The object of this study is a technique for assessing the accuracy of measuring the torques of electric motors. This technique is based on the improvement of dynamic torque measurement processes under transient operating modes. Special attention was paid to devising adaptive methods to normalize the output signal, which take into account vibrations and nonlinearities of the measuring channel.

In order to improve the accuracy of measurements under conditions when the controlled parameter has different deviations from its average value, a technique for integrating time measurement intervals was proposed. That has made it possible to generalize parameter fluctuations, providing more stable measurement results.

This paper reports the simulation of the process of measuring torques of electric motors under transient operating modes and under vibration conditions. That has made it possible to test the proposed technique for estimating the variance of the methodological error, which includes the integration of measurement time intervals and makes it possible to increase the accuracy of the measurement under the conditions of transient modes in electric motor operation.

An algorithm for correcting the error of the dynamic torque of the electric motor has been proposed, which allows it to be corrected. This becomes possible owing to the use of a reference measure and the proposed technique for determining the deviations of the controlled parameter of the measured quantity, as well as the automatic calibration of measuring transducers.

The algorithm allows for flexible settings of the corrective action, expanding the potential of electric motor control systems. It can complement soft measurement methods, as well as adjust the threshold values of deviations under different operating modes of electric motors. This allows the measured systems to better adapt to changes in operating conditions, to adjust the specified measurement accuracy under conditions of uncertainty

Keywords: torque, measurement accuracy, measurement error, measuring device

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DEVISING A TECHNIQUE FOR ASSESSING THE ACCURACY OF MEASURING ELECTRIC MOTOR TORQUE

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1. Introduction

The basic requirement for measuring information systems, as well as for electric motor control systems, is to enable the specified accuracy of torque measurements under operational conditions. Such requirements are set when measuring the parameters of electric motors under static and dynamic modes. In the state of the stabilized mode of operation, fluctuations of the measured parameters are usually recorded, which are taken into account for further error correction. However, the analysis of transient processes caused by changes in the speed of rotation of electric motors requires a wider study.

So, in the process of measuring dynamic moments, it is necessary to take into account the sampling frequency of the signal during the transition of the electric motor to a stable mode since this is associated with the increase in the nonlinearity of the transformation of shaft vibration sensors. This, in turn, requires the correction of methodological and instrumental errors based on parameters of deviations from rated values.

At the same time, the speed of measuring devices cannot always ensure the fixation of instantaneous loads on the shaft of the electric motor. For example, when drilling non-homogeneous materials, or as a result of braking of electric vehicles, when rotational forces are generated by manipulators of robotic equipment, etc.

In turn, it is not always possible to solve the problem by increasing the speed of measuring devices since this is a significant increase in the cost of the measuring device, and, in many cases, the lack of an opportunity to determine sudden changes in the load in general.

Thus, obtaining the specified accuracy when measuring the dynamic moments of electric motors is a complex measurement procedure since this process is affected by a significant number of factors, both dynamic and static. There are difficulties with ensuring the proper linearity of the measuring channel. Signal processing also requires additional filtering.

When measuring static moments, the rotational force of the rotor is determined in a stationary state. This determination is based on the product of two quantities: the distance of the arm from the center of the shaft axis to the point of application of the force and the force acting on this arm. In the context of dynamic moments, the determination is to find the product of the moment of inertia and the angular acceleration, where many more factors have an influence and the accuracy of the measurement.

Therefore, the task to assess the accuracy of measurements under conditions when the rate of change of the measured quantity exceeds the discrete measurement interval remains unsolved. This, in turn, requires an assessment of accuracy even under conditions of uncertainty.

When testing electric motors, the time base on which mediation must be carried out varies from a few seconds to 1–1.5 minutes. The maximum time of generalization of the average value of the parameter can be limited by many factors, including changes in the engine operating mode. Such changes cause a deviation of the measured value from the specified accuracy throughout the entire measurement interval and require clarification, depending on the features of the electric motor, its modes of operation, speed of rotation, and loads on the shaft.

2. Literature review and problem statement

In contrast to the measurement of static moments, when the rotational force of the rotor is determined in a stationary state, the dynamic moment is measured as the product of the moment of inertia by the angular acceleration [1]. This greatly complicates the possibility of obtaining accurate data, which is associated with a significant number of destabilizing factors affecting the specified physical quantities.

In modern literature, the issues of measuring dynamic moments under the conditions of fast transient processes are not sufficiently covered. These complexities include the need to accurately account for rapidly changing angular acceleration and moment of inertia, ensuring the adequacy and accuracy of measurement systems to capture these parameters.

Depending on the method for measuring the torque, the elimination of such shortcomings can be solved during the transformation of the electrical parameters of the electric motor, or directly by force-measuring means.

Methods for measuring dynamic moments based on electrical quantities do not provide sufficient accuracy, which is associated with a significant number of transformations and errors of means of measuring electrical parameters.

Therefore, the method for direct measurement of the torque on the shaft is more accurate but requires filtering of the signal under vibration conditions, elimination of nonlinearities caused by the elastic properties of dynamometric elements. It is important to power the primary sensors located directly on the shaft.

In work [2], classical techniques for direct measurement of the rotational moment on the shaft are presented, taking into account the speed and power of the electric motor, but individual destabilizing factors that have a significant impact on the measurement error when using classical methods are not sufficiently taken into account. For example, the influence of temperature factors on the non-linearity of measuring channels. A change in temperature can affect the elasticity of dynamometric force-measuring elements. However, depending on the speed of rotation of the shaft, the structure of the electric motor, loads on the shaft, such an effect can have different intensity. All this gives reason to assert that, depending on the operating conditions of the electric motor and its functional features, a special error correction can be applied for the specified factors.

Thus, the application of torque measurement methods, which are based on electrical characteristics, does not provide the same accuracy as it can be realized using force-measuring sensors. However, measuring directly on the shaft has a rather complex structure. At the same time, it is not always possible to take into account rapidly changing transient processes.

At the same time, attention should be paid to research aimed at minimizing errors in the measurement of torques, as well as methods and means of their implementation. For example, in [3], the results of research on the accuracy of dynamic moment measurement using a power analyzer are given. It is shown that to improve the accuracy of measurements, simple algorithms based on the determination of electrical costs over a certain period of time can be used. The proposed method involves carrying out idle tests of the converter before the actual measurement and makes it possible to achieve relatively good results during measurements under the 25–100 % speed and load modes. However, the disadvantages of indirect measurements are the accumulation of error that occurs as a result of a significant number of measurement transformations. Therefore, the accuracy of the proposed method depends not only on destabilizing factors caused, for example, by vibration, but also on changes in the elasticity of the shaft as a result of heating.

Usually, they try to compensate for vibration at the stage of occurrence of this phenomenon, using various methods. At the same time, this technique does not require expensive force measuring equipment. All this gives reason to claim that it is advisable to use combined methods for measuring the dependence on the needs of a given accuracy. This is the approach used in work [4]. Thus, to minimize the impact of vibration arising as a result of electromagnetic processes, two-phase stepper motors were used, which were used as adjustable electric dampers and energy harvesters. However, the measurement process must be adapted to filter out such phenomena. For example, in work [5], artificial intelligence methods were used to measure the dynamic moment taking into account destabilizing factors. In the study, the torque was measured by attaching individual weights to the shaft. They rotated at different speeds at variable distances in the range of angles from 0° to 345° degrees. That made it possible to observe different torque values created by the DC motor. The results of the experiment showed that in some cases the moment indicator at low speeds can have non-linear values. Thus, an attempt to apply artificial intelligence to take into account the influence of destabilizing factors made it possible to show that their influence has regular changes. Also, it is possible to determine the accuracy of the measuring device depending on the operating mode of the electric motor.

Performance was compared according to the mean square error (MSE), regression coefficient (R^2), root mean square error (RSE), and mean absolute error (MAE). But considering the possibility of improving the measurement accuracy in this way, increasing the computing power of the measuring device significantly increases the cost of the measuring device. In addition, depending on the type of electric motor and the conditions of its use, it is necessary to additionally train the model, which increases operating costs.

The aforementioned, as well as a significant number of works related to moment measurement using neural networks, gives grounds to claim that it is advisable to implement intelligent techniques of accuracy assessment under the transient modes of operation of the electric motor. In general, the advantage of devices where neural networks are used is the correction of accuracy by calculating the dependences between individual physical quantities. In this regard, the procedure for simultaneous measurement of the moment of inertia and the braking moment of the rotor of an electric motor, which is presented in [6], deserves attention. The method is based on delay tests on the engine with the addition of additional loads in the form of steel disks on the rotor with different moments of inertia, but the same masses. The optimal values of moments of inertia and load were determined, at which the errors were minimal. At the same time, if the measurements were carried out at a constant temperature of the bearings, where the optimal values of moments of inertia and load were used, then in this case experimental errors can be minimized. Under optimal measurement conditions, the relative accuracy of the method for measuring the moment of inertia was 4.3–5.3 %, while for measuring the braking moment it was 3–6 % in the angular velocity range from 30 to 120 rad/s. However, this method, although it makes it possible to increase the accuracy of the measurement, does not take into account the possibility of identifying fast spiking signals arising as a result of resonance phenomena under conditions of increased vibration.

At an angular velocity of less than 30 rad/s, methodological errors were significantly higher. Therefore, among various sources of error, methodological errors play a decisive role as they are related to the limitations of measurement methods. Thus, the study and analysis of these errors, as well as the construction of mathematical models to describe them, is an important step towards improving the accuracy of measurements.

The reviewed works offer an increase in the accuracy of measuring torques by filtering signals, obtaining additional informative parameters, and increasing computing power. But their disadvantage is that measurements under the conditions of jump-like transient loads on the shaft cannot always be registered. Therefore, the accuracy of measurements must be adjusted depending on the mode of operation of the electric motor since the speed of the measuring device is not always sufficient to record such transient processes.

Depending on the means of measurement, the sampling frequency of the received signal can also be adjusted if necessary. Accordingly, by increasing the sampling frequency of the measuring transducer and increasing the quantization range, as well as by using several informative parameters to measure the moment, it is possible to achieve greater accuracy under the transient modes of operation of the electric motor. But in the case of the impossibility of improving such characteristics of the measured device, there must be a technique that would make it possible to evaluate its accuracy, taking into account the fast-changing transient processes that are not recorded by the devices, that is, under conditions of uncertainty.

3. The aim and objectives of the study

The purpose of our study is to determine the possibility of increasing the accuracy of measurements of the torques of electric motors under transient modes of operation. This will make it possible to reduce the impact of random and systematic errors, thereby ensuring higher reliability of measurements.

To achieve the goal, the following tasks were set:

– to propose a technique for estimating the variance of the methodological error of the dynamic torque of the electric motor under different operating modes;

– to develop an algorithm for controlling and correcting the error of the dynamic torque of the electric motor within the given limit level.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is a technique for assessing the accuracy of measurements of torques of electric motors.

The hypothesis of the research assumes that there is an opportunity to increase the accuracy of measurements of torques of electric motors under transient modes of operation. For this purpose, it is proposed to devise a technique for assessing the accuracy of measurements, which is based on the analysis of generalized deviations of the measured value from the average value over the entire measurement interval. To validate this technique, an algorithm of control and correction of methodological error is used within the framework of its given limit level. It is assumed that this will minimize the impact of random and systematic errors throughout the measurement interval, thus ensuring higher measurement reliability. It is also expected that the algorithm will provide automatic correction of errors arising because of increased vibration under transient operating modes, which will allow maintaining the proper accuracy of measurements within the maximum permissible level.

4. 2. Requirements for assessing the accuracy of measuring the dynamic torque of electric motors

Some simplifications have been accepted in the framework of this study: the analysis is carried out only on the value of the dynamic moment, without taking into account other possible parameters of the electric motor that could affect the measurements. That made it possible to focus on the key aspects that are most relevant for the measurement of rotational loads on the shaft.

To provide an objective assessment of the dynamic moment of the electric motor, the average values of the parameters determined on the same time base during the entire period of operation were used. This is critically important in the process of testing electric motors since the time base for summarizing measurements can vary from a few seconds to one to one and a half minutes. This time range can be limited by various factors, including changes in the engine's operating mode, which requires ensuring the accuracy of the measurements throughout the activity period, especially taking into account the moments of acceleration and deceleration.

An analysis of the dynamic moment was carried out at the set time interval, which includes the dependence of the measured value $x(t)$ on time at the time of acceleration of the electric motor. The purpose of such an analysis was to generalize the parameters of the deviation of the measured value from its average value over the entire measurement interval.

Taking into account the transient processes that can change faster than the sampling frequency of the measuring device, the deviation from the average value of the measured value under different operating modes of the electric motor was investigated. At the same time, the technique for approximate integration was used. That made it possible to obtain a comprehensive assessment of the accuracy of a series of repeated direct measurements over the entire measurement interval.

Such a process involves studying the variability of measurement results and allows correcting possible sources of errors that negatively affect the reliability of measurement data.

4. 3. Requirements for the development of the torque error correction algorithm

The development of the error correction algorithm for the measurement of the torques of the electric motor involves the practical implementation of the proposed technique for determining the accuracy of torque measurement. It is assumed that the algorithm should include a reference measure to calibrate the measuring device. To this end, a method for partial shaft loading was used, in which an important component is the use of an arm and a lever at its end, which together form a reference moment (Fig. 1):

$$M = F \cdot R = F \cdot R \cdot \sin a, \quad (1)$$

where M is the moment of force; F – force (H); R – force arm (m); a is the angle between the force vector F and the arm vector of force R.

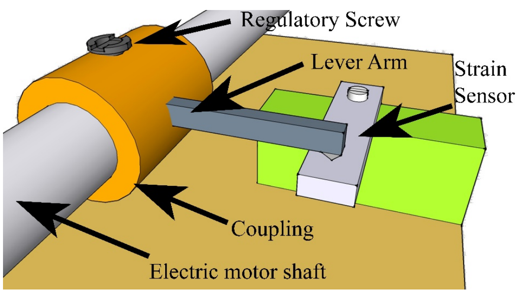

Fig. 1. The principle of measuring the torque of an electric motor. *Note: drawn by using SketchUp*

The angular velocity is proposed to be determined using induction sensors [7] (Fig. 2).

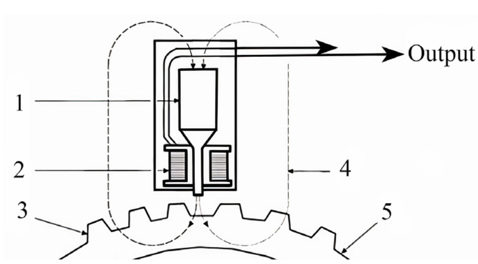

Fig. 2. Shaft rotation speed sensor: 1 — magnet; 2 — coil; 3 — tooth; 4 — magnetic force line; 5 — rotor [2]

The algorithm uses the possibility of parallel determination of the moment using the basic equation of the dynamics of rotary motion, which takes into account the moment of inertia of the rotor, the driving moment, and the brake loading moment [8].

To test the algorithm, the acceleration model of a direct current electric motor was used [9]. This model made it possible to obtain torque data over the entire measurement interval, providing full coverage of all engine operating modes.

The algorithm should provide feedback for automatic error correction based on the analysis of the received data.

The Python programming language was used to implement the algorithm and model the measurement process, as well as software libraries designed for data calculation and visualization.

5. Results of investigating the accuracy of measuring the torques of electric motors

5. 1. Estimating the variance of methodological error in the dynamic torque of electric motor under different operating modes

Fig. 3 provides a visual representation of the average value of the dynamic torque function during acceleration of a direct current electric motor, taking into account transient modes of operation (starting and braking, acceleration):

$$\bar{x}_{av} = \frac{1}{T_S} \int_0^{T_S} x(t)\,\mathrm{d}t, \quad (2)$$

where $\bar{x}_{av}$ is the average value of the parameter; T_S – specified averaging time.

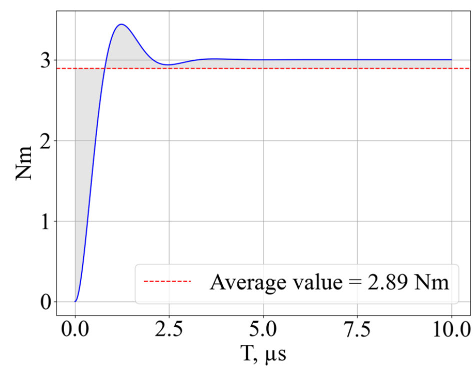

Fig. 3. Average value of dynamic torque during acceleration of the electric motor

In Fig. 1, one can observe the process of averaging the values of the function $x(t)$ by integration, which allows smoothing the variability of the function during a given time interval. At the same time, it can be seen that with significant deviations, this technique does not allow obtaining an average value, taking into account further stabilization of the output signal.

When testing electric motors, the time base on which it is necessary to generalize measurements ranges from a few seconds to 1–1.5 minutes. The maximum time of generalization of the average value of the parameter can be limited by many factors, including changes in the engine operating mode.

Therefore, there is a need to ensure measurement accuracy over the entire period of electric motor operation, taking into account the moments of acceleration and braking.

During the testing of electric motors, multiple measurements of all controlled parameters are carried out during the specified time interval T_S with subsequent averaging of the obtained results for each parameter.

If the measuring device of the automatic system reacts quickly and provides instantaneous values of $x(t)$ after each measurement, then standard error estimation methods [10] can be used to calculate the variance, assuming that $x(t)$ is a stationary random process.

In the case when the measuring link of the automatic system is characterized by low inertia, it can be assumed that the instantaneous value of $x(t)$ is obtained after each measurement. In this case, to calculate the variance, based on the assumption that $x(t)$ is a stationary random process, it is possible to apply dependences to estimate the error of approximate integration (2). It is advisable to use this technique under the stable mode of electric motor operation since signal spikes will not give an accurate result of averaging.

However, in this case, it will not be possible to obtain an adjustable generalization, taking into account all modes of operation at a given measurement interval. Therefore, it becomes necessary to divide the measurement intervals by time into separate parts by calculating the average value of the function $x(t)$ for several consecutive time intervals, and not for one continuous time interval.

To take into account such needs, it is possible to perform successive measurements on the time base T_S at time intervals T. Thus, over a part of the interval T, namely during T_1, averaging of a separate segment of the measurement interval takes place. After that, there is a break of $T-T_1$ duration to control other parameters. Then the cycle repeats. Over the entire T_S time, $n=T_S/T$ measurements are performed, on the basis of which the average value of the controlled parameter is determined:

$$\bar{x}_{av} = \frac{1}{nT_1}\left[\begin{array}{l}\int_0^{T_1} x(t)\mathrm{d}t + \int_T^{T+T_1} x(t)\mathrm{d}t + \ldots + \\ + \int_{(n-1)}^{T(n-1)+T_1} x(t)\mathrm{d}t\end{array}\right]. \quad (3)$$

Thus, with the help of integral expressions in formula (3), it is possible to calculate the sum of $x(t)$ values for each of n intervals of length T_1. As a result, this sum is then normalized by dividing by the total length of time under consideration, which is equal to nT_1. By dividing the acceleration time into 3 periods, a more approximate average value is obtained compared to Fig. 3 (Fig. 4). Thus, expression (3), unlike (2), calculates the average value of function $x(t)$ for several consecutive time intervals, and not over one continuous time interval.

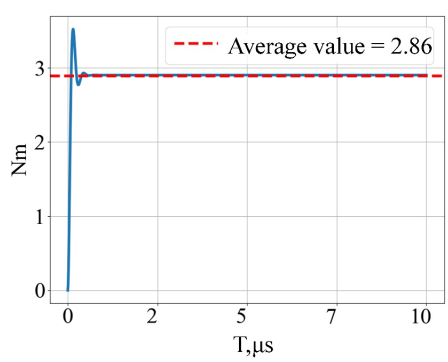

Fig. 4. The average value of the dynamic moment during electric motor acceleration, obtained from expression (3) with the distribution of the acceleration time into 3 periods

Thus, expression (3), unlike (2), calculates the average value of function x(t) over several consecutive time intervals, and not over one continuous time interval.

To further investigate the possibilities of obtaining the average value of the measured value, white noise was added to the model of acceleration of the direct current electric motor (Fig. 5). This will make it possible to compare the results obtained under different operating modes of the electric motor.

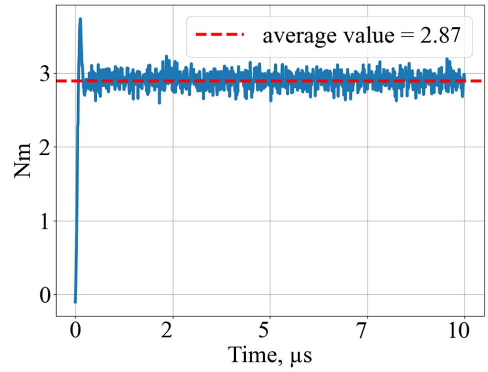

Fig. 5. Acceleration curve considering white noise

Taking into account destabilizing factors, such as vibration at the time of acceleration in Fig. 6, its increased influence can be observed.

Thus, from the simulated sample of torque data, using expression (2), taking into account transient processes, the root mean square deviation of the measured value under the stabilized operating mode was obtained (Fig. 6, *a*). With the application of expression (3), the root mean square deviation of the measured value under the stabilized engine operation mode decreased (Fig. 6, *b*). The results of modeling according to expression (3), but with the addition of the generation of random deviations that can reflect vibration, are shown in Fig. 6, *c*.

So, this technique makes it possible to set the range of deviation of the measured value from its average value over a given measurement interval. This will make it possible to further adjust the measurement accuracy depending on the specified accuracy of the measuring device under a certain mode of electric motor operation.

Using expressions (2) and (3) and performing the operation of centering the random function $x(t)$, one can get the methodological error of this estimate:

$$\Delta = \frac{1}{n}(\xi_1 + \xi_2 + \ldots + \xi_n) - \xi_{n+1}, \quad (4)$$

where ξ_i ($i=1,\ldots n$) is the average value of deviation of $x(t)$ from $\bar{x}_{av}$ in each of the n intervals, where T_i is the length of each interval; ξ_{n+1} is the average value of the deviation of $x(t)$ from $\bar{x}_{av}$ over the entire given measurement interval – T_S, which includes all n intervals.

The average value of deviations for each time interval, the measurement can be represented by the following expressions:

$$\xi_1 = \frac{1}{T_0}\int_0^{T_1} \dot{x}(t)\mathrm{d}t,$$

$$\xi_2 = \frac{1}{T_1}\int_{T_1}^{T+T_1} \dot{x}(t)\mathrm{d}t, \quad (5)$$

$$\xi_n = \frac{1}{T_n}\int_{T(n-1)}^{T(n-1)+T_1} \dot{x}(t)\mathrm{d}t,$$

$$\xi_{n+1} = \frac{1}{T_S}\int_0^{T_S} \dot{x}(t)\mathrm{d}t,$$

where $\dot{x}(t) = x(t) - \bar{x}_{av}$, is the deviation of the value of function $x(t)$ from its average value.

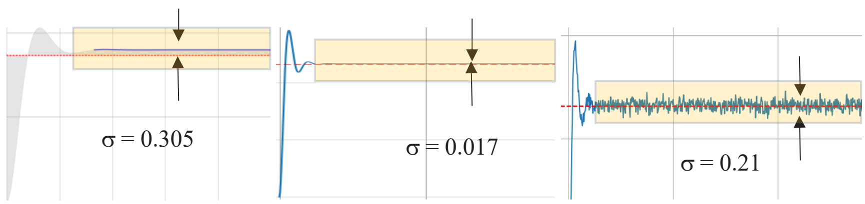

Fig. 6. Root mean square deviation under the stabilized mode of electric motor operation when using different techniques for calculating the average value of the measured quantity: *a* — using the total integration time; *b* — dividing into three intervals; *c* — dividing into three intervals taking into account vibration

Since the error Δ is a linear function of several random variables, its variance can be represented by the following expression:

$$D(\Delta)=\frac{D_{\xi_1}}{n}+D_{\xi_{n+1}}+\frac{2}{n^2T_1^2}\sum_{i<j}k_{ij}-\frac{2}{nT_1T_3}\sum_{i=1}^{n}k_{i,n+1}, \quad (6)$$

where D_{ξ_1}, $D_{\xi_{n+1}}$ – variances of random variables:

$$\left.\begin{aligned} D_{\xi_1}&=\frac{2}{T_1}\int_0^{T_1}\left(1-\frac{\tau}{T_1}\right)k(\tau)\mathrm{d}\tau;\\ D_{\varepsilon_{n+1}}&=\frac{2}{T_S}\int_0^{T_S}\left(1-\frac{\tau}{T_S}\right)k(\tau)\mathrm{d}\tau,\end{aligned}\right\}, \quad (7)$$

where $k(\tau)$ is the correlation function.

Dispersions D_{ξ_1}, $D_{\xi_{n+1}}$ are related to measurements of deviations from the mean value of function $x(t)$ over different time intervals but they differ in their purpose. Thus, D_{ξ_1} is determined on the first time interval, which lasts from 0 to T_1 and takes into account the spread of deviations within the first interval. It is calculated based on the correlation function $k(\tau)$, where τ varies from 0 to T_1. $D_{\xi_{n+1}}$ is the variance of deviations for estimation based on the entire T_S time range, which can cover all n intervals. It measures the spread of deviations on the general interval and is calculated according to a similar principle but over a longer time. Based on this, the variance of the methodological error during the measurement of dynamic moments under the transient modes of electric motor operation can be determined by modeling the measurement process using a software algorithm based on the proposed expressions. This will make it possible to generalize the deviation of the output signal of the measuring transducer under different operating modes of the electric motor.

After centering the random variable according to expression (4) and dividing the average values of deviation $x(t)$ from $\bar{x}$ into 300 intervals ξ_n according to expression (5), the indicator of the average deviation of the entire measurement interval T_S was obtained (Fig. 7).

Fig. 7 shows that each interval ξ_n is characterized by a separate deviation depending on the period, which is due to transient processes and dispersion depending on the mode of electric motor operation. Thus, D_{ξ_1} is significantly determined on the first time interval, which lasts from 0 to T_1. It takes into account the spread of deviations within the first interval and is calculated based on the correlation function $k(\tau)$, where τ varies from 0 to T_1.

$D_{\xi_{n+1}}$ is the variance obtained on the basis of the entire T_S time range, which can cover all n intervals, determines the spread of deviations on the general interval, and is calculated according to a similar principle but over a longer time.

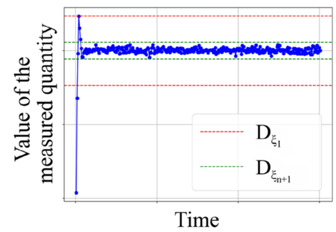

Fig. 7. The average value of $x(t)$ deviation from $\bar{x}$ on each of the n intervals

From the obtained simulation data sample of the acceleration curve (Fig. 7), it can be concluded that there is a need to measure the dynamic moment depending on the operating mode. This is due to a significant deviation from the average value during the start of the electric motor. Therefore, there is a need to determine the operating modes of the electric motor under which the deviation from the specified value will be within the permissible norms.

Considering the fact that the weight of transient modes increases the influence of destabilizing factors, such as vibration, the proposed technique for determining the deviation from the average value of the measured value will make it possible to optimize the assessment of the measurement reliability range.

5. 3. Development of the torque error correction algorithm

The algorithm for determining the accuracy of the dynamic moment measurement may take the following form (Fig. 8).

This sequence of steps includes checking and completing all previous processes before starting a new measurement cycle. At the beginning, the parameters for the measurement are selected, namely, the determination of the measurement settings by means of the measurement range, the sensitivity of the sensors, the error of the measuring devices and the operating modes of the electric motor. After that, the sensors used for data collection are activated. At the same time, error data is taken into account. The electric motor starts. Under the mode of step-by-step transition to different operating modes, the torque sensors are calibrated to ensure the accuracy of the measurements. Then the engine switches to standard operation mode and data collection is implemented in parallel at certain time intervals, which ensures representativeness and completeness of information. After that, a technique for determining the accuracy of measurements is implemented by analyzing the level of deviation of the measurement parameter from its average value. A comparison is performed to the reference value. After that, the level of deviation of the error from its set value is determined and the error is corrected based on feedback.

These steps form the general structure of the algorithm for correcting the torque measurement error within the limits of its given limit level.

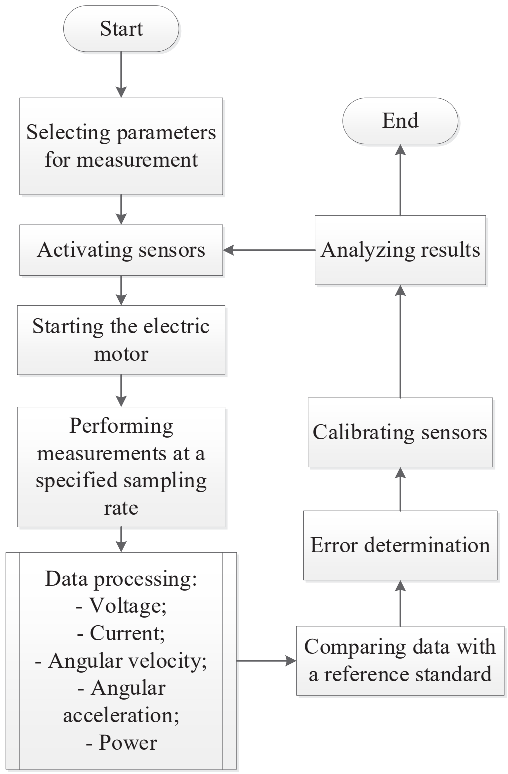

Fig. 8. An algorithm for determining the accuracy of dynamic torque measurement. *Note: built by using Microsoft Visio*

In turn, ensuring the accuracy of the measurement of the rotational parameters of the electric motor can be implemented using feedback, correcting the error.

6. Discussion of results of assessing the accuracy of measurements of dynamic moments and angular accelerations of electric motors

The results of increasing the accuracy of measuring the dynamic torque of electric motors reported in this study could be used for practical application.

Thus, the simulation of the process of measuring the dynamic moment during acceleration of the electric motor taking into account the transient modes of operation according to the expression (3) (Fig. 3) showed that the deviation from the average value of the measured value would spread over the general range of the measurement interval. This, in turn, requires adaptive approaches to measuring dynamic moments during acceleration, steady state operation, and braking.

The employed technique for dividing the measurement time into separate intervals for a more accurate calculation of the average value of function $x(t)$ made it possible to analyze the average values for several consecutive time periods. So, instead of integrating one continuous interval, as shown in Fig. 3, using the integration of separate time intervals T_n in the general measuring interval T_S according to expression (3), the sum of $x(t)$ values for each of the intervals is obtained. As a result, the root mean square deviation of the measured value under the stabilized mode of electric motor operation, over the entire measurement interval, was reduced from 0.305 to 0.017 (Fig. 4). After simulating the vibration by adding a random impulse of ±0–10 % to the total measured value, the root mean square deviation was 0.21 (Fig. 5). The comparative characteristics are shown in Fig. 6.

As a result of the centering of the random variable, by dividing the average values of $x(t)$ deviation into 300 intervals, the deviation from the average value of the measured value was obtained depending on the operating mode of the electric motor (Fig. 7).

From Fig. 7 it follows that each range ξ_n has its own deviation characteristics caused by transient processes depending on the operating mode of the electric motor. Particularly significant deviations are observed in the first time interval from 0 to T_1, where the deviations are calculated based on the correlation function $k(\tau)$, where τ varies from 0 to T_1. Thus, from Fig. 7, it can be seen that the largest deviation was observed precisely at the moment of start-up, which is due to the greatest load on the shaft.

It can be observed that the variance for the entire time range T_S can include all n intervals and determines the spread of deviations on the total interval. It can be calculated by expression (6).

Thus, it is necessary to measure the dynamic moment depending on the operating mode of the electric motor since a significant deviation from the average value is observed during start-up. To this end, it is important to determine the operating modes of the electric motor, under which the deviations will be within the permissible norms. To a large extent, this applies to the facts when, under the transient modes of operation of measuring devices, the period of change in the measured value exceeds the period of discretization of the measuring signal.

The proposed algorithm for controlling and correcting an error of the dynamic torque of electric motor within the given limit level will make it possible to implement the proposed technique for assessing the accuracy of measurements at the stage of their implementation. It can complement the soft methods of moment measurement [11], as well as determine the threshold values of deviations under different operating modes of electric motors. Unlike the algorithms implemented in electric motor control systems [8], the proposed algorithm (Fig. 8) makes it possible to create flexible settings for determining the error-correcting action.

At the same time, there are also shortcomings in our proposals. Thus, the suggested algorithm for correcting a measurement error under transient modes of electric motor operation requires significant computing resources, which can complicate the implementation of measuring systems in low-budget devices. Also, in the presence of multiplicative errors, there is a need for additional normalization of the output signal. This can complicate the process of measurement and data analysis as the effect of various factors must be accurately determined for each individual output signal level.

The proposed technique for determining the average value of the controlled parameter (3) also requires significant dusting power, which can create obstacles for its real-time application on equipment with limited computing resources. Although the simulation results show a decrease in the deviation of the measured value from its average value (Fig. 6), these results require further verification under the real operating conditions of the electric motor. Simulated data may not reflect all factors and conditions of the actual measurement process. Limitations that can be taken into account to our proposals relate to the minimization of delays associated with the analysis of the received data, which can negatively affect the overall measurement process. There may be limitations on the volume of data generated as a result of the application of the proposed techniques for assessing measurement accuracy. This may require additional computing resources.

The proposed technique for determining the variance of methodological error (6) includes a technique for integrating time intervals, which may not take into account all possible sources of errors under real operating conditions. This approach can be limited in its accuracy for very small or very large values of the measured quantity.

Further development of our research may include refinement and adaptation of the proposed approaches to specific destabilizing factors. This will allow for a better understanding of the impact of errors on the accuracy of measurements.

7. Conclusions

1. Simulating the process of measuring the torques of electric motors under transient modes of operation, with the aim of improving measurement procedures, showed that under the conditions of transient processes, which are caused by changes in the loads on the shaft, multiplicative phenomena occur. Such phenomena require adaptive approaches to measurements and normalization of the output signal. In particular, the influence of vibrations and nonlinearities of the measuring channel creates the need to break down the measurement intervals since under different operating modes the deviation of the controlled parameter from the average value has different indicators. This especially applies to unstable modes of operation. At the same time, the proposed technique for determining the variance of methodological error, which includes the integration of time intervals, can be used to obtain adjusted accuracy indicators under the conditions of periodic transient regimes.

As part of our study, it was found that taking into account destabilizing factors that affect the accuracy of measuring the torques of electric motors, such as vibration, their influence increases with increasing loads on the shaft.

The proposed technique for determining the deviation of measured value from its average value under the stabilized mode of electric motor operation showed a decrease in the root mean square deviation from 0.305 to 0.017. Under conditions of vibration, which was modeled separately, the root mean square deviation was 0.21.

2. The proposed algorithm for correcting the error of the dynamic torque of electric motor allows for its correction. This becomes possible owing to the use of a reference measure and the proposed technique for determining deviations of the controlled parameter from its average value, as well as automatic calibration of measuring transducers.

The algorithm allows for flexible settings of the corrective action, expanding the capabilities of electric motor control systems. Therefore, it can effectively complement soft measurement methods, as well as correct the threshold values of deviations under different operating modes 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.

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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 current work.

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