

System Approach to the Evaluation of the Traction Electric Motor Quality

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Abstract

The electric motor (EM) is one of the main components of any system. The EM quality is set at the design and manufacturing stages, and its technical condition is maintained during operation. Therefore, the development of methods for the EM quality determining at its all life cycle stages is urgent. In the paper, for the first time, we proposed the system approach to traction EM quality estimation on the vibration parameter basis. This approach differs in that the study of EM vibration is carried out in 1/3 octave spectrum of frequencies from 50 Hz to 10 kHz (dB), which allows revealing all existing faults or "weak places" of EM. This method is universal for all types of EM. It is based on the results of the large-scale experiments using the system analysis and the objectives tree method and allows combining individual problem solutions to improve the quality of design, manufacture, and operation of EM into a single integrated system of quality assessment.

Keywords: smart grid, resilient technologies, clean power technologies, energy, intelligent systems, online monitoring, diagnostics, protection, training systems, electric power industry, education technologies, industrial electrical equipment and robots.

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1. Introduction

Ecological problems and needs of our time in energy efficiency, natural resources savings and technological effectiveness of equipment force scientists from all over the world to work on the development of alternative energy sources [1–6]. The transport sector [7–9] plays a special role in solving these issues because it is a powerful consumer of natural resources and an environmental pollution source. Therefore, nowadays we observe replacing cars with ICE by electric cars [10–12] around the world. Electric motor (EM) is the heart of the electric car and reliability, safety and environmental friendliness of the whole vehicle depend on EM quality. Asynchronous electric motors (AMs) are the most commonly used as traction motors, therefore an important task is to develop a systematic approach to the quality

assessment of traction EM of electric vehicles [13–16].

No matter all AM advantages, their resource does not always satisfy the requirements for their usage as traction motors [16]. According to the paper [17], annually about 20–25% of the total number of installed AM need to be repaired. Depending on the type of failure, AMs are repaired by the company itself (within the enterprise exploiting the electric motor), or by the specialized organization. The reasons for such failures are insufficient quality control of design, manufacturing, and operation. Repair of electric motors is often carried out with disassembling and replacing components. In this case, the reliability of engines is significantly decreasing [18, 19]. In this regard, diagnosing the quality of EM at the manufacturing stage, during acceptance testing and in the process of operation is one of the most important ways to increase the reliability and cost-effectiveness of equipment. Therefore, the AM technical condition needs

to be evaluated at different stages of its life cycle. This is the AM reliable work guarantee. In this case, the research method choice of EMs, that are exploiting in dynamic modes of operation of mechanical and electrical loads, is becoming particularly important [18].

Despite the fact that there are state and international standards for electric rotating machines [20], scientists and engineers around the world are drawing a lot of attention to improving methods for determining EMs quality, finding the criteria that most widely describe EMs state and developing methods for their diagnosis [21–23].

For example, in paper [21], there are described the procedures of the technical standard IEC 60034-18-41 for the engines type I quality assessment using (offline) test with partial discharge. Authors of paper [21] compare offline and online measurements that had been performed on one engine. Based on the given analysis, the advantages and disadvantages of this standard are highlighted.

Modern electric motors are operated by semiconductor transducers, and now we can say that over the past 20 years they have shown a high failure rate. Such transducers are able to generate voltage pulses that have a very short growth time (from 50 ns to several thousand microseconds) and high switching frequency (up to 20 kHz). On the one hand, mentioned transducers are extremely effective in the EM speed control, on the other hand, they can significantly increase the risk of engine failure, especially if the insulation of the winding is improperly designed or executed. In articles [22, 23] it was shown that the voltage that occurs on the engine clamps can essentially differ from the voltage on the output of the transducer. This is due to pulsations that are repeated in the electrical circuit. They may occur on EM clamps because of the mismatch between the EM and connecting cables resistances. The magnitude of such pulsations depends on the cable length, time of the transducer growth and the temperature load caused by dielectric heating at a high switching frequency. They can cause acceleration of winding isolation aging and trigger untimely failure.

The American researchers have developed a model based on the EM defect-detection system, which is presented in the patent [24]. An advantage of this invention is its method and system are based on software and use data getting from non-intrusive measurements. This greatly reduces costs. The system contains computer tools connected to sensors that provide continuous real-time information about the input parameters: voltage, current and motor speed. The system and method use a multi-parameter experimental simulation algorithm to obtain the engine mathematical description. The algorithm compares the simulated result with the measured one. It analyses the differences and draws the conclusion of whether the engine works without errors. If the algorithm identifies signs of defects, the program evaluates measured changes in engine parameters, determines the deviation from the reference value and concludes about probable failure or defective component.

The paper [25] presents the method that is a supplement to the conventional spectral analysis. There are clarifying of AM defects by CZT and ZoomFFT methods - rotor bar breakage and eccentricity.

The authors of the article [26] discuss the method of detecting rotor defects in AM based on the square of the Park's Vector modulus. In comparison with FFT method, it has a higher frequency resolution, and it is more precise and easier to calculate, which is important for real-time monitoring.

The authors of the article [27] conducted the technical state diagnosis of the traction AMs of a tipping truck using wavelet analysis. It showed the possibility of selective control of diagnostic frequencies during wavelet analysis.

The paper [28] presents the system of EM final quality evaluation with electronic commutation. But this system is only intended to use at the EM production stage.

Article [29] provides the method to estimate the probability of asynchronous EM failure. It is based on the comprehensive diagnostic method of vibrational and electrical characteristics, taking into account the power supply network quality and operation conditions. This system uses artificial neural networks.

A significant number of existing methods for assessing the quality and diagnosing of electric motors does not solve the problem generally. Most methods are targeted at engines operating in special conditions of use, and therefore they are not universal. In addition, they are quite complicated and aimed at identifying specific defects (for example, defects of a rotor or stator, or a winding, or insulation, or a bearing block, etc.). Therefore, a systematic approach to assessing the AM quality will give the opportunity to develop a universal method for monitoring their technical state at all stages of the life cycle.

For the achievement of this goal, we need:

- to carry out the analysis of diagnostic methods for assessing the AM technical state;
- to justify estimations of traction EM quality according to the vibration diagnosis characteristics;
- to develop a systematic approach to assessing the quality of traction EM based on the vibration parameter;
- to justify the advantages of using EMs quality assessment methods according to the vibration diagnosis characteristics at all stages of their life cycle;
- to develop a methodological system approach for the EMs quality improvement based on the vibration parameter.

In purpose to justify the development and use of quality estimation methods (by the vibration parameter) of design, manufacture, and operation of traction EM, the system analysis, and the objectives tree method are applied.

The proposed method is based on the results of

experiments conducted by authors and published in publications [16, 19, 30]. The vibration study was carried out in a 1/3 octave spectrum of frequencies from 50 Hz to 10 kHz (in decibels), which allowed obtaining a linear dependence of vibration on the signal frequency and simplifying the EM quality determination.

2. Diagnosis methods of the asynchronous electric motor technical state assessment

The choice of the method for assessing AM technical state depends on many conditions, including on what AM life cycle stage diagnostic study is conducted, table. 1 [18].

It is important to note that the operational defects by developmental rate are divided into categories that are represented in Fig. 1 [16, 18].

So, to summarize, all existing methods of AM diagnosis can be represented in the form of a structural scheme, that is presented in Fig. 2.

It is clear that each of the methods has its advantages and disadvantages, but as we can see the most informative, and therefore the most effective of all methods is the vibration method. This is due to the fact that the vibration signal contains all the necessary information about the changing all components that determine the technical state of the electric motor in real-time at the stage of design, manufacturing, and operation [16, 18].

The main sources of AM vibration with electromagnetic, mechanical and aerodynamic origin were presented in [16].

Table 1. Stages of diagnosing electric motors quality evaluation

The stages of EM life cycle	The purpose of diagnosing EM	The main types of EM defects
Stage of manufacture	Control of optimal design and debugging, to achieve reliability and durability	Kinematic errors of the engine part manufacture, reaching structural parameters beyond the valid values, assembly defects (imbalance, the presence of eccentricity, various kinds of skewness and gaps, relative movements between interacting engine parts, non-compliance with technology, etc.)
Stage of acceptance tests	Quality control of manufactured engines, defining a technical condition class	Changing EM parameters that lead to defects and failures.
Stage of operation	Detection of diagnostic parameters deviations from norms and processes of components aging	Any defects and failures that remain at the manufacturing stage or that are appeared during the exploitation phase
Stage of repair	Pre-repair and post-repair control of the technical condition in order to identify defects and the repair quality, respectively	

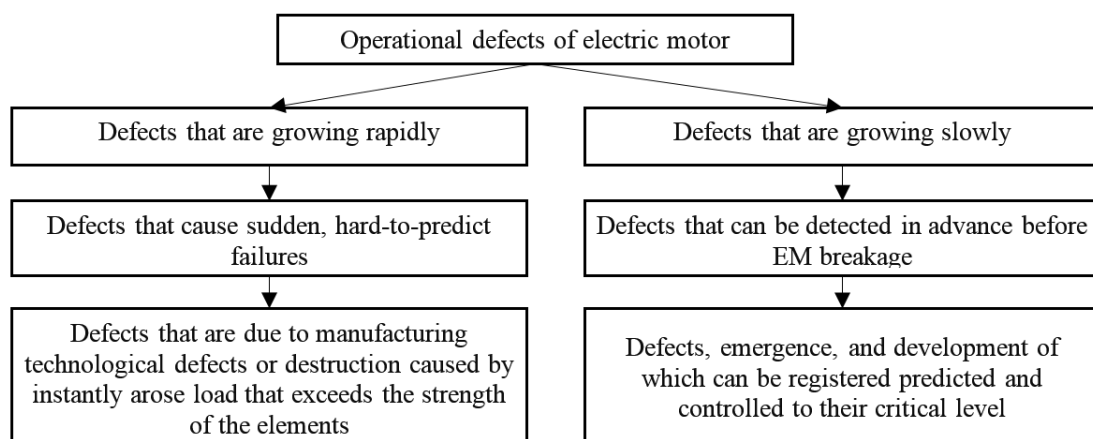


Figure 1. Categories of operational defects by the developmental rate

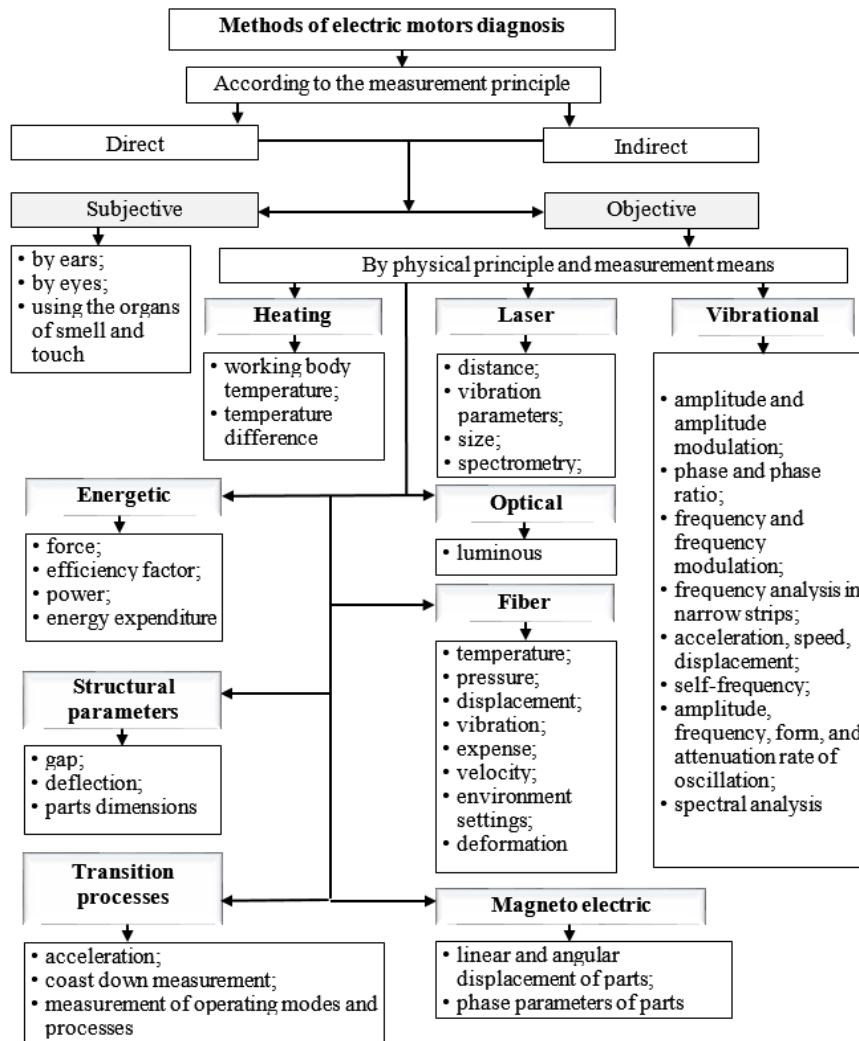


Figure 2. Classification of diagnosis methods

3. Justification of quality estimation of asynchronous traction electric motors for electric vehicles according to the vibration diagnosis characteristics

The relevance of the application of methods for assessing the quality of traction aggregates used in electric vehicles, according to vibration diagnostic characteristics (VDCh), is primarily due to the peculiarity of their operation modes. Especially this refers to electric buses that are intended for the transportation of passengers in urban operation conditions. These operating modes are characterized by random interchange of acceleration, braking and movement with a steady speed, overcoming climbs and descents, short-term staying at stops, traffic jams, traffic lights, crossroads and "accidental" loading on a traction electric drive system. Such dynamics are the reason for EM increased vibration [30]. The main sources of AM vibration with electromagnetic, mechanical and aerodynamic origin are discussed in detail in paper [16].

The vibrating signal contains all the necessary

information about all components changes that determine the EM technical state in real-time mode at the design, manufacturing and operation stage.

Advantages to the VDCh study for EM quality assessment include [16]:

- the proportional dependence of the vibration changes on the load and speed of rotation, on the gap and on the geometric errors values;
- the physical properties of vibration excitation, which allow dynamic signs to be used as a diagnostic parameter;
- the vibration signals properties to respond quickly on the technical state changes. It allows in real-time mode to observe and compare the responses of all EM components, that are interconnected by the correlation dependence, on changes of design, work processes flow and changes in operating modes;
- the possibilities of using modern computer technologies for quick obtaining the information on the technical condition, increasing the technical condition diagnosis accuracy, reducing the labor

intensity of resource and operational tests and diagnostics.

The self-oscillations of the separate elements of mechanical system, which lie within the frequency range of acting forces, the structure rigidity, that changes at the specific operational mode and external force action, the materials deformations and their viscous-elastic properties changes and the mechanical system eigenfrequency spectrum are always potential reliability problems. Therefore, EM resource is determined not only by working processes, loads and established strength and durability, manufacture accuracy and mechanisms operation, but also the actual vibration load and mechanical systems and parts possibility to have in certain conditions a resonant frequency. Consequently, EM vibration characteristics are a complex indicator of quality.

It is impossible to produce an engine that does not have vibrations at all, but there are levels of vibration that we can regard as permissible. An increase of vibration to a higher than permissible level or lower than normal state indicates defects, malfunctions, and changes in operating modes. Each defect excites vibrations at a certain frequency, frequency group, or a wide frequency strip [16]. It allows us to determine EM technical state. Since conclusion about defect presence or absence, we make by the simple definition of vibration process spectral components levels and comparison them with the original value.

From the classification of EM diagnosis methods (Fig.3) and the system analysis of their technical capabilities [16], it follows that the effectiveness of the vibration methods use at all stages of the EMs life cycle is due to the high sensitivity of vibration processes to changes in structure, technology and dynamic conditions of units and parts, to the distribution of pulsations, load or pressure in the units operation environments, to the field of force influences, operation conditions, to the workflow processes and operation modes changes.

Vibration diagnosis reliability is ensured by the direct connection of vibration processes with structural parameters of gaps of kinematic and geometric errors of components and operation of mechanisms.

The main distinguishing feature of the vibration diagnosis methods is the use as diagnostic parameters dynamic signs that are the result of external influence and interaction of EM components during its operation. Wide frequency and dynamic ranges of oscillatory processes, fast-response time, high velocity of vibroacoustic waves distribution in EM components and body cause the fast response of the vibration signal on changes of the technical state. These qualities are critical for the rapid determination of technical condition, the use of on-board emergency control systems when the speed of diagnosis and decision-making is a guarantee of preventing emergencies.

Modern experimental vibration diagnosis methods with the use of vibration analyzer and software at EM

debugging stage are becoming convenient tools for the fast acquisition of information that is necessary to eliminate dynamic problems and make constructive decisions to optimizing work processes and operation modes. It allows us to apply the most economically effective method of vibrational organization of EM construction dynamic and technological properties, that consists in the manufacture of prototypes based on engineering knowledge and experience with further conducting their vibration testing in laboratory conditions. In addition, it is much easier for a specialist to use vibration diagnosis methods. With their help, it is possible more quickly to determine the parameters and characteristics that significantly improve the efficiency of EM debugging in the design process.

Vibration diagnosis is the most informative and universal method in comparison with other nondestructive testing methods, parametric testing, and tribodiagnostics. The high universality of the method is based on the vibration processes properties that are common for all types of mechanisms and systems. So, the vibration characteristics studying methods allow us to approach the analysis of the state of EM components and units with different physical processes of their functioning, but with unified common position of the vibration processes appearance. It gives us the possibility to create low-cost unified automation means for diagnosis processes to ensure EM diagnosability.

Let's consider the basic properties of the vibration signals that are applied to assess the traction EM quality for electric vehicles.

- (i) Proportional dependence of vibration changes on load and rotation speed, gap, values of geometric errors, which allow normalizing output and landmark value of errors for quality control of design, manufacture, and operation of the electric motor.
- (ii) High universality, sensitivity, and selectivity of the vibration signal to the parameters of EM technical state, that allow:
 - to diagnose most defects of mechanical systems and ones, that contain the flow;
 - to detect emerging defects;
 - to diagnose defects in the assembly of components and units (disalignments, bends, skewnesses, imbalances).
- (iii) Vibration excitation physical properties that allow using dynamic complex signs of the structural, functional, and dynamic EM states as diagnostic parameters:
 - EM vibration diagnosis characteristics;
 - self frequencies in the assembly of parts, units, and aggregates;
 - resonance phenomena;
 - stiffness properties of units and systems.

- (iv) Vibration signal properties to quickly respond on changes in the EM technical state, that allow to observe and compare in real-time the reaction of all components - the structural, functional and dynamic mechanisms state on changes in: design; technologies of manufacture and assembly; workflow processes; operating modes; checking and adjustment works; correlation dependence of mechanisms defects.
- (v) Possibility to create automation systems for control and prevention of emergencies and management of EM work.
- (vi) Possibility to create modern computer and microprocessor on-board, stationary and portable systems for fast receiving reliable information about the EM technical state at the stages of debugging construction, manufacture, and operation.
- (vii) The presence of a large amount of information in one measurement of vibration.
- (viii) High reliability of vibration diagnosis.
- (ix) Progressive diagnostic technology (without disassembly) and high mobility of funds.
- (x) Decreasing the complexity of resource and operational testing and diagnosis.

Computer and microprocessor systems give the possibility of vibration diagnosis of mockups and prototypes; the manufacture and operation quality due to replacement units (cards) of storage devices, software, and the unifying metrological support, which makes them affordable in terms of cost; staff training and convenience in operation.

The capabilities of computer and microprocessor systems to automatize EM diagnostic process enable the creation of universal embedded (on-board and regular) and external (portable and stationary) diagnostic tools, suitable for use by driver, diagnostician, operator, in any forms of a technical service organization.

4. System approach for the traction electric motor quality assessment

4.1. The structural model for the development of EM quality assessment methods by vibration characteristics

The problem of developing vibration methods for assessing EM quality in the life cycle, in terms of system engineering, is a large system of complex physical and technical, internal and external factors. To understand the problem and the essence of the ways of its solution, we applied logical system analysis, an objectives tree method. The objective tree is shown in Fig. 3.

At the first level of the model of the problem-solving system is the task of complex achievement of three objectives (2.1, 3.1, 4.1) – development of methods for

the quality assessment of design, manufacture, and operation, Fig. 3. The optimal path to achieve these goals is to develop vibration standards of EM quality design and control at the stages of debugging, manufacture, and operation - objectives 2.2, 3.2, 4.2. At these levels, the system operates in time as an integral whole to achieve a single goal setting for the entire system. Scientifically substantiated vibration standards have to reflect the functional optimum state and, in this way, to provide qualitative and quantitative management of the processes of EM design, manufacture, and operation. Each objective (2.2, 3.2, 4.2) at the third level is divided into smaller goals that provide the solution of the problem and sufficiently reveal the content, the stage, and the fact of their achievement.

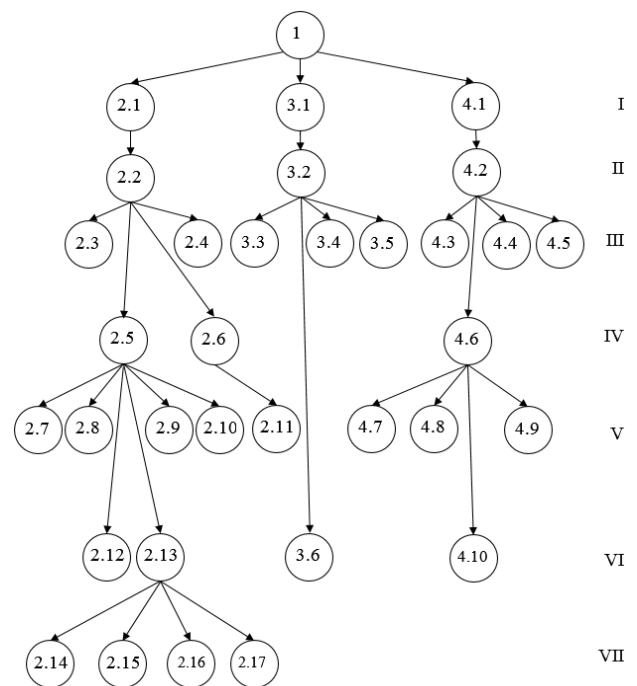


Figure 3. The objectives tree and the study tasks

Since the output levels of vibration diagnosis characteristics are influenced mostly by the controlling actions associated with the structural changes in the EM parameters, we set the objectives for the development of methods and means to reduce vibration (2.5, Fig. 3) to the given vibration class (objective 2.2) at the fourth stage. The detailing level of the debugging (objective 2.1) directly affects the output levels of vibration diagnosis characteristics of unit, mechanism, element. It is meaningful carrying out an accumulation of sufficient statistical data concerned the vibration reduction for each controlling actions type using different means and methods (achievement of the objectives 2.5, 2.13, Fig. 3). The influence of each controlling actions (2.7-2.10, 2.14-2.17) on the output levels of the system vibration diagnosis characteristics is evaluated qualitatively and

quantitatively by the nature and level of vibration change of the specific mechanism or the whole system. This allows giving an objective assessment of the impact of each controlling action on EM technical state rapidly per the change in vibration, without waiting for the complete cycle of tests. It also allows the development of specific recommendations for active intervention in the upgrading process of EM to achieve a given vibration class and the building of a model for reducing vibration and increasing EM reliability. So, at the stage of laboratory-bench tests, there is a significant change in the level of EM vibration and reliability. EM debugging by the developed methods 2.5 - 2.17 is conducted until the levels of vibration diagnosis characteristics reach given parameters of vibration class, the relevant reliability, and resources.

Control and individual adjustment of vibration parameters to the standards are also performed throughout EM manufacture during the achieving sub-objectives 3.3-3.6. Similar control and accounting for changes in vibration levels occur at the operation stage when achieving sub-objectives 4.3-4.5, as well as after the completion of the technical resource (objectives 4.8, 4.9). The objectives 2.6-2.11 have been achieving for complex metrological support using tests and diagnosis.

We were first who developed such systematic approach to the creation of unified methods and tools for diagnosis, which allows effectively managing the design and manufacture quality and maintaining asynchronous EM [16, 18]. In these papers, the authors have substantiated and developed vibration criteria and methods for assessing EM technical state at all life cycle stages.

4.2. Analysis of the estimating methods system of the traction electric motor quality for electric vehicles

Dedicated from the main objective of the three subsystems (2.1, 3.1, 4.1) of the objectives (Fig. 3) can be considered as independent systems of the corresponding hierarchy level. But the maximum technical and economic effect will be possible when the main objective is achieved comprehensively at the design stage. In the first stage, we achieve the objectives 2.1-2.17, the second - objectives 3.1 - 3.6, the third - objective 4.1 its sub-objectives, and we solve the detailed tasks 4.2-4.10.

Traditional approaches to the dedication and study of individual subsystems and their narrow systematization are ineffective. So, suppose that the first level is aimed at developing vibration methods for improving EM quality control of manufacture (objective 3.1, Fig. 3), which are in mass production, and did not pass the stage of solving objectives 2.1-2.17. It means that there is an unupgraded and uninspectable EM (objectives 2.5, 2.10) in mass production. To solve completely objectives 2.1-2.17 at the stage of manufacture or operation it is not always technically feasible without changing EM elements construction. Without sufficient information about systems properties that we obtain at the stage of achieving

objectives 2.1 2.17, it is difficult to solve the objectives 3.1 - 3.6 at the appropriate technical level. As a result of a forced compromise in solving these problems, it is reduced the effectiveness of the system 3.1 of manufacture quality control in practice. Likewise, the diagnosis system efficiency 4.1 (Fig. 3) will be as less as weaker the subsystems 2.1 and 3.1 properties research concerning EM vibration inspectability maintenance, elimination of resonant phenomena, instability of working processes and, accordingly, vibration parameters. Moving away from such a sequence of problem-solving the vibrational diagnosis methods implementation is the most common mistake among practitioners. So, the implementation of important scientific results and diagnosis tools in practice may not bring the desired effect.

Thus, the proposed system of quality evaluation sequence allows to eliminate defects gradually and thereby provide the EM quality improvement, to receive reliable individual input information about its technical condition when the EM is putting into operation, which gives an opportunity to increase the resource and predicting with greater accuracy the output data about technical condition changes.

Taking into account the multidimensionality and complexity of inter-relationships between the EM quality assurance indicators in the stages of designing, debugging, manufacture, operation and after technical maintenance (Fig. 1, Fig. 3), the development of criteria for assessing the technical condition is carried out based on the requirements for the creation of unified means, methodology and metrological support, allowing to diagnose EM with one device. The proposed sequence of the solving scientific problem, Fig. 3, links the directions and tasks of the developing EM quality assessment methods according to the vibration diagnosis characteristics at the stage of designing, manufacture, and operation.

The developed method is based on the results of large-scale research that was conducted by the authors. This method is universal. For different types of electrical motors (not only for AM) there will be different just the permissible vibration levels and vibration ranges that characterize the EM quality level.

6. Conclusions

In the paper, the analysis of diagnosis methods for assessing EM technical state has been carried out. Also, the substantiation for assessing the quality of asynchronous traction EM for electric vehicles according to the vibration diagnosis characteristics was made.

The systematic approach for assessing the traction electric motor quality based on the vibration parameters has been proposed for the first time. This approach allows us to combine individual problems solution for the EM design, manufacture and operation quality improvement in a single integrated system of quality assessment.

The developed method is based on the results of large-scale research that was conducted by the authors. It is universal and can be applied to different types of electrical motors.

There have been substantiated the advantages of using methods for EM quality assessment according to the vibration diagnosis characteristics at all life cycle stages.

For the first time, it has been proposed to evaluate the EM quality at all life cycle stages by vibration parameters, as a deviation from the given vibration standards.

The developed methodological system approach to improve the EM quality according to a single indicator (the vibration parameter) is based on the standardizing vibration by the criterion of providing a given reliability and resource at the design stage and by the criterion of design quality maintenance at the manufacture and operation stages, which is the significant growth of assessment methods of the quality of traction electric motors for electric vehicles when they are produced and operated.

To substantiate the development and use of methods for estimating the quality of design, manufacture, and operation of traction electric motors, the systematic analysis, and the objectives tree method were used.

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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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