DOI:10.32703/2617-9040-2025-46-13

УДК 621.3

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Improvement of the impregnation technology of traction motor windings in order to improve the parameters of rotor imbalance

The work is devoted to improving the quality indicators of balancing rotors of electric machines by technological methods on the example of overhaul of traction electric motors of electric trains of series EP2, EP9, EPL2, EPL9, ED9 at PrJSC "Kyiv Electric Wagon Repair Plant". The features of the technological process of eliminating mechanical imbalance of rotors during the manufacture and repair of electric motors are analyzed. The causes of mechanical imbalance of rotors are clarified. The degree of influence on the imbalance of rotors of uneven distribution of impregnation compound over the volume of electrical windings is experimentally investigated. The hypothesis put forward about the possibility of partial compensation of static imbalance of rotors by controlling the distribution of the compound during application of electrical insulation (impregnation) of windings is confirmed. A method of controlling the distribution of the compound during impregnation is proposed. The essence of the method is to fix the rotor in the drying chamber in a position corresponding to the phase angle of the "heavy spot", namely by placing it with the "heavy spot" up. Controlling the distribution of the compound over the rotor volume can be considered as a technological method for improving balancing performance. The method makes it possible to improve the quality of balancing by reducing the mass of balancing loads during the final balancing of rotors by up to 70%.

Keywords: *railway transport, wagons, electric train, rotor balancing, traction electric motors, electrical insulation of windings, impregnation of windings.*

Introduction. A characteristic feature of the technological process of manufacturing and repairing electric motors is the need to eliminate mechanical imbalance of the rotor in the last technological operations. Such operations are operations related to the impregnation of electrical windings with a special insulating varnish – compound.

The cause of the imbalance may be deviations in the installation of the armature components: shaft, core plates, windings, collector components, etc. Another factor affecting the rotor imbalance is the uneven distribution of the compound over the volume during winding impregnation. The mass of the compound for impregnating the rotors of an electric motor can be up to 3% of the mass of the rotor itself [1]. The distribution of the compound over the rotor can be significantly uneven [2]. In this regard, the idea of controlling the distribution of the compound during the impregnation of the armature windings to improve its mechanical balancing characteristics seems attractive.

Analysis of recent research and problem statement. In the article [3], the thermal and electrical characteristics of polyester resins for impregnation of electric motor insulation are considered. The task of the work is to determine which of the resins can best perform the function of insulation of powerful electric motors with inverter power supply with wide-pulse modulation. Several resin formulations with different viscosity characteristics are considered. The results obtained confirm the importance of choosing the optimal viscosity of impregnating resins for reliable insulation of electric motor rotors.

In the paper [4] the requirements for rotors of powerful high-speed electric motors are analyzed. In particular, it is stated that the requirements for the minimum initial unbalance and the change in unbalance during operation can be a problem in operation. It is emphasized that for economically viable and resource-saving production of high-efficiency motors, solutions are needed to reduce unbalance. An overview of technical problems and potential solutions for reducing unbalance in the production and repair of rotors of rotating electrical machines is presented.

A thorough analysis of the causes of unbalance in rotors of electrical machines is presented in the article [5]. It is emphasized that the most common malfunction of electrical machines is residual unbalance of rotors. The causes of unbalance are analyzed: manufacturing errors; anisotropy of material properties; thermal deformation; wear during operation; structural changes in electrical insulation.

The modern approach to diagnosing unbalance is based on the latest system of technical maintenance (TM) of electrical machines. In this case, the corrective TM system is replaced by a preventive system of operational monitoring of the electric motor [6]. The advantage of internal diagnostic systems is substantiated, which allows detecting malfunctions during operation at an early stage based on vibration analysis. The possibility of reducing costs associated with electric motor failures is attractive. The results of work [6] allow to systematize the causes of rotor imbalance and obtain promising directions for improving the parameters of rotor balancing of electric machines.

Based on the statistical analysis of the operation of asynchronous electric motors, the most frequent cause of electric motor failures was found out in work [7]. Such a cause is considered to be the presence of an imbalance acquired during operation. Imbalance can be the cause of significant vibrations of engine elements, which in turn can lead to their breakdown. It is argued that the vibration response can provide information about existing engine defects directly in the mode of its operation without stopping it. The prospects of the method of diagnosing defects in electric motors based on vibration analysis are substantiated.

In article [8], the issues of increasing the reliability of electric machines of traction rolling stock using local methods of strengthening electrical insulation are considered. The method of infrared radiation during the production and repair of traction electric motors of electric locomotives is considered. The reasons for the low reliability of collector electric motors are analyzed. It is argued that the low reliability of electrical machines is associated with the limited life of winding insulation. Existing insulation restoration methods are not able to properly ensure high-quality insulation strengthening during depot and factory repairs.

The article [9] is devoted to the analysis of the thermal regime of heating and cooling of electrical machine windings. The heat exchange between copper conductors, core, housing and air is studied. Cases of winding overheating and its effect on aging and structural changes in electrical insulation are considered. The article contains a review of research on technologies that contribute to winding cooling, such as winding topology with more effective heat dissipation, impregnating material with high thermal conductivity and improved direct winding. Cooling control methods are considered and classified, and recommendations are given for the design of high-torque electrical machines for better winding cooling.

The study [10] is devoted to improving the quality of impregnation of stator windings of an electric motor. Attention is drawn to the fact that the reliability of electric motors depends on the insulation of the windings, which is determined by the quality of the materials used and the impregnation technology. Impregnation of electric windings is an important technological process for ensuring the durability of electric motors. As a result of impregnation, the air pores between the windings and the gaps in the fiber insulation are filled with a compound, which ensures reliable fixation of the windings. There are various methods that ensure effective filling of pores and cavities with a compound. The article provides general information about the varnishes used for impregnation of electric motor windings, according to their composition. The article shows the scheme of stator rotation during the drying process after impregnation. The mechanism of implementation of the proposed method is also given.

The article [11] is devoted to the analysis of the thermal behavior of insulating impregnating materials of electric machines. Attention is drawn to a typical picture of uneven filling of the cavities between the winding elements with a compound. The influence of the impregnation quality on the process of heat removal from the windings is discussed.

The results of a comparative analysis of the thermal properties of electrical windings impregnated with alternative varnish materials are presented in [12]. The impregnation quality coefficient is considered, which allows taking into account the uneven distribution of the compound over the volume of the windings. The experimental results are supplemented by a theoretical analysis of the impregnation quality of the windings.

The article [13] considers methods for optimizing the distribution of unbalance in rotating machines. It is noted that classical methods for balancing rotating machines are based on the assumption of the linearity of the nature of the unbalance. An example of classical balancing methods is a method based on taking into account the influence coefficient. However, if nonlinearity appears in the structure, these methods give errors, and the results obtained regarding the corrective loads and their corresponding angular positions are unsatisfactory. On the other hand, the choice of the number and location of the corrective planes depends on the possible availability, which differs for each machine. In this work, a new method designed to identify rotating machines and distribute the unbalance in linear and nonlinear conditions is implemented using pseudo-random optimization methods. In this case, the system modeling is performed using the well-known finite element method.

In the article [14], the possibility of improving the quality of balancing rotors of traction electric motors of electric trains on stationary balancing machines is considered. According to the traditional balancing technology, the rotor to be balanced is installed on the supports of the balancing machine with support surfaces, which, as a rule, have mechanical defects. These defects, due to the peculiarities of the rotor repair technology, cannot be eliminated by mechanical processing. Theoretical and experimental studies of the influence of damage to the rotor support surfaces on the balancing parameters were carried out. It has been proven that the properties of the rotor support surfaces during its balancing on a balancing machine significantly affect the results of determining the imbalance. In this case, the deviation of the masses of the corrective weights can reach 25%. This is explained by the fact that damage to the rotor support surfaces creates false signals that are not related to the imbalance. To increase the accuracy of determining the mass of the balancing weights during rotor balancing, an improvement of the balancing process is proposed. The improvement consists in including a frequency filter in the acceleration sensor signal conversion circuit. The filter is designed to separate signals with a frequency higher than the rotor speed.

Analysis of known studies allows to conclude that when impregnating electric motor rotors, there is an uneven distribution of the compound over the volume of the windings. Thus, the impregnation operation is an additional factor in the formation of the motor rotor imbalance. The accumulation of the compound on the "heavy" side of the rotor is inevitable if the rotor drying process after impregnation is not corrected. Due to these considerations, a hypothesis was put forward about the possibility of improving the balancing parameters of the rotor of an electric motor by adjusting the winding impregnation operation.

The aim and objectives of the study. The aim of the study is to substantiate the feasibility of adjusting the technology of impregnation of the windings of a traction motor in order to improve the rotor balancing parameters.

Analysis of the unbalance indicators of rotors of electric machines. Unbalance, as a measure of rotor unbalance, is usually determined by the formula [15]:

$$\bar{d} = m \cdot \bar{r}, \tag{1}$$

where m – unbalanced mass;

$\bar{r}$ – eccentricity vector – the distance between the center of gravity of the unbalanced mass and the axis of rotation of the rotor.

The imbalance according to formula (1) is an absolute imbalance, which does not give an idea of its level. Sometimes the specific imbalance *D* is used, as the ratio of the absolute imbalance to the rotor mass [16]:

$$D = \frac{m \cdot r}{m_r}, \tag{2}$$

where m_r – the rotor mass.

However, formulas (1) and (2) require the value of the unbalanced mass m, and the location of its center of gravity. There is no method for determining these parameters. Thus, formulas (1), (2) are purely theoretical.

For a practical assessment of the degree of static imbalance, static imbalance can be used:

$$d_s = m_r \cdot e, \tag{3}$$

where *e* – the rotor eccentricity – the distance from the center of gravity of the rotor to the axis of its rotation.

The theoretical provisions regarding dynamic imbalance are mentioned in many studies [17]. Dynamic imbalance is associated with the moment created by reactions in the rotor supports. Dynamic imbalance can be eliminated by changing the location of the supports. Fig. 1 shows a diagram of the forces acting on a rotor with imbalance.

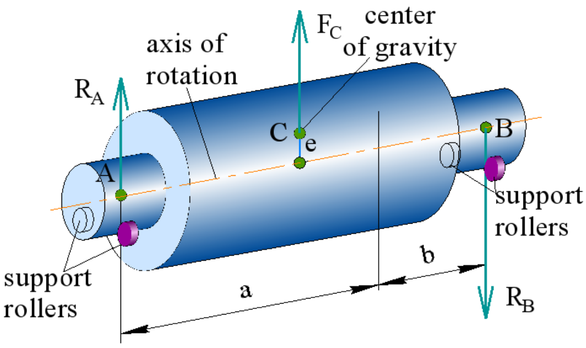


Fig. 1. **Scheme of forces acting on a rotor with imbalance**

Dynamic reactions in the rotor supports associated with the presence of imbalance can be determined by the formulas:

$$R_A = F_C \cdot \frac{a}{a+b}; \quad R_B = F_C \cdot \frac{a}{a+b}, \tag{4}$$

where *a* and *b* – the distances of the rotor center of gravity from the roller supports.

The condition for the absence of dynamic imbalance can be a symmetrical arrangement of the supports relative to the rotor center of gravity, i.e. when a = b. Thus, any imbalance can be reduced to static if it is possible to change the position of the rotor supports. However, in practice, as a rule, eliminating dynamic imbalance by changing the position of the supports is not possible.

A feature of the technological process of manufacturing and repairing electric motors is the uneven distribution of the compound over the volume when impregnating the rotor windings. Despite the insignificant mass of the compound, it is possible to shift the rotor center of gravity relative to the supports by controlling its volume distribution.

Conditions for conducting the experiment. The experiment was conducted with two rotors of the 1DT-003 engine (EPL2T electric train). The rotor imbalance was checked twice: before impregnation and after impregnation. The imbalance and balancing parameters were checked on the EI2000 balancing machine (manufacturer "NORMA-UA" – Ukraine). The main technical characteristics of the EI2000 machine are given in Table 1.

Table 1. **Technical characteristics of the EI-2000 balancing machine**

Parameter name	Value
Range of rotor masses to be balanced	10-2000 kg
Maximum rotor diameter	1800 mm
Maximum rotor diameter above the drive	1300 mm
Distance between the centers of the rotor support necks, minimum/maximum	250–3000 mm
Permissible diameters of the rotor support necks	25–225 mm
Range of rotor rotation frequencies	200–1200 **rpm**
Minimum residual specific unbalance	0,2 g mm/kg
Type of drive motor	Frequency-controlled asynchronous
Power supply network parameters	380±10% V, Ph, 50±1% Hz
Power of the AIR 112M2 electric motor	7,5 kW
Type of rotor rotation transmission	Belt drive
Measuring system	Digivibe MX M10
Floating supports	S/N YBF230103
Control panel	J00496R:2023-PC
Laser phase marker	OP20-5P S/N FOL5212083
Additional devices	USB – interface GX-400 S/N FIGH4211845
Overall dimensions	3150x1500x1500 mm

The balancing machine has the following means of recording and processing experimental data:

– acceleration sensors of the type ADXL202 (Analog Devices);

– analog-to-digital converter of the type KADL-06;

– recording complex with a device for outputting test protocols to the display and in electronic form for downloading.

Fig. 2. **Balancing machine EI2000 with the rotor of the electric motor 1DT-003 installed for balancing**

The test load method (three-start method) was used during balancing. The method involves performing three test starts to determine the dynamic impact coefficient. Input data for the balancing machine: rotor weight, distance between the machine supports.

According to the results of checking the rotor imbalance before impregnation, the phase of the imbalance location was determined and the “heavy spot” was noted by core drilling on the end surface of the shaft.

The technological process of impregnation is analyzed using the example of a major overhaul of traction electric motors at PrJSC “Kyiv Electric Wagon Repair Plant”. The technological process consists of three technological processes (TP): moisture removal, impregnation and drying. Equipment for performing operations - drying cabinet, autoclave, drying oven.

1st TP. Moisture removal is performed to remove moisture from the rotor holes, including capillary holes. Moisture removal takes place in three operations:

- heating in a drying oven to a temperature of 70°C;
- holding at this temperature for four hours;
- cooling to a temperature of 45°C.

2nd TP. Impregnation in an autoclave consists of the following operations:

- placing the heated armature in an autoclave (Fig. 3);
- evacuating the autoclave with a residual pressure of 0.003-0.005 MPa for 30–40 minutes;
- filling the autoclave with an impregnating compound (compound – Elplast 155 ID);
- holding the rotor in an autoclave under a pressure of 0.38–0.4 MPa for 60 minutes;
- draining the compound from the autoclave and reducing the pressure to atmospheric;
- holding the rotor in an autoclave for 30 minutes to drain off any remaining compound.

a)

b)

Fig. 3. **Autoclave for rotor impregnation (a) and drying oven for drying (b)**

3rd TP. Drying the rotor in a drying oven. The impregnated rotor is installed on supports (Fig. 4) in the space of the drying oven, where it warms up. The Elplast-155ID compound acquires the greatest fluidity at a temperature of 60-90 °C, while the viscosity becomes about 30-40 s (conditional viscosity according to the VZ-246 viscometer - 4mm). The gelatinization process occurs at a temperature of 130°C. The drying oven reaches the 130°C mode in 3.5 hours. The total time for warming up and gelatinization usually takes up to 5 hours. By the time the gelatinization process is complete, the compound may flow down and accumulate in the lower part of the windings.

The first two operations – moisture extraction and impregnation – were performed for the two test samples in the same way. The procedure for the third operation – drying – was different for the first and second samples. The first rotor was installed in the drying chamber with the "heavy place" down, and the second – with the "heavy place" up. Fig. 4 schematically shows the installation position of the first and second rotor samples in the drying oven.

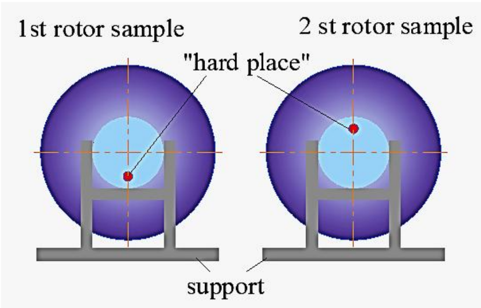


Fig. 4. **Installation positions of the 1st and 2nd rotor samples in the drying oven**

Thus, different conditions for the influence of uneven compound distribution on unbalance were created. For the first rotor, an increase in unbalance was expected during the drying process due to additional compound accumulation in the "hard place". For the second rotor, a decrease in unbalance was expected due to the accumulation of compound residues in the part of the rotor opposite the "hard place".

The used method of controlling the compound distribution over the rotor volume can be considered a unique case of improving the balancing of rotating masses. Of course, this method can be applied exclusively to rotors of electric machines undergoing the winding impregnation operation.

Obtaining results during the experiments. The results of measuring vibration parameters (vibration speeds) were obtained from the test protocols of the balancing machine. Digivibe MX M10 software was used to visualize the measurement results. Table 2 presents the results of five steps of balancing one of the rotors before impregnation. The balancing results are given in the form of tables of vibration speeds for plane A and plane B. Planes A and B are balancing planes, that is, planes in which it is structurally possible to install balancing weights.

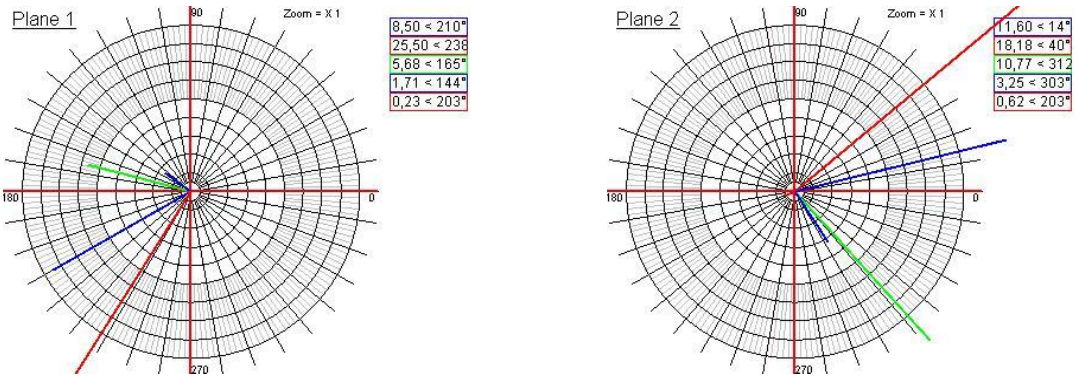
Table 2. **Results of determining vibration speed from rotor imbalance before impregnation**

Step	Common, mm/s	Filter, mm/s	Max, mm/s	Phase, degree	Step	Common, mm/s	Filter, mm/s	Max, mm/s	Phase, degree
Balancing plane A					**Balancing plane B**				
Step 1	14,19	8,50	8,96	210	**Step 1**	18,38	11,60	12,23	14
Step 2	39,59	25,50	26,35	238	**Step 2**	28,08	18,18	18,76	40
Step 3	9,78	5,68	5,92	165	**Step 3**	16,74	10,77	11,15	312
Step 4	6,48	1,71	2,87	144	**Step 4**	5,58	3,25	3,41	303
Step 5	5,53	0,23	2,48	203	**Step 5**	2,06	0,62	0,64	203

The designations adopted in Table 2:
- Step 1… Step 5 – steps for determining the imbalance indicators;
- Step 1 – determination of vibration speed for the initial rotor imbalance;

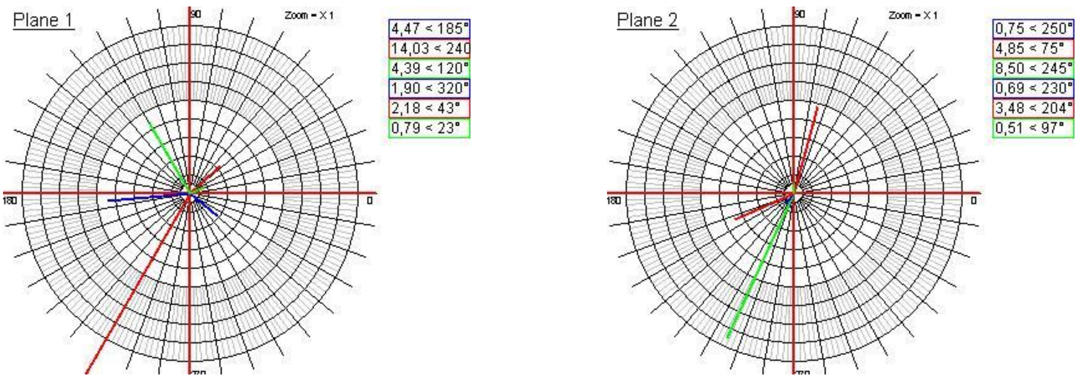
- Step 2 – measurement of vibration speed of the rotor with imbalance from a test load of arbitrary mass placed in the balancing plane A;
- Step 3 – measurement of vibration speed of the rotor with imbalance from a test load of arbitrary mass placed in the balancing plane B;
- Step 4 – determination of rotor imbalance with balancing loads placed in the plane A and plane B;
- Step 5 – control step for correcting the results.
- Common – value of vibration speed of the general vibration background. Due to the high sensitivity of the vibration sensors, they record any vibrations, including those not related to imbalance;
- Filter – value of vibration speed of vibrations filtered from external interference;
- Max – maximum peak value of vibration speed;
- Phase – unbalance phase.

Fig. 5–8 shows hodographs of unbalance phases when performing measurements in steps Step 1… Step 5 for the 1st and 2nd rotor samples before and after impregnation.



a) b)

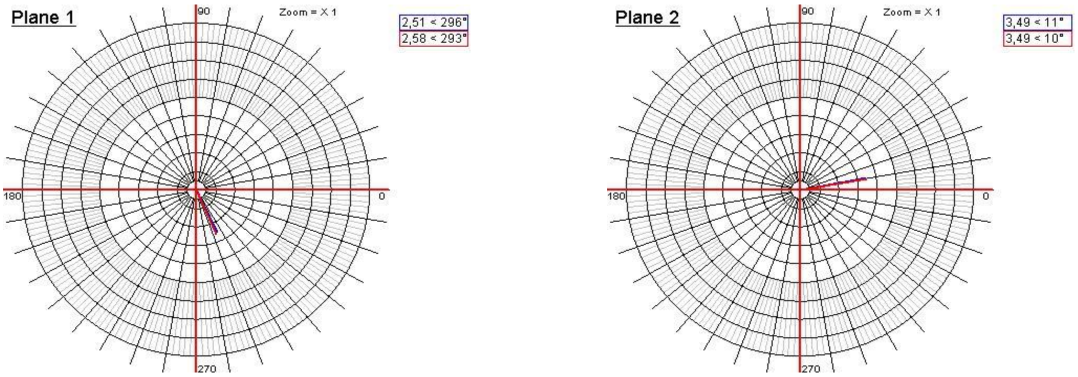
Fig. 5. **Hodographs of vibration speed at different steps of balancing the 1st rotor sample (balancing before impregnation m): a – balancing plane A; b – balancing plane B**



a) b)

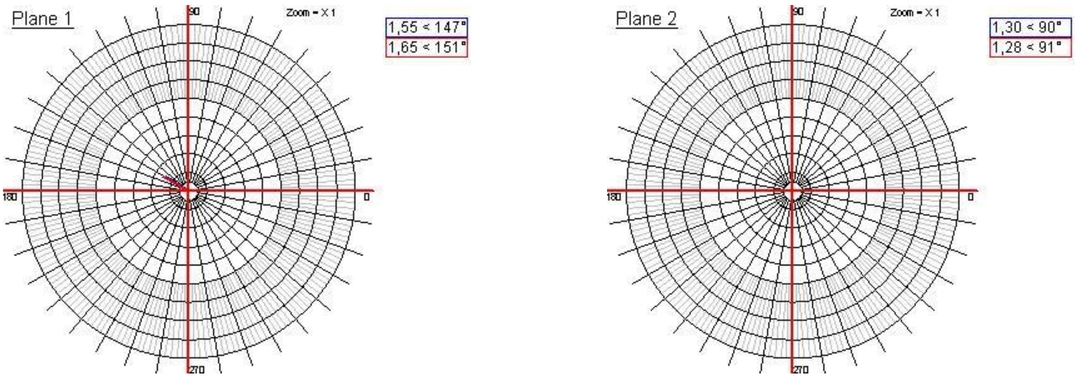
Fig. 6. **Hodographs of vibration speed at different steps of balancing the 1st rotor sample (balancing after impregnation): a – balancing plane A; b – balancing plane B**

As can be seen from the results presented, the difference in the magnitude of the vibration velocities associated with the rotor imbalance measured before and after impregnation is quite significant. Moreover, as expected, for the 1st sample, the imbalance increased by 86% – for balancing plane A and 52% – for balancing plane B. On the contrary, for the 2nd sample, the imbalance decreased, respectively – by 69% and 83%.



a) b)

Fig. 7. **Hodographs of vibration speed at different steps of balancing the 2nd rotor sample (balancing before impregnation m): a – balancing plane A; b – balancing plane B**



a) b)

Fig. 8. **Hodographs of vibration speed at different steps of balancing the 2nd rotor sample (balancing after impregnation): a – balancing plane A; b – balancing plane B**

Table 3. **Comparative values of rotor vibration speed and phase imbalance before and after impregnation of windings**

Rotor condition	**balancing plane A**		**balancing plane B**	
	vibration speed, mm/s	phase imbalance, degree	vibration speed, mm/s	phase imbalance, degree
1st rotor sample				
before impregnation	0,23	203	0,62	203
after impregnation	1,69	151	1,28	91
relative change in unbalance index, %	86%		52%	
2st rotor sample				
before impregnation	2,58	293	3,49	10
after impregnation	0,79	23	0,59	97
relative change in unbalance index, %	-69%		-83%	

It is clear that this does not exclude the need to balance the rotor after the impregnation operation. However, impregnation using the "heavy place up" method reduces the mass of the balancing loads, which improves the balancing parameters. The expected decrease in the mass of the balancing loads is proportional to the decrease in vibration velocities, as an indirect indicator of imbalance.

Conclusions. The results of the conducted research confirm the hypothesis that it is possible to partially compensate for the static imbalance of rotors by controlling the distribution of the compound when applying electrical insulation (impregnation) of the windings. Controlling the distribution of the compound consists in fixing the rotor in the drying chamber in a position corresponding to the phase angle of the "heavy spot", namely by placing it upwards. Controlling the distribution of the compound over the rotor volume can be considered as a method of improving balancing performance by technological means.

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Удосконалення технології просочення обмоток тягових двигунів з метою поліпшення параметрів розбалансу ротора

Анотація. *Робота присвячена поліпшенню якісних показників балансування роторів електричних машин технологічними методами на прикладі капітального ремонту тягових електродвигунів електропоїздів серій ЕР2, ЕР9, ЕПЛ2, ЕПЛ9, ЕД9 на ПрАТ «Київський електровагоноремонтний завод». Проаналізовано особливості технологічного процесу усунення механічного дисбалансу роторів при виготовленні і ремонті електричних двигунів. З'ясовано причини механічного дисбалансу роторів. Експериментально досліджено ступінь впливу на дисбаланс роторів нерівномірності розподілу компаунду просочення по об'єму електричних обмоток. Підтверджено висунуту гіпотезу про можливість часткової компенсації статичного дисбалансу роторів шляхом управління розподілом компаунда при нанесенні електричної ізоляції (просочуванні) обмоток. Запропоновано метод управління розподілом компаунду при просочуванні. Сутність методу полягає у фіксації ротора у сушильній камері у положенні, що відповідає фазовому куту «важкого місця», а саме – шляхом його розташування «важким місцем» вверх. Управління розподілом компаунда по об'єму ротора може розглядатися, як технологічний метод поліпшення показників балансування. Метод дає можливість поліпшити якісні показники балансування за рахунок зменшення маси балансувальних вантажів при остаточному балансуванні роторів на величину до 70%.*

Ключові слова: *залізничний транспорт, вагони, електропоїзд, балансування роторів, тягові електродвигуни, електрична ізоляція обмоток, просочення обмоток.*