

# Determining the Quality of Electric Motors by Vibro-Diagnostic Characteristics

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## Abstract

Experimental studies of vibrations of asynchronous electric motors (EMs) of the electric bus traction electric drive are carried out in the paper. The presented studies are based on generalization of the diagnostic features of vibration characteristics and statistics concerning the limiting values of vibration parameters of EMs and their dependence on the technical condition. The analysis of the obtained results allowed us to determine the permissible vibration levels of EMs in the frequency range from 5 Hz to 10 kHz. The method of diagnosing EMs traction electric drive according to the indicators of vibration levels is developed, which allows to evaluate their technical condition. The values of the permissible vibrational accelerations of the electric bus EMs are determined, which enable to estimate their technical level. This method allowed to develop classes of evaluation of the EMs technical condition by the level of their vibration, which makes possible to predict their resource.

**Keywords:** electric car, asynchronous traction motors, vibration level, electric motor vibration class, vibrodiagnostic.

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## 1. Introduction

Environmental and fuel-resource problems that have arisen around the world have caused the popularization of vehicles with electric traction (electric vehicles, electric buses). This is especially true for big cities and metropolitan areas. There buses are actively used as public transport.

Meeting two basic conditions is very important for the distribution of urban buses. The first is equipment of the appropriate infrastructure that will enable their charging / recharging. This infrastructure must include additional alternative energy sources such as, for example, solar panels, energy-generating roads, platforms [1–5].

The second is to ensure the reliability of vehicles, which is achieved by increasing the reliability of their

main parts: traction energy source and traction motor, by controlling the technical level and condition at all stages of the life cycle [6–9].

The authors of [10, 11] determined that by the criterion of optimality (minimum losses and maximum efficiency) as a traction motor, an asynchronous motor (AM) with a short-circuit rotor is most suitable. AM combines several advantages: minimum cost; minimum weight; minimum of conductive and ferromagnetic materials, etc.

Because electric buses are a relatively new mode of transport, statistics on failures or problems arising from the operation of traction electric motors (EMs) of electric buses are not found in open sources. But it is possible to assume with high probability that for electric buses the number of failures of EM will be high enough because operation in urban conditions is characterized by alternation of modes of acceleration, run-in and braking,

overcoming descents and ascents, short-term parking. Under these conditions, the EMs operates almost at constant change of control influence, that is, in transient modes of operation. Therefore, choosing quality and reliable EMs and diagnosing faults at the stage of their development is very important [8].

Depending on the type of EMs failures, their repair is carried out by the own efforts (within the operating company) or by specialized organizations. The reasons for such failures are insufficient quality control of design, manufacture and operation. EMs repair is often done with disassembly and replacement of parts. However, the reliability of the EMs are significantly reduced. In this regard, diagnosing EMs quality at the design, production, acceptance and testing stages is one of the most important ways to increase the reliability and cost-effectiveness of equipment. But the choice of EM study method is of particular importance is [12].

Despite the fact that there are national and international standards for electric rotary machines, the problem of improving the methods of determining their quality, finding the criteria that most broadly describe the condition of the engine and the development of methods for their diagnosis is paid much attention by scientists and engineers around the world [12].

For example, article [13] describes the procedures of IEC 60034-18-41 technical standard for assessing the quality of type I engines by means of a (stand-alone) partial-discharge test. The work compares stand-alone and online measurements made on an engine that could have passed the test, but did not do it shortly after powering through the PWM inverter because it was damaged during the tests. Based on this analysis, the advantages and disadvantages of this standard are determined.

Modern EMs are controlled by semiconductor converters (inverters). Such converters can generate voltage pulses with very short rise times (from 50 ns to several thousand microseconds) and high switching frequency (up to 20 kHz). On the one hand, inverters are extremely effective in regulating EM speed, and on the other hand, they can significantly increase the risk of EM failure. In addition, inverters cause undesirable voltage on the shaft of the EM, which adversely affects the operation of the bearings [14].

The repetitive and fast pulses supplied to the motor in addition to the bearings also cause damage to the EM windings [15, 16]. This is due to the ripple in the electrical circuit. They can occur on the EM terminals due to the mismatch of the EM resistance and the connecting cables.

A model has been developed by US researchers based on a patented EM fault detection system [17]. The advantage of the present invention is that it is software based, and it uses data obtained from non-intrusive measurements. This significantly reduces costs. The system uses a multi-parameter experimental simulation algorithm to obtain a mathematical description of the EM that compares the simulated result with the measured result. The operator analyzes the result and determines whether the engine is running without errors. After detecting the signs of malfunction, the operator evaluates the measured changes in

the parameters of the EM, determines the deviation from the reference value and issues a diagnosis of a probable failure or a faulty component.

The large number of existing methods of quality assessment and diagnosing EM does not solve the problem as a whole. In addition, they are quite complex and aimed at detecting specific damage (E.g., rotor [18] or stator [19], or insulation [20], or bearing assembly [21], etc.). Therefore, a systematic approach to the quality assessment of EM will allow developing a universal method of monitoring their technical condition both at the design stage and at the production, operation and repair stages.

The purpose of the work is developing a method for determining the technical condition of the traction electric motor according to the vibro-diagnostic characteristics. To achieve this goal it is necessary: to carry out experimental studies of the vibrations of induction motors; to process the obtained results and determine the acceptable vibration levels of motors in the frequency range from 5 Hz to 10 kHz.

The studies presented in this paper are based on the generalization of the diagnostic features of vibration characteristics and statistics on the limiting values of EM vibration parameters and their dependence on the technical condition; on statistical methods of normalizing EM diagnostic parameters. The experimental results were processed using mathematical statistics methods, in particular, the series criterion method based on the sample median and the criterion of consecutive relations, squares, and the method of variance nonparametric analysis using the Friedman test.

## 2. Objects, methods, equipment and ways to measure electric motor vibrations

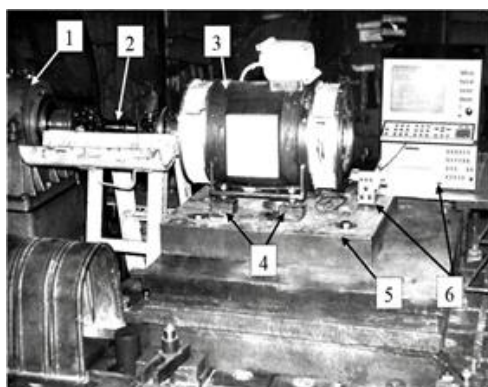
The known proportional, or close to it, dependence of the change in vibration levels on the technical state of asynchronous electric motor, load, speed, clearances, kinematic and geometrical parameters of bearing units was taken as the initial position. The specified properties of vibration signals can be observed in real time using vibration analyzers. It is essential to oppose the reaction of all components, structural, functional ones and the dynamic properties of bearing units that are related by correlation dependence to changes in design, production technology, working processes, operating modes and the ability to quickly receive information on the technical condition of a particular unit or the electric motor as a whole in compliance with the requirements of vibration standards. When designing, vibration levels exceeding the specified norms are considered to be unacceptable, requiring fine-tuning, and an increase in vibration levels above the allowable limit during the operation is considered as a parametric failure.

The research methods were field vibration tests of separate bearings belonging to different noise classes, bearing assemblies with different values of the fit on the shaft and into the housing, as well as asynchronous motor

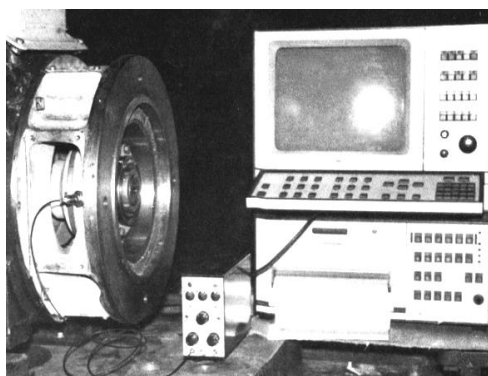
assemblies. Using the comparative analysis of the vibration spectra, the optimal structural parameters of the bearing unit and the compliance of the latter with vibration standards were determined.

10 high-quality asynchronous motors (AMs) of the ANU 92-2 type used in transport have been selected for experimental research.

The object of the study is the vibration characteristics of the AM of an ANU 92-2 type. Experimental studies were carried out on a outfit in a vibroacoustic chamber with the connection of measuring equipment, Fig. 1.



(a) general view: 1 – loading machine; 2 – cardan shaft; 3 – investigated EM; 4 – vibration isolators; 5 – outfit plate; 6 – measuring equipment



(b) connection of measuring equipment

**Figure 1.** Outfit of vibroacoustic chamber for testing the motor

EM vibration levels were measured in decibels by the mean square vibration acceleration. For the baseline vibration characteristics of AM, three-octave levels of vibration acceleration and narrow-band vibration spectra with a bandwidth of 3-10% in the range from 5 Hz to 10 kHz are taken.

The following equipment of Bruel & Kjaer (Denmark) was used for the research: frequency analyzers of type

2120, 2130 and 2133; 4376 vibration transducer (accelerometer); 2635 type power amplifier.

All devices underwent routine calibration and additional calibration at the Kharkiv National Scientific Center “Institute of Metrology”.

Measurement of EM vibration was carried out after the EMs previous idling for 30 minutes.

### 3. Experimental research

In the first phase of the study, the vibration levels of EM were determined in decibels by the mean square value of the vibrational acceleration. The acceleration  $a=3 \cdot 10^{-4} \text{ m/s}^2$  is taken as the conditional zero vibration level.

The investigated AMs had the trapezoidal shape of the closed rotor grooves. Bearings with vibration level requirements of Sh1 were used during the experiment.

After the measurements of the AM vibration, the statistical processing of the obtained results was performed.

The values of vibration acceleration (dB) averaged over the results of 3 measurements of each of the investigated AMs are presented in the form of a matrix  $W = (W_{ij})$  in which the rows  $i = 1, 2, \dots, 24$  correspond to the spectrum of the studied frequencies, columns  $j = 1, 2, \dots, 10$  – to the engine number on which the vibration value was obtained.

The statistical mean square deviations  $\sigma$  and the coefficient of variation of the entire set of engines were determined by the formulas:

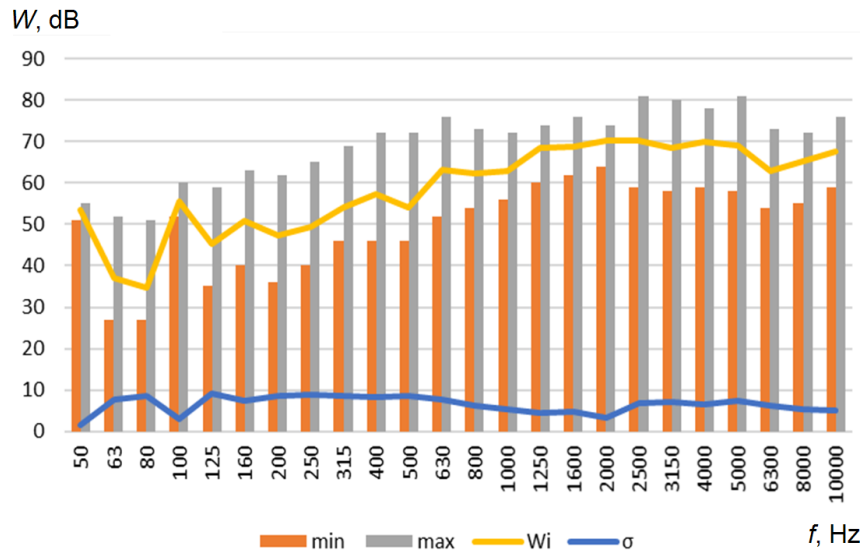
$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (W_{ij} - \bar{W})^2}. \quad (1)$$

$$v_i = \bar{W} / \sigma. \quad (2)$$

The results of the calculations showed a great heterogeneity of the results obtained.

Based on the obtained values, the spectrograms of vibrations of the investigated AM are built, from which it was difficult to make a conclusion about the randomness of the investigated sample of the AM. Therefore, an additional analysis of the results was made. For this purpose, the series criterion method, based on the median of the sample and the criterion of squares of successive dependencies, was applied. These methods are described in detail in [21].

The data series  $W = W_1, W_2, \dots, W_b, W_{i-1}, W_n, n = 24$  is considered to apply the median sample method based on the sample median. The numerical values of the elements in this row correspond to the data in the  $W_i$  column presented in Fig. 2.



**Figure 2.** Primary processing of the results of EM ANU 92-2 vibrational characteristics spectrograms (Main statistical characteristics of EM vibro acceleration, dB)

Let us transform this series into a variational one, that is, for which the rule holds:  $(W) = (W_1), (W_2), \dots, (W_i), (W_{i-1}), (W_n)$ , where  $(W_i) = \min W_i, (W_n) = \max W_i$ . For the  $(W_{i-1}), (W_i)$  sequence, the  $W_{i-1} \leq W_i$  condition holds. The median of a sequence  $(W)$ , equal to the value of  $W_{med}(n)$ , is defined by the rule:

$$W_{med}(n) = \begin{cases} (W_{\frac{n+1}{2}}), & \text{if } n = 2k + 1 \\ \frac{1}{2} \left[ \left( W_{\frac{n}{2}} \right) + \left( W_{\frac{n}{2} + 1} \right) \right], & \text{if } n = 2k \end{cases} \quad (3)$$

Let us build the sequence  $\sigma$ , each element  $\sigma_i$  of which is obtained by the rule:

$$\sigma_i = \begin{cases} a & \text{if } \bar{W} - W_{med}(n) < 0 \\ b & \text{if } \bar{W} - W_{med}(n) > 0 \end{cases} \quad (4)$$

If there is a difference  $\Delta_i = \bar{W} - W_{med}(n) = 0$ , then  $W_i$  element is ignored. A sequence of identical characters is called a series. It is assumed that the value of  $v(n)$  is equal to the total number of series, the value of  $\tau(n)$  is equal to the number of elements in the longest series, regardless of the symbol.

We add up a system of inequalities where it is assumed that  $[A]$  is an integral part of number A:

$$\begin{cases} v(n) > v_0(n); & v_0(n) = \left\lfloor \frac{1}{2}(2n-1) - 1,96\sqrt{\frac{16n-29}{90}} \right\rfloor \\ \tau(n) < \tau_0(n); & \tau_0(n) = \lfloor 3,3(\lg n + 1) \rfloor \end{cases} \quad (5)$$

If the system of inequalities (5) is fulfilled, then it should be assumed that the sample under study is random.

The values of  $\tau_0(n)$  are given in [20]. In this case, when the number of observations over the value is 24, then  $\tau(n) = 5$ .

The following expressions were calculated to test the hypothesis of random sampling using the criterion of sequential relations squares:

$$\bar{W} = \frac{1}{n} \sum_{i=1}^n W_{ij}; \quad (6)$$

$$S^2 = \frac{1}{n-1} \sum_{i=1}^n \left( W_i - \bar{W} \right)^2; \quad (7)$$

$$q^2 = \frac{1}{2(n-1)} \sum_{i=1}^{n-1} (W_{i+1} - W_i)^2; \quad (8)$$

$$\gamma = q^2 / S^2; \quad (9)$$

$$\gamma_\alpha = 1 + \frac{u_\alpha}{\sqrt{n+1}}, \quad (10)$$

where  $S^2$  – is an empirical variance – an index of variability of separate vibration levels in the sample;  $u_\alpha$  – equals to  $\alpha$  – quantiles of normal distribution. In this case, at  $\alpha = 0.95$ ,  $u_\alpha = 1.64$  (for  $\gamma > \gamma_\alpha$ , the hypothesis of statistical independence of the sample should be rejected).

The calculations confirmed that the obtained sequence of average values of the research results is not random, which confirms the reliability of the obtained results.

#### 4. Analyzing the results of the first stage of the research

EM vibration depends not only on the design and quality of manufacture, but also on the quality of electricity in the power supply system, the quality of technological operations of the units assembly, the appearance of wear, defects in electrical and magnetic circuits, and in cooling systems [8].

The classification of the main causes and sources of EM vibration [8] shows that virtually all types of EM defects affect their resource, change the parameters of the vibration signal. The results of the experiments enable us to evaluate the possibility of reducing the vibration when making some changes in the EM design.

Mechanical, magnetic and aerodynamic sources influence the vibration activity of EM. As for the latter, they only affect the frequency  $zn/60$  ( $z$  is the number of rotor grooves) and the fan is their source. The major way to reduce these vibrations is to use water cooling or to install silencers. Mechanical sources of vibration include: unbalance of the rotor, double stiffness and ovality of the rotor/pivot pins, which are manifested at frequencies  $n/60$  and  $2n/60$ . These data were obtained during experimental studies. It should be noted that they coincide with existing data, which confirms the adequacy and reliability of the results [12, 18-21].

These sources of vibration have already been sufficiently studied and there are recommendations for their removal. Based on existing recommendations, a decision has been made to use Sh-3 instead of Sh-1 to reduce vibration. The greatest influence on vibration in EM is made by magnetic forces in the frequency range from 100 Hz to 5 kHz [8]. Further research is therefore aimed at eliminating their causes.

Magnetic forces cause axial, radial and tangential vibrations of the EM. In the air gap of the AM, in addition to the basic harmonic of the field, which creates useful torque, there are additional harmonics. They arise due to:

- non-sinusoidality and asymmetry of the supply voltage;
- saturation of the EM magnetic circle (uneven permeability of steel along and across the rolling);
- discrete distribution of stator and rotor windings along the bore;
- uneven air gap caused by the opening of the stator and rotor grooves;
- static and dynamic eccentricity.

Higher harmonic fields have their amplitudes, frequencies, and wavelengths. In the general case, the frequency of vibration caused by magnetic fields is determined by the formula:

$$f = f_p \cdot z_2 \cdot k_1, \quad (11)$$

where  $f_p$  – is the frequency of rotor rotations, Hz;  $z_2$  – is the number of rotor grooves;  $k = 1, 2, 3$  – is the harmonics order.

The fundamental role in creating vibration is played by harmonic of the field, which creates a force wave with the order of  $r = 2p$  and frequency  $f = 2f_0$ , where  $f_0$  is the frequency of voltage;  $p$  is the number of the poles pairs. Significant vibration is caused by rotary gear harmonics from the fundamental field harmonics, that have the order:

$$\mu = \pm k \cdot z_2 / p. \quad (12)$$

When these harmonics interact with stator field harmonics, the radial forces appear with the order and frequency:

$$f = f_0 [2 \pm k \cdot z_2 / p(1-S)], \quad (13)$$

and for  $r = p\mu + p\nu$ :

$$f = f_0 \left[ k \frac{z_2}{p} (1-S) \right]. \quad (14)$$

where  $\nu$  – is the order of stator field harmonics;  $r$  – is the order of radial force;  $p$  – is the number of poles pairs of the main field harmonics;  $\mu$  – is the order of rotor harmonics of the field;  $S$  – slippage in the idle mode.

The tooth forces can create significant deformations of the stator, especially at low oscillations and can, at certain rotational speeds, coincide with the natural oscillation frequency of the stator. In these cases, the amplitude of the deformation and vibroacoustic radiation significantly increases, which is especially manifested in the process of starting and in EM with wide limits of regulation of the rotation speed.

Low order forces arise if  $|z_1 - z_2| = p; p \pm 1; p \pm 2; 2p; 2p \pm 1; 2p \pm 2; 3p; 3p \pm 1$  ( $z_1$  – is the number of stator grooves). Zero order forces arise when  $(z_1 - z_2) = 0; p; 2p$ .

The forces frequency equals:

$$f = 2f_0 [z_2 / p \cdot (1-S) \pm 1] \quad (15)$$

Dangerous vibration is caused by the harmonics of the field at rotor eccentricity, since in this case there is a first-order radial force, i.e. the force of unilateral magnetic gravity. With static eccentricity, the fundamental frequency of vibration is equal to twice the frequency of the power supply network, and at dynamic eccentricity, the frequency of basic vibration is equal to the frequency of rotation of the rotor.

Axial forces cause periodic loosening and compression of packets of blended steel. Under the action of axial forces, there may be a displacement of the rotor pack relative to the stator pack, which results in an asymmetric arrangement of the stator and rotor. Tangential forces cause oscillations of the teeth, which in large EMs reach large values. Under their action, the insulation of the windings is broken, the lifetime of the EM is reduced. Radial forces cause deformation of the stator package, rotor package, resulting in deformation of the frame.

Deformation of individual parts and components in general is the cause of vibration of the entire EM, whose intensity depends on the magnitude of the forces, elastic properties of the materials used in the EM, the design and its acoustic properties.

Rotary closure in the rotors can cause significant vibration. The closure of the part of the winding of the AM phase rotor causes vibration with a frequency of sliding.

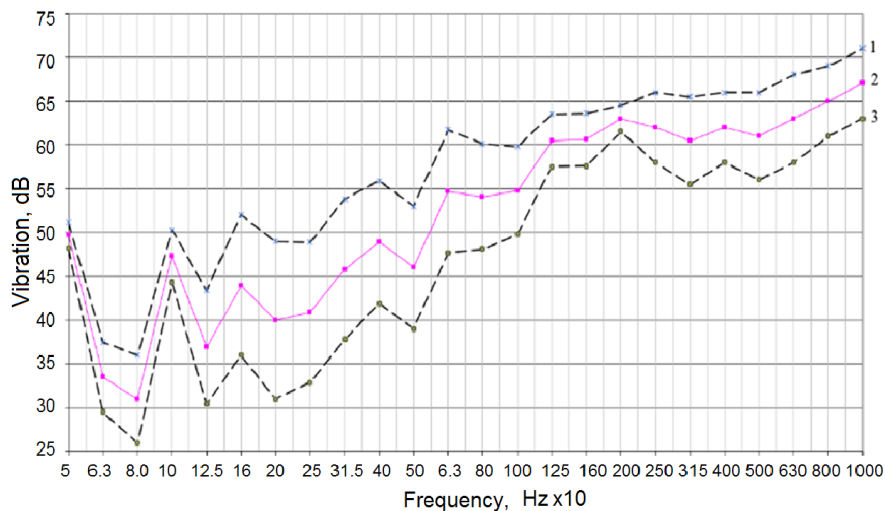
Electrical asymmetry of different types of EM leads to tangential oscillations of the stator, which is detected especially at frequencies  $f_p$ ;  $2f_0$ ;  $2pf_p$ ;  $2Sf_0$ .

The reduction of magnetic vibrations is achieved by a successfully chosen ratio of the numbers of grooves of the stator and rotor, the correct value of the air gap between the magnetic lines of the stator and rotor, the bevel of the rotor grooves, reducing the eccentricity of the air gap and other structural and technological solutions.

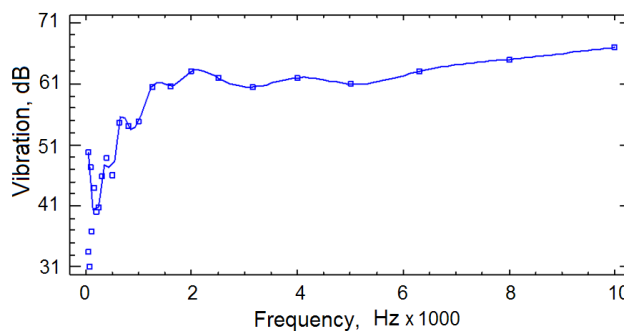
One such solution is to change the shape of the rotor groove. Trapezoidal, t-shaped and arcuate closed grooves of asynchronous EMs were investigated. In the arc-shaped posture, the slope of the arc varied from left to right along the groove length by 20 mm [8]. Studies have shown that the groove shape of the rotor core package significantly affects the vibration levels of the EM in the magnetic frequency range and has little effect on other parts of the spectrum from rotational speeds up to 1000 Hz.

### 5. Processing the results of the research

After measuring the vibration of the EM on the 1/3 octave frequency spectrum from 50 Hz to 10 kHz, the statistical processing of the obtained results was performed. The results are presented in Fig. 3 (a).



(a) vibration spectrograms: 1, 3 are the mean square deviations of vibration levels; 2 - average values of vibration levels



(b) spline vibration approximation

Figure 3. Results of experimental research processing

The spline approximation in the STATGRAPHICS V.15 software package is built, Fig. 3 (b).

A series criterion method based on the median of the sample and the criterion of squares of successive relationships was used for the analysis. The regression equation of the form is obtained:

$$\hat{\ln}(W_i) = \sqrt{9,45998 + 0,9220 \cdot \ln f_i} \quad (16)$$

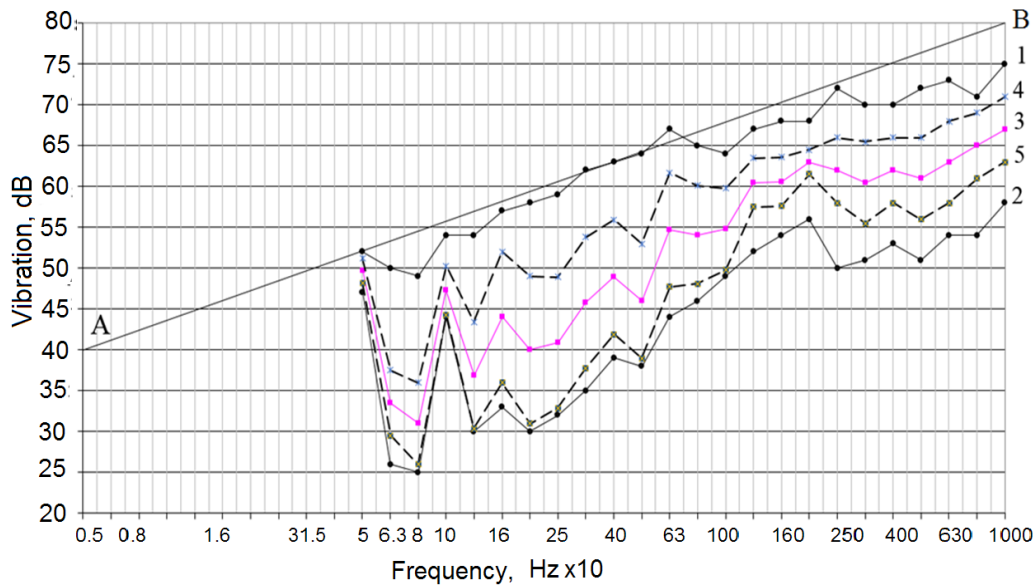
The graph shows that all but one of the points of the actual experimental values are within their range, which means that the quality of the approximation is satisfactory.

The graph corresponding to this equation is shown in Fig. 4.

For further improvement of the quality (reliability and resource) of the EM, the achieved values of the spectra approximated by the direct AB (Fig. 4) were taken at the basic initial vibration levels, with a difference of vibration levels of 40 dB at 5 Hz and 80 dB at 10 kHz.

The slope of a direct AB with a difference of 40 dB between the frequency of 5 Hz and the frequency of 10 kHz is an equal resource requirement for the levels of vibration excited by all defects of EM.

Reducing the vibration of the EM by 8 dB below the direct AB indicates the transition of the EM to another (higher) class of technical condition.



**Figure 3.** EM ANU 92-2 vibrations spectrogram: 1, 2 – maximum and minimum values of the levels; 3 – average values of the levels; 4, 5 – mean square deviation of the levels [8]

It is proved that with reducing the vibration by 8 dB, the EM resource is doubled, and at the reduction by 16 dB – it increases by three times. Accordingly, and on the basis of the studies conducted, using the methods of estimating the vibration characteristics of the vehicle resource, it can be proved that the EM resource of Class D is three times larger than of Class B and twice that of Class C. This means that increasing the EM class by at least one (i.e. from Class B to C or from C to D) we can predict that its resource will be doubled.

### 5. Conclusions

The method of diagnostics of electric traction electric motors of electric buses by the indicators of vibration levels allows to estimate their technical condition in accordance with the developed classes.

The values of permissible vibration acceleration of traction electric motors of electric buses, which allow to estimate their technical level are determined:

- permissible vibrations are vibration levels limited by a direct 40 dB at frequency of 5 Hz and 80 dB at 10 kHz;
- vibration levels that exceed 40 dB direct at 5 Hz and 80 dB at 10 kHz are not acceptable vibrations;
- the defined method enabled to develop classes of assessment of the motors technical condition by their vibration level. This makes it possible to predict their resource:
  - a. Class B (the zone is limited from the top by a vibration level of 40 dB at a frequency of 5 Hz; 80 dB at a frequency of 10 kHz, and from the bottom by a straight line, which is the upper limit of Class C);
  - b. Class C (the zone is limited from above by a line with vibration levels of 32 dB at a frequency of 5 Hz; 72 dB at a frequency of 10 kHz and below by a line which is the upper limit of Class D);
  - c. Class D (the top-restricted zone with vibration levels of 24 dB at 5 Hz; 64 dB at 10 kHz);

- vibration levels should not exceed the vibration levels of the new electric motor by more than 4 dB in the quality control of the traction electric motor.

The developed method can be applied at all stages of the life cycle of electric motors. Namely, during design, during acceptance work, during operation, as well as after repairs.

It should be noted that the proposed method of diagnostics of electric traction electric motors of electric buses can be applied not only for induction motors but also for other types of electric motors. To do this, you need to know the level of vibration characteristics of electric motors.

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### Conflict of interests.

The authors declare that there is no conflict of interests regarding the publication of this paper.

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