimental studies were carried out at the designed bench for measuring the torque, angular velocity, current, and voltage of the collector electric motor.

The simulated data were planned to be used to assess the reliability of the measurements of the torques of the electric motors through the established criteria for the reliability of the data in the uncertainty set. This will make it possible to apply these criteria for the experiment, which was to be carried out on an experimental measuring bench in order to detect deviations in the operation of the electric motor. At the same time, under the conditions of noisy signals, to determine anomalies during the measurement of torques, it is proposed to use a neural network taking into account additional informative parameters, such as electric motor power and angular velocity. In parallel with this, it is proposed to apply a neural network to determine changes in the signal, which are dependent on a number of informative parameters, such as electric motor power and angular velocity.

4. 2. Requirements for modeling the measurement of rotational parameters of an electric motor under vibration conditions

The structural diagram of the model for measuring the torque of an electric motor under conditions of a noisy signal, using separate pulse generators, can be represented by using transfer functions.

Thus, the conversion function of the measuring channel of the DC collector electric motor may take the following form:

$$W_y(s)=\frac{I_A(s)}{U_y(s)}=\frac{k_I s}{\left(T_m T_e s^2+T_m s+1\right)}, \qquad (1)$$

where $T_m = JR_A/C_w C_e$ is the mechanical time constant of the engine; $T_e = L_A/R_A$ – electrotechnical constant of engine operation time; $k_I = J/C_w C_e$ – current transfer coefficient; I_A – current in the armature circuit of the electric motor; R_A is the resistance of the armature circuit, which is equal to the sum of the resistance of the armature windings ED and the input resistance of the amplifier, Ohm; L_A is the sum of the inductances of the armature circuit of the motor and the output circuit of the amplifier, Gn; J – moment of inertia of the armature, N·m^2; C_e – force moment coefficient, N·m; C_w – speed, V·s/rad; s is the Laplace operator; U_y is voltage.

The torque, in turn, can be expressed through the rotation speed ω and other parameters of the system. To this end, you need to take into account the engine dynamics equation:

$$M = J\frac{d\omega}{dt} + B\omega. \quad (2)$$

The influence of vibration on the change in torque can be described by an oscillatory chain of the second order. General structural diagram taking into account: reverse electromotive force (EMF); moment of resistance, driving moment, total moment M_o, M_p, M, B, the coefficient of friction, is shown in Fig. 1.

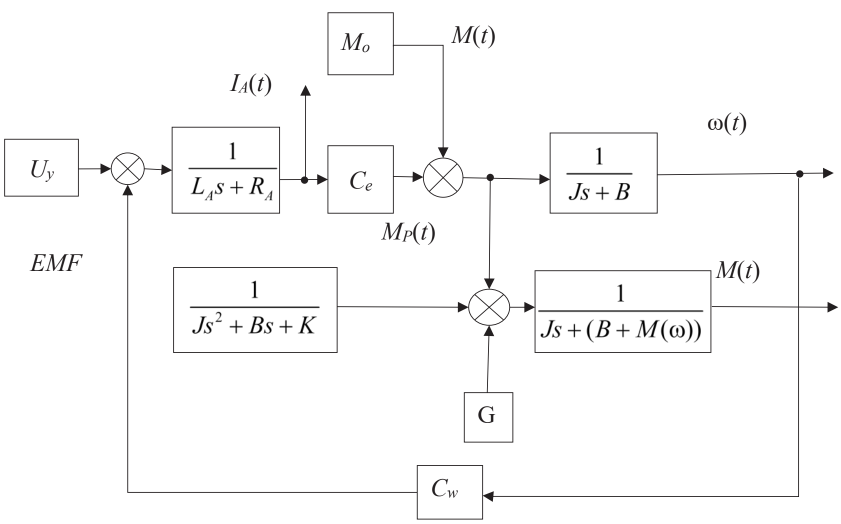


Fig. 1. Block diagram of DC commutator motor

Thus, taking into account the proposed structural scheme, modeling of such parameters as angular velocity and torque can be carried out taking into account loads on the shaft and vibrations.

4. 3. Requirements for the procedure for assessing the reliability of torque measurements of electric motors

Evaluation of the deviation from the standard mode of operation of the measuring device in accordance with its technical characteristics can be carried out using fuzzy logic, which makes it possible to evaluate the uncertainty of the measurement results by determining the degree of their belonging to a given uncertainty interval. This does not reduce uncertainty, however, with the help of the theory of fuzzy logic, it is possible to expand the toolkit for processing and analyzing the data of measurement results under conditions of uncertainty by experimentally or expertly establishing the form of the trapezoidal membership function:

$$\mu(W;a;b;c;d) = \begin{cases} 0, \ W < a, \\ \frac{W-a}{b-a}, \ a < W < b, \\ 1, \ b < W < c, \\ \frac{d-W}{d-c}, \ c < W < d, \\ 0, \ W > d, \end{cases} \quad (3)$$

where W is the torque value; a, b, c, d are parameters of the function of W membership to the uncertainty interval.

A series of sequential steps can provide the procedure for determining the reliability of measurement data with the necessary algorithm, namely: determining the input parameters of the membership function. They can be established both experimentally on the basis of conducting a number of experiments, and expertly; creation of software and hardware for single torque measurement; calculating the received data according to expression (3) and establishing whether the measurement value belongs to the uncertainty set; ensuring the storage of the obtained results throughout the entire series of measurements. This is necessary to obtain transient characteristics of individual dynamic parameters of the electric motor. And taking into account the low speed of measurement due to the need to process the measurement results for each obtained value, such calculations can be carried out after a series of measurements. This will make it possible to identify both the stable operating mode of the electric motor, in which the measurement of the rotational moment occurs with the specified accuracy, and the abnormal operating modes, under which there may be deviations from the specified accuracy.

It is possible to ensure the proper performance of such an approach during real-time measurement using the calculation according to expression (3), but it is necessary to use powerful computing tools, which increases the cost of the measuring device several times.

At the same time, to determine anomalies in the operation of measuring devices, especially during sharp transients, under conditions of white noise, methods of identifying hopping random signals are used.

The toolkit for this is quite wide: carrying out signal differentiation; application of separate filters; statistical methods; wavelet analysis; time series analysis, as well as intelligent machine learning methods. Among which, taking into account the specificity of the dynamic characteristics of the signal under noise conditions, for the vast majority of sensors measuring rotational moments, the most optimal methods for determining anomalies may be wavelet analysis methods and a number of intelligent analysis methods.

The ability to identify resonance phenomena, changes in vibration characteristics, as well as non-linearities caused by changes in the elastic properties of the electric motor shaft, can be provided by methods of discrete wavelet analysis. This will make it possible to conduct a study of non-stationary signals, for example, during the acquisition of the transient characteristics of the starting moment of the electric motor (Fig. 2), which includes both frequency and amplitude non-stationary signal changes, the identification of which requires separate detectors.

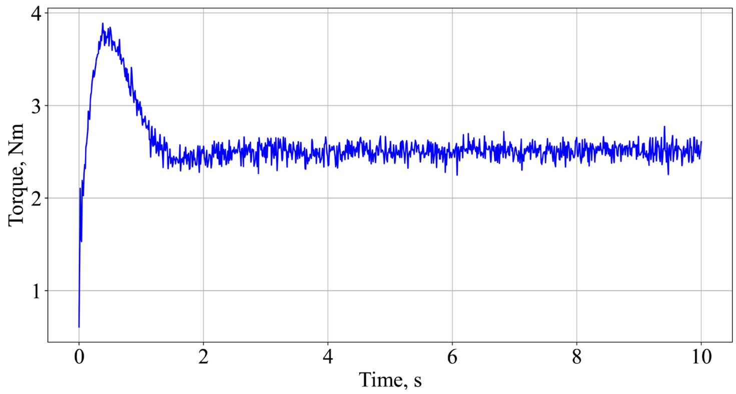


Fig. 2. Transient characteristic of the starting torque of the electric motor

Discrete wavelet analysis makes it possible to represent a continuous signal function:

$$f(t)=\sum_{j,k=-\infty}^{\infty} d_{j,k}\cdot\psi_{j,k}(t), \tag{4}$$

$$\psi_{j,k}(t)=\frac{1}{\sqrt{2^{j}}}\psi\left(\frac{t-k\cdot 2^{j}}{2^{j}}\right), \tag{5}$$

where $\psi(t)$ is the scaled or «mother» wavelet function, j and k determine the scale and position of the wavelet, $\psi_{j,k}(t)$ is the wavelet function, and $d_{j,k}$ are the coefficients of the discrete wavelet transformation.

Several approaches can be used applying this function to detect anomalies in the signals coming from the torque sensors. One of them is the analysis of wavelet coefficients to detect uncharacteristic deviations or changes in the signal. To this end, the signal $s(t)$ received from the sensor is first decomposed using the wavelet transform:

$$W_s(a,b)=\int s(t)\cdot\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)\mathrm{d}t, \tag{6}$$

where $s(t)$ is the signal from the sensor, a is the scale, b is the displacement, $\psi(t)$ is the wavelet function.

Then the obtained wavelet coefficients are analyzed for uncharacteristic deviations or anomalies. Namely, the statistical characteristics of the coefficients for operation under the stable mode of operation of the electric motor are determined. Zones are revealed where the wavelet coefficients differ significantly from the indicators under the stable mode of operation, which may indicate anomalies.

After that, anomalies can be determined based on the comparison of the coefficients with the established limit values:

$$Anomaly \Leftrightarrow \left|W_s(a,b)-\mu\right| > k\cdot\sigma, \tag{7}$$

where μ and σ are the average and standard deviation of the wavelet coefficients for the steady-state operation of the electric motor, k – limiting factor.

Taking into account the possibility of decomposing the signal into separate amplitude-frequency components for their further analysis, there are anomalies that are also characteristic of the steady mode of operation of the electric motor, for example, the change of individual harmonics in the signal, which is associated with the wear of bearings and the creation of additional vibrations, or the unevenness of the change magnetic field, due to an uneven number of turns on the stator coils, etc.

However, when the sampling frequency of the measurement signal is increased, individual pulses will not be recorded, which is related to the speed of the measuring device.

This problem can be solved by applying methods of intelligent data analysis, which are based on artificial neural networks. Among their many types, one can note Autoencoder-type neural networks, which, after training, can be used to detect anomalies by comparing the input data with their reconstruction.

Estimating the dependence of individual information parameters such as voltage, current, angular velocity, and acceleration can be useful for detecting such anomalies under high-frequency measurement conditions. Therefore, the principle of implementation of this network can be based on the estimation of data reconstruction error.

So, after training on already existing data including power, torque, and rotational speed, the model is used to recover all the data. In this case, anomalous modes of operation will have a higher reconstruction error. After the reconstruction error exceeds a fixed threshold, anomalies are fixed (Fig. 3).

The input data of the neural network will be the vector $X=[x_1, x_2, x_3]$, where x_1 is the speed of rotation, x_2 is the electric power, and x_3 is the torque. The coding layer can be described as $h=f(W_eX+b_e)$, where W_e and b_e are the weights and biases of the coding layer, and f is the activation function.

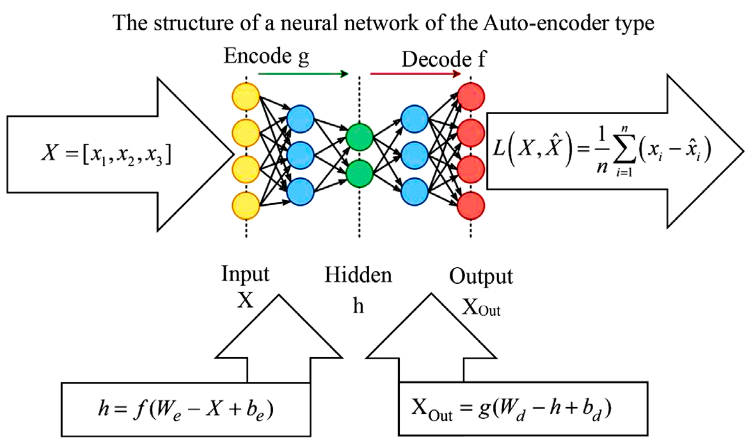


Fig. 3. The structure of the Auto-encoder type neural network: x_1 — speed of rotation; x_2 — electric power; x_3 — torque; W_e and b_e are the weights and offsets of the coding layer; f is the activation function of the coding layer; W_d and b_d are the weights and offsets of the decoding layer; g is the activation function of the decoding layer

Decoding can be described as follows: $\widehat{X}=g\left(W_d\cdot h+b_d\right)$, where W_d and b_d are the weights and offsets of the decoding layer, and g is the activation function (Fig. 8).

The root mean square error is used to measure the difference between the input data and its reproduction:

$$L(X,\widehat{X})=\frac{1}{n}\sum_{i=1}^{n}\left(x_i-\widehat{x}_i\right)^2, \tag{8}$$

If $L(X,\widehat{X})$ exceeds a certain threshold level, the input is considered abnormal. The Adam optimization algorithm can be used to minimize the loss function and train the weights of the encoding and decoding layers.

5. Results of investigating the methodology for assessing the reliability of measurements of torques of electric motors

5. 1. Modeling of the channel for measuring the angular velocity and torque of a direct current electric motor under conditions of a noisy signal

The built model of the measuring channel for angular velocity and torque (Fig. 1), taking into account vibration, moment of resistance, as well as electrical parameters, was implemented for the purpose of investigating anomalies in the transient characteristics of signals under white noise conditions. To this end, the parameters of the model are defined, in particular: current < 700 mA; rotation speed < 4000 rpm; electric power < 24 W. The variable input parameter of the model is voltage. The output parameters are the torque and the speed of rotation of the shaft.

As a result, the following transient characteristics were obtained (Fig. 4). The modeling process was carried out using the software library for simulating dynamic control chains [10].

Thus, having the criteria for determining anomalous signal changes that characterize the operation of the measuring transducer, white noise $(\varepsilon_n)_n$, variance σ^2 and the sequence of observations $(\varepsilon_n)_n$ should be distinguished among them, which can be described by the known ratio:

$$y_n = \mu_n + \varepsilon_n, \qquad (9)$$

$$\mu_n = \begin{cases} \mu_0, & \text{if} \quad n \le r-1, \\ \mu_1, & \text{if} \quad n \ge r, \end{cases} \qquad (10)$$

where μ_n is a mathematical expectation that can be of two types depending on the value of n: μ_1 and μ_0; n and r are indices used to control terms in the sequences.

A method based on discrete wavelet transformation of the signal $s(t)$ received from the torque sensor was used to detect anomalies in signals with abrupt changes in amplitude and frequency characteristics. This method includes the application of statistical criteria.

With a limited number of expansion levels, the sequence of discrete values of the analyzed signal $s(t_j)$ is represented as an ordered set of expansion coefficients in the system of scaling and wavelet functions:

$$s(t_i) = \sum_{k=1}^{2^{N-M}} a_{m,k}\varphi_{m,k}(t_i) + \sum_{m=1}^{M}\sum_{k=1}^{2^{N-M}} d_{m,k}\psi_{m,k}(t_i), m,k \in I, \qquad (11)$$

where $\varphi_{m,k}(t_i)$ is the basic scaling function; $\psi_{m,k}(t_i)$ – $a_{m,k}$, d_m; m, k – scale and shift parameters in the space of integers; N is the total number of signal sampling levels. In the context of the discrete wavelet transform, N defines the depth of the signal decomposition. M is the number of levels at which signal detailing is performed.

To adapt the wavelet transform to real-time data analysis, the software code was used, which made it possible to implement the identification technique with two sliding windows W_1 and W_2, which move in time with a defined step, fixing the torque values that are within each window. The use of these windows allows detecting anomalies in the signal. As a result, anomalies were determined at the time of acceleration of the electric motor, which is caused by a change in both the amplitude and frequency characteristics of the signal (Fig. 5).

As a result, it was possible to determine the pulse, the amplitude of which exceeds the limit level. This makes it possible to identify additional anomalies in noisy signals. However, from Fig. 4, it can be seen that individual pulses, marked as abnormal, appear not only during the starting moment but also under the steady mode of operation of the electric motor since their amplitude exceeds the specified threshold. Such periodicity cannot be called abnormal, due to the fact that it is related to the cyclicity specific to the operation of the electric motor.

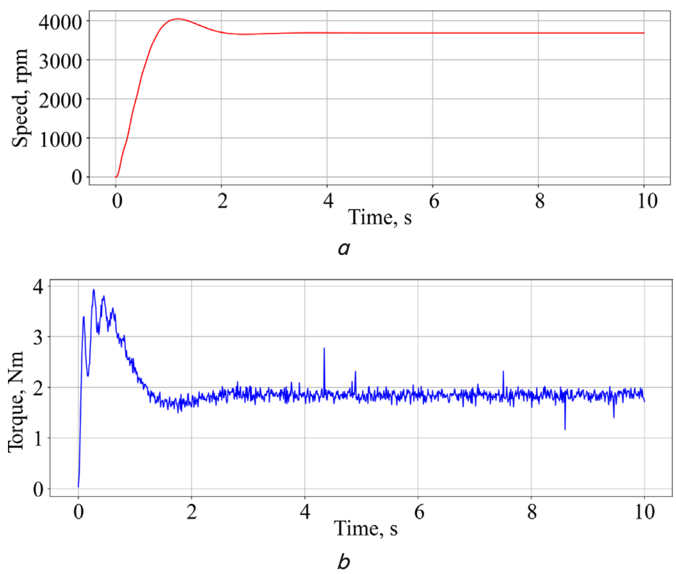


Fig. 4. Transient characteristics of rotational moment and angular velocity: *a* – angular velocity; *b* – torque

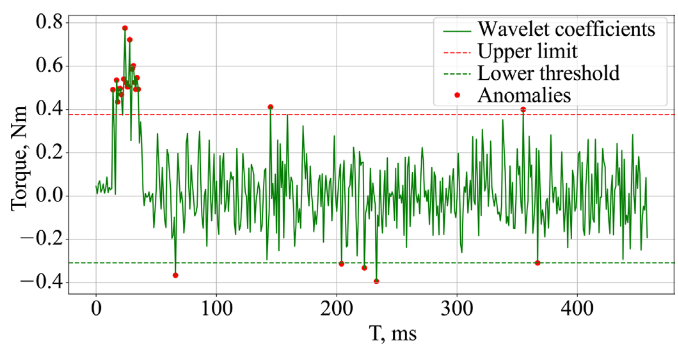


Fig. 5. Identification of anomalous signal deviations using wavelet functions

In this case, there is a need to analyze one or another periodicity of such pulses using intelligent means of analysis, for example using neural networks.

5. 2. Procedure for assessing the reliability of electric motor torque measurements based on fuzzy logic and discrete wavelet analysis

The use of fuzzy sets makes it possible to effectively estimate the uncertainty of the results of measuring the torques of electric motors. Therefore, without reducing the uncertainty, but expanding the toolkit for data analysis using the considered trapezoidal membership function (3), based on experimental or expert evaluations of a number of its parameters, a procedure for assessing the membership of measurement values to uncertainty is proposed.

Such a procedure can be implemented as follows; each measurement value is evaluated by a trapezoidal membership function (Fig. 6).

Application of such an algorithm will make it possible to assess the extent to which the measurement parameter can be attributed to a separate set characterized by more stable indicators.

Using the proposed procedure for assessing the adequacy of measurement results (Fig. 7), a program code was developed for its implementation.

Thus, having a simulated sample of data (Fig. 7, *b*), a curve of the degree of belonging of the measured values to the uncertainty interval was constructed (Fig. 7, *a*).

Fig. 7, *a* demonstrates that the degree of compliance of the measurement results with the uncertainty interval increases with the establishment of a stable mode of operation of the electric motor.

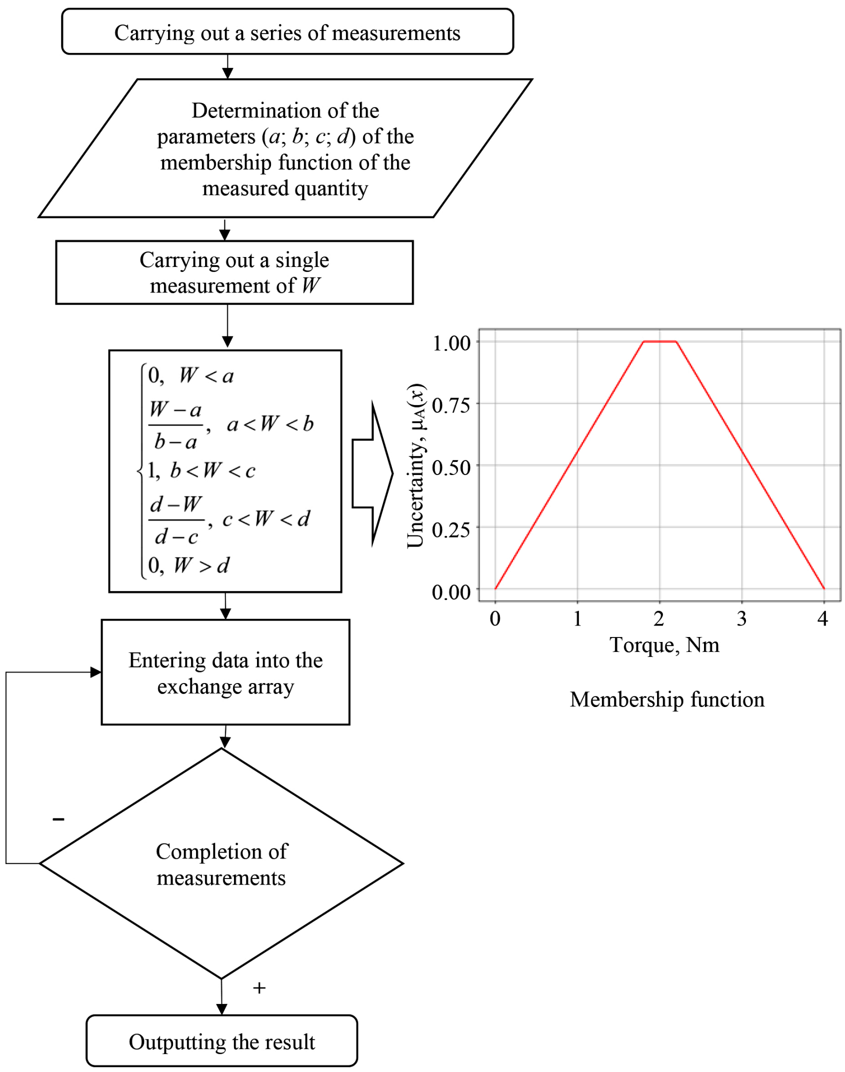


Fig. 6. Procedure for assessing the uncertainty of torque measurements of electric motors

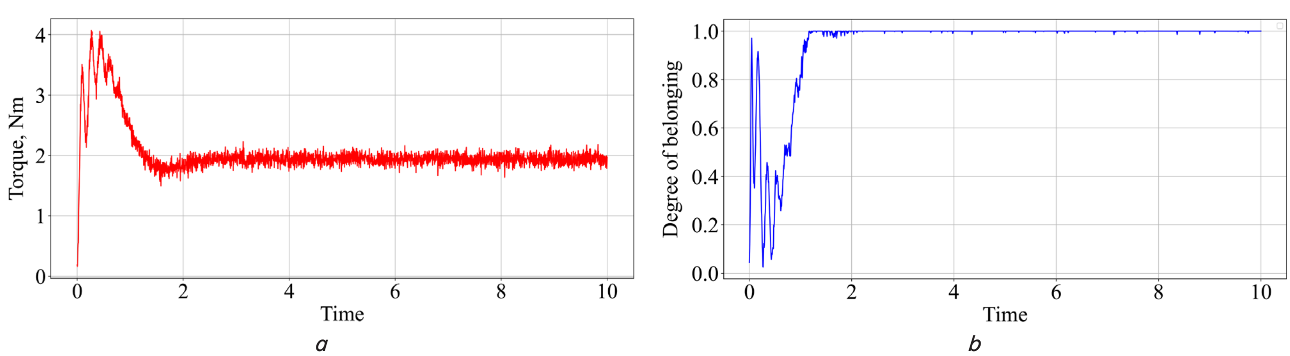


Fig. 7. Simulation of electric motor torque measurements:
a – taking into account vibration; *b* – degree of measurement data belonging to the uncertainty interval

And despite the possibility of determining individual criteria for the stability of measurements, which are determined by the level of the signal within the framework limited by the reliability function, it is impossible to detect anomalous periodicity in pulses under conditions of a noisy signal without intelligent means of analysis.

5. 3. Design of an experimental prototype for identification of abnormal signal deviations based on neural networks

The basic characteristics of the bench are presented on its functional and electrical diagram (Fig. 8).

The device works as follows. The signal from the strain gauge is sent to the HX71 converter. The strain gauge uses a Whiston resistor bridge consisting of four resistors R1...R3 of known resistance and a resistor R_X of unknown resistance to be measured.

Given that this bridge is used for a strain gauge, the VG+ (Voltage Gain Positive) and VG– (Voltage Gain Negative) outputs are used to power it. VO+ (Voltage Output Positive) and VO– (Voltage Output Negative) are the signal outputs of the strain gauge. The voltage difference between VO+ and VO– is measured depending on the amount of force applied to the strain gauge sensor.

So, the signal from the strain gauge goes to the HX71 integrated circuit, which is an analog-to-digital converter (ADC), which allows the analog signal received from the strain gauge to be converted into a 24-bit value at the output. The microcircuit includes an integrated voltage stabilizer, which eliminates the need to use an external stabilizer. In addition, this chip has a built-in low-noise operational amplifier.

Next, the digital signal through the ADC outputs, namely DT and SCK, goes to the ESP8266 microcontroller, where this signal is processed.

The role of the strain gauge in measuring torque is to use a special brake clutch that is attached to the arm. In this case, the torque is equal to the vector product:

$$\vec{M} = \vec{F}\cdot\vec{R} = F\cdot R\cdot \sin a, \qquad (12)$$

where $\vec{M}$ – momet (Nm); $\vec{F}$ – force (N); $\vec{R}$ – force arm (cm); a is the angle between the force vector $\vec{F}$ and the force arm vector $\vec{R}$.

To obtain the frequency characteristic of the angular velocity, a phototransistor is used, which changes its logic state in one rotation of the electric motor shaft. The received frequency characteristics from the phototransistor are also transmitted to this microcontroller.

The calculated data are sent to the web application, where their data sample is stored, and a procedure is implemented to detect abnormal changes in the signal.

The resulting experimental sample of measured data on shaft rotation speed and torque with a fixed load, which is provided by the brake clutch of the measuring bench, is shown in Fig. 9.

The web application uses a neural network of the Autoencoder type (Fig. 3), the inputs of which were fed with data of torque, electric power, and speed of rotation.

As a result of neural network training, a model was built. Its testing was carried out with the use of a new electric motor, receiving evaluations of abnormal signals. As a result, it made it possible to recognize the anomalies of loads, rotation speed, and electric power Fig. 10.

Our results indicate the detection of abnormal signals during the start of the electric motor. This has made it possible to recognize additional vibrations and loads associated with bearing wear during the start-up period, which was not observed in steady-state operation.

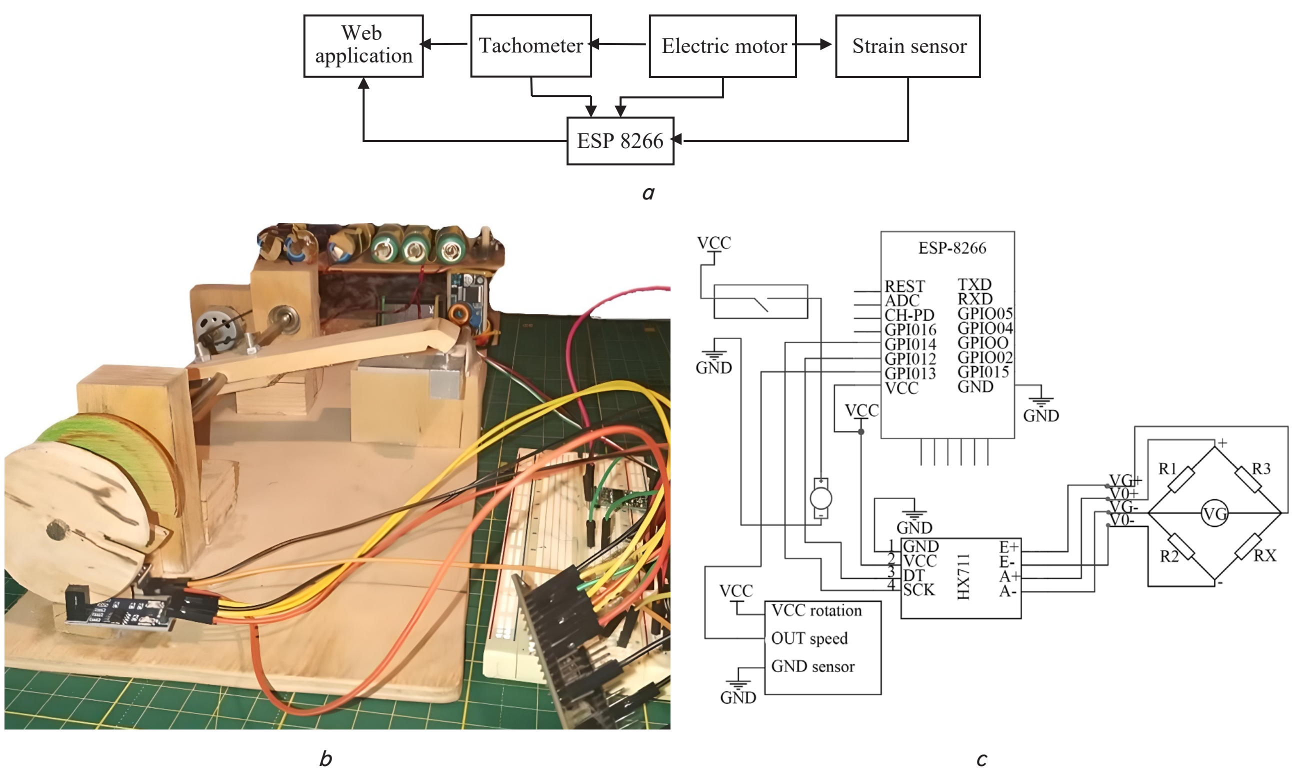
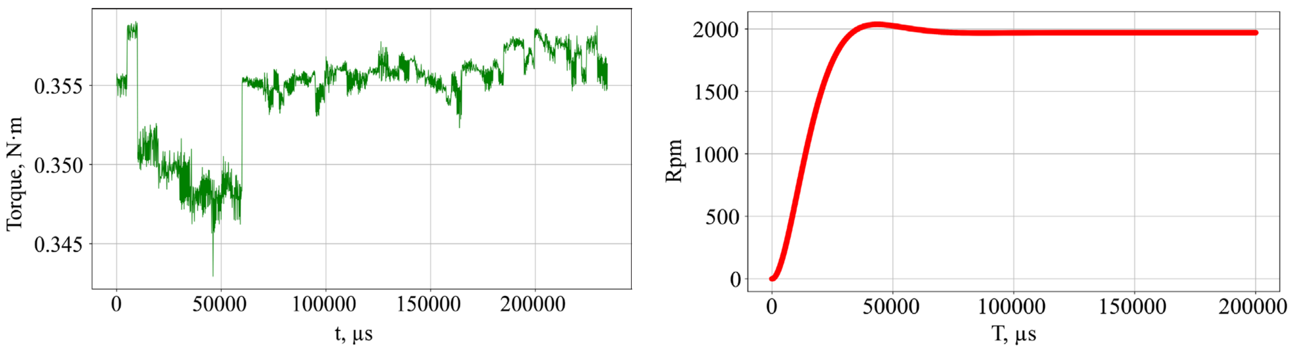
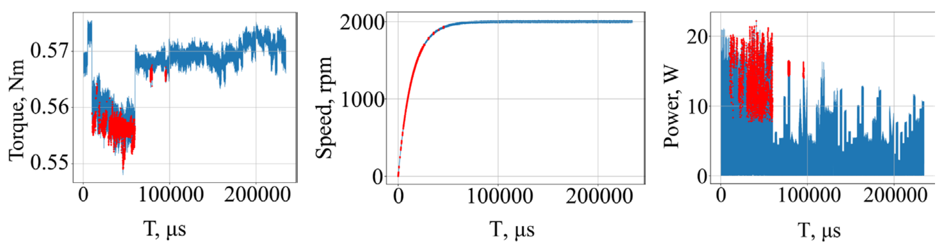


Fig. 8. Bench for measuring torques of electric motors: *a* – functional diagram; *b* – layout; *c* – electrical diagram



a *b*

Fig. 9. Transient characteristics of the torque and angular velocity of the electric motor using a measuring bench: *a* – torque indicators; *b* – indicators of angular velocity



a *b* *c*

Fig. 10. Identification of abnormal signals from sensors: *a* – measurement of torque; *b* – measurement of angular velocity; *c* – measurement of electric power

6. Discussion of results of investigating the methods and means for assessing the reliability of measurements of rotational parameters of electric motors

The results of the current study are based on simulated data of rotational parameters of direct current electric motors and real data obtained using a measuring bench.

The structural diagram of the model, shown in Fig. 1, demonstrates the effect of random signals under white noise conditions, and also describes the interaction of electrical and mechanical parameters of electric motors. With the use of this model, a study of the algorithm for assessing the reliability of measurements of torques of electric motors under conditions of uncertainty was carried out. To establish reliability criteria, a trapezoidal membership function (3) was used, the parameters of which were determined on the basis of experimental data.

This function makes it possible to estimate how much the value of the torque belongs to the range of uncertainty. This function was implemented using the scikit-fuzzy software library. And the sequence of determining the reliability of measurement data is performed using the proposed procedure for determining anomalies in the signal (Fig. 6). As a result of its implementation, it was established that the degree of compliance of the measurement values with the known measurement range increases with the stabilization of the engine operating mode (Fig. 7). This is explained by the fact that under a stable mode of operation, the influence of certain destabilizing factors, such as vibrations, voltage instability, etc., is reduced. However, quite often there are random impulses that influence the measurement result.

To identify such signals under the conditions of white noise, a method of identifying anomalous signal deviations is proposed, which is based on the discrete wavelet transformation of signal (4) to (7), (11). The results of the software implementation of this method demonstrate the determination of spiking signals under conditions of white noise (Fig. 5). However, individual pulses that go beyond the limit values of the transformation function may have a specific cyclicity that requires more detailed analysis using intelligent means.

Such periodicity cannot be called abnormal, due to the fact that it is related to the cyclicity specific to the operation of the electric motor. Therefore, for the determination of specific anomalies, this method may not be effective. In particular, when there is a consistently increasing number of signals that are abnormal for a single parameter of the electric motor. Or in the absence of jump-like changes and in the presence of hidden signal changes in white noise.The designed prototype of the measuring bench was used to test the proposed methods for researching signal anomalies during the measurement of rotational parameters of a direct current electric motor. Taking into account the problems of identifying hidden changes in a noisy signal, a neural network was built, which is implemented on a separate server. The results of training a neural network on the data obtained using a prototype with an exemplary electric motor made it possible to detect anomalies in the operation of another electric motor caused by the processes of bearing wear (Fig. 10).

Given the various features of the measurement, which are determined by the angular velocity, power, vibrations, temperature regimes, as well as the operating conditions of electric motors, it is quite difficult to determine abnormal deviations of noise-like signals. Therefore, the neural network can be used to identify not only individual pulses, limited in amplitude and time, but also the sequence of such pulses, which will make it possible to detect hidden deviations.

In contrast to [11], where this result was obtained taking into account vibration, the recognition of anomalous deviations can thus be improved by increasing the informative parameters. This is made possible by the use of an Autoencoder-type neural network architecture that can learn from the input data of a sample electric motor, which allows applying the training sample to other electric motors of a similar type.

In contrast to known methods for measuring the rotational parameters of electric motors, such as [12, 13], the proposed technique provides an opportunity to adapt to changes in the characteristics of the electric motor by adjusting the neural network.

The proposed procedure for assessing the degree of reliability of measurements, unlike the solution suggested in [3], has the ability to automatically set the reliability criteria of the obtained values. This makes it flexible in terms of adaptation to changes in the operating conditions of the electric motor. It creates the ability to integrate with various measurement systems without the need for modifications. It gives an advantage compared to the methods presented in [1], which are limited by their specificity.

Existing means of working with a noisy signal demonstrate the effectiveness of eliminating such types of noise that are taken into account in advance, as for example in [4]. If the filtering of additive noise can be implemented by classical filters, then in the event of anomalous noise effects or individual random pulses, it is necessary to use more flexible filtering methods.

Therefore, in contrast to classical methods for recognizing abnormal deviations in noisy signals, using the proposed method, it is possible to implement training on large data sets. This makes it possible to recognize new types of noise and adapt to changes in signals, without the need for manual adjustment of separate anomaly detection algorithms.

For the practical implementation of the proposed procedure for assessing the reliability of measurement, it is necessary to ensure the compatibility of measuring devices with existing data transmission interfaces. Provide high speed data transfer. You can create a user interface to monitor parameters in real time. A powerful computing server is required to meet real industrial needs.

However, the corresponding procedure, which is based on fuzzy logic, has its specific disadvantages. For example, the rules of fuzzy logic can be extremely unclear from a scientific point of view, which calls into question their objectivity. Also, the selection of optimal membership functions and reliability criteria may require numerous experiments and tests, which, in turn, increases the system setup time. In some cases, it is not always possible to determine which factors are key for the algorithm, which can negatively affect its accuracy.

The proposed prototype of the measuring bench, which uses a neural network, is also not without shortcomings. Thus, additional noise and signal anomalies that were not represented in the training data can become an obstacle to their identification.

7. Conclusions

1. The built model of the operation of a direct current electric motor allows simulating its operation during acceleration. The peculiarity of this model is the consideration of the structural diagram of the measurement of the rotational moment and angular velocity, taking into account the noise-like signal and the generator of additional noises, which is implemented using transfer functions.

The model combines several key components. In particular: the conversion function of the measuring channel of the electric motor, which takes into account the mechanical and electrical time constants of the motor, current transfer coefficients, and other electrical parameters. The model takes into account the second-order oscillatory chain, which describes the effect of vibrations on the change in torque. In addition, elements of reverse electromotive force (EMF), moments of resistance, driving torque, as well as the coefficient of friction in bearings are taken into account. The approbation of this model made it possible to analyze the operation of a direct current electric motor under various conditions, in particular, during exposure to vibrations and noise, which makes it useful for practical applications and further scientific research.

2. The proposed procedure for assessing the reliability of measurements of torques of electric motors based on fuzzy logic and discrete wavelet analysis allows us to assess the reliability of measurements by constructing a function of the dependence of measurement values on uncertainty. Such a function includes reliability criteria that can be adjusted depending on the measurement needs. The experiments showed the possibility of identifying stable modes of engine operation and detecting anomalies by identifying individual frequency and professional characteristics of spiky signals. Although this method does not reduce measurement uncertainty, it improves data analysis under conditions of uncertainty. However, it can be less effective for detecting specific anomalies, especially when the measurement reliability criteria changes, or when hidden pulse sequences occur. In this case, the membership function parameters can be adjusted.

The wavelet transform was adapted for real-time data analysis using a software code incorporating a technique with two sliding windows $W1$ and $W2$. These windows, moving in time, record the value of the torque, which makes it possible to detect anomalies, especially during acceleration of the electric motor. Thus, anomalies were detected, which are characterized by a change in the amplitude and frequency characteristics of the signal. However, some pulses, marked as anomalous, appear not only during start-up but also under a stable mode, which is related to the cyclical operation of the engine. This requires additional analysis of the periodicity of such pulses using intelligent means.

3. The designed measuring bench differs from existing analogs by the integration with a neural network located on an external server. Bench testing was conducted by training the neural network on one type of electric motor and then testing it on another electric motor of the same type. In the testing process, this made it possible to recognize additional vibrations and loads associated with bearing wear during the start-up period, which was not observed in steady-state operation. However, the evaluation of the efficiency of the model depends on a number of factors, including the characteristics of the electric motor and the permissible limits of deviation.

The measuring bench can be widely used in various fields. In industry, the bench can be used to control the quality of electric motors at the stages of design, production, and operation, making it possible to optimize the process of testing electric motors. At research institutions, it can serve as a means for conducting experiments and studying the characteristics of electric motors.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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