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THE METHOD FOR INCREASING THE EFFICIENCY OF EQUIPMENT'S MAINTENANCE IN RAILWAY TRACTION POWER SUPPLY SYSTEMS

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Abstract:

Purpose. To develop the method for increasing the efficiency of the equipment's maintenance and repair system, ensuring necessary level of operational reliability of the equipment, safety and reliability of the electric equipment with minimal expenses on operation. Relevance. Aging of the power equipment in railway power supply systems sharply raised a need for assessment of its states and degree of risk for operation outside rated service life. In critical conditions of technological processes and operational modes of the railways it is necessary to increase the equipment's operational reliability. The scheduled maintenance and repair system whose main technical and economic criterion is the minimum of equipment's downtimes on the basis of a rigid regulation of repair cycles, in the conditions of market regulations in the field of repair in many cases does not provide the optimal decisions due to insufficient financing. The solution of this problem is possible by improvement of the maintenance and repair system. Under these conditions the main direction for supporting the operational reliability of power electric equipment on TS is a development of the modern methods based on individual supervision over real changes of technical condition of power equipment. Scientific novelty. In this article the authors proposed an integrated approach, on the basis of which can be developed the effective maintenance and repair system for traction power supply systems. Proposed approach allowed to react quickly to changes of service conditions on traction substations, to control the technical condition of power electric equipment under the conditions of uncertainty, to establish interrelation between quality of service and operational reliability of the equipment, to choose a service strategy on traction substations. Practical importance. The validity of the developed method was confirmed by the results of calculations and practically by choosing the optimal maintenance's option for transformer TDTN-25000/150-70 U1 (ТДТН-25000/150-70 У1) on traction power supply substation.

Key words:
efficiency, model, power supply, electric equipment, maintenance, traction substation

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1. Introduction

The maintenance of technical objects on railway transport at a high operational level, which ensures traffic safety and high efficient transportation process, is impossible without objective information about a technical condition of the equipment. Objects of railway transport have a large number of devices. The long operation of these devices can lead to failure and significant material damage. Gradual aging of the equipment, decreasing of the resistance's margin in modern power equipment sharply raised a question of an assessment of its state and degree of risk of operation outside the rated service life. The solution of these problems on railways is impossible without ensuring the reliable work of traction power supply system that depends on reliability of functioning of the power electric equipment on traction substations (TS). The electric equipment on TS has rather high design level of reliability. However, in operation technical properties of the equipment are continuously changing. Firstly, isolation is getting older. Secondly, conducting parts, contact system, windings of electrical machines, separate knots and details of electric equipment are wearing. This violates the conditions of its normal functioning and increases the probability of equipment' failures. Therefore, in critical conditions of technological processes and operating modes of power electric equipment it is necessary to increase its operational reliability by improvement of maintenance and repair system.

2. Relevance and purpose of work

Currently the operational process of electric equipment on TS is carried out, on the one hand thank to the considerable design resource, and on the other hand - system of maintenance and repair. The maintenance and repair (M and R) system is set of the interconnected means, documentation and performers needed for maintenance and restoration of a resource of the objects that take part in this system (International standard. System of maintenance and repair of equipment, 1998). This system is based on carrying out the planned preventive maintenance (PPM) in which the maintenance event is preplanned and all future maintenance is preprogramed. However, sometimes such maintenance leads to unjustified expenses as a real technical state of electric equipment on TS at the time of maintenance event cannot demand maintenance, and the replaced details did not reach the critical degree of wearing. Besides, currently practically there is no necessary financial and technical resources ensuring carrying out PPM in full. Aging of the power equipment in railway power supply systems sharply raised a need for assessment of its states and degree of risk for operation outside rated service life (for example, on the Ukrainian railways 82,9% of the main power equipment on TS is operated outside rated service life more than 30 years) (Analysis of work of the Department of electrification and power supply in 2013, 2014).

Taking into account current conditions regarding TS operation a main objective of the improvement of the maintenance and repair system is following - ensuring necessary level of reliability, safety and efficiency of functioning of the electric equipment at the minimum costs of operation. Improvement of maintenance and repair system concerns generally control methods of parameters in the course of diagnosing of technical condition and methods of resource calculation. However, the efficiency of operation of the equipment in TS more becomes dependent on skill level of operational personal, level of their technical equipment, the organization and management for ensuring qualitative maintenance and repair.

Considered above confirms the relevance of carrying out scientific researches for ensuring the reliability of the equipment of traction power supply on railway transport by increasing the effectiveness of maintenance and repair system for main power electric equipment on TS.

3. Review of literature

There are many approach for increasing the efficiency of the equipment on TS. In the work (Qunzhan, Li , 2015) the author proposed a new concept of segmental power supply technology that allows to diagnose faults quickly and accurately. The work (Matusiewicz, O. et al., 2016) discusses the application of the FMEA method (Failure Modes, Effects and Criticality Analysis) for improving repair and maintenance system on the basis of ranking of the severity of the consequences of failure and prioritizing the preventive actions. In (Sychenko, V., Mironov, D., 2017) the authors proposed a general-

ized indicator of the technical condition of the electrical equipment to unify the information obtained during repair and maintenance works.
One of the main problems of power supply on the electrified railways is to make a decision about using those power electric equipment on the traction substations (TS), whose service life exceeds the rated value. Currently, for some power supply distances on Ukrainian Railways the number of the aging power equipment on TS exceeds 50% (Analysis of work of the Department of electrification and power supply in 2013, 2014). The sharpness of this problem is defined by a real ratio of increased number of the aging equipment and possibility of its updating. Additional material and financial expenses are a negative consequence of increased number of aging power supply equipment. The scheduled maintenance and repair system whose main technical and economic criterion is the minimum of equipment's downtimes on the basis of a rigid regulation of repair cycles, in the conditions of market regulations in the field of repair in many cases does not provide the optimal decisions due to insufficient financing. Under these conditions the main direction for supporting the operational reliability of power electric equipment on TS is a development of the modern methods based on individual supervision over real changes of technical condition of power equipment. The analysis of modern methods for development the efficiency of functioning of the enterprises shows (ISO/IEC 31010:2009, 2009; Matusevich, 2015; Matusevicz, O et al. 2016, Anokhin et al., 1997) that improvement of maintenance and repair system taking into account risks of possible failures and accidents is effective means for increasing the efficiency of operation of electric equipment, continuation of service life and decreasing expenses and losses on repairs. Currently, the main direction for improvement of the maintenance and repair system is the development of advanced methods for parameters' control in the course of diagnosing of technical condition and methods for calculation of residual service life (Mustafa Isreb. Prog. Amer. Power. Conf, 1998; Sitnikov et al., 2007,Szelag, A., 2017). However, an efficiency of operation of the equipment on TS is becoming more dependent on a skill level of repair staff, a level of technical equipment, the organizational level for ensuring carrying out high-quality maintenance and repair. The core basis of these problems is not the equipment by itself, but in many cases it is the operation and maintenance system at all stages of life cycle and management of this system (IEC 60300-3-11:2009, 2009). Furthermore, the concept of "Technologies of reliability" as the instrument of improvement of the maintenance and repair system in accordance to the principles of IORS: 2010 has to meet the requirements of the international standard IEC 60300-3-11 : 2009 Dependability in technics. Reliability cantered maintenance (MEK 60300-3-11: 2009 "Management of reliability. Maintenance which is focused on non-failure operation").

4. Increasing of the equipment maintenance efficiency on traction substations

Application of new methods of the system analysis of technical condition and service of objects in traction power supply systems caused high-level requirements to reliability and safety of rail transportation. Practical experience shows that increase of maintenance system effectiveness can be generally reached in three main interdependent directions (technical, economic, organizational) that demands to work towards the following main objectives: improvement of maintenance and repair strategy (M and R) of equipment; improvement of operational and repair documentation; improvement of the organization of M and R, including material support; improvement of technological processes of M and P; optimization of staff involved in M and R etc. According to requirements of normative and technical documents, the M and R system regarding TS on the electrified railways has to possess the following properties - to work under the conditions of high uncertainty in terms of initial information; simplicity of installation, universality, complexity, practical orientation, the possibility of extension. Possibilities of M and R system regarding TS must provide the following - quickly react to changes of operating conditions on TS; to control an operational condition of power equipment on TS under the conditions of uncertainty; to establish interrelation between quality of system of service and efficiency of equipment' operation; optimal strategy of service on TS etc. In order to solve the considered scientific problem the authors propose the model of complex improvement and increasing the effectiveness of M and R system for power electric equipment on TS that is shown on fig. 1.

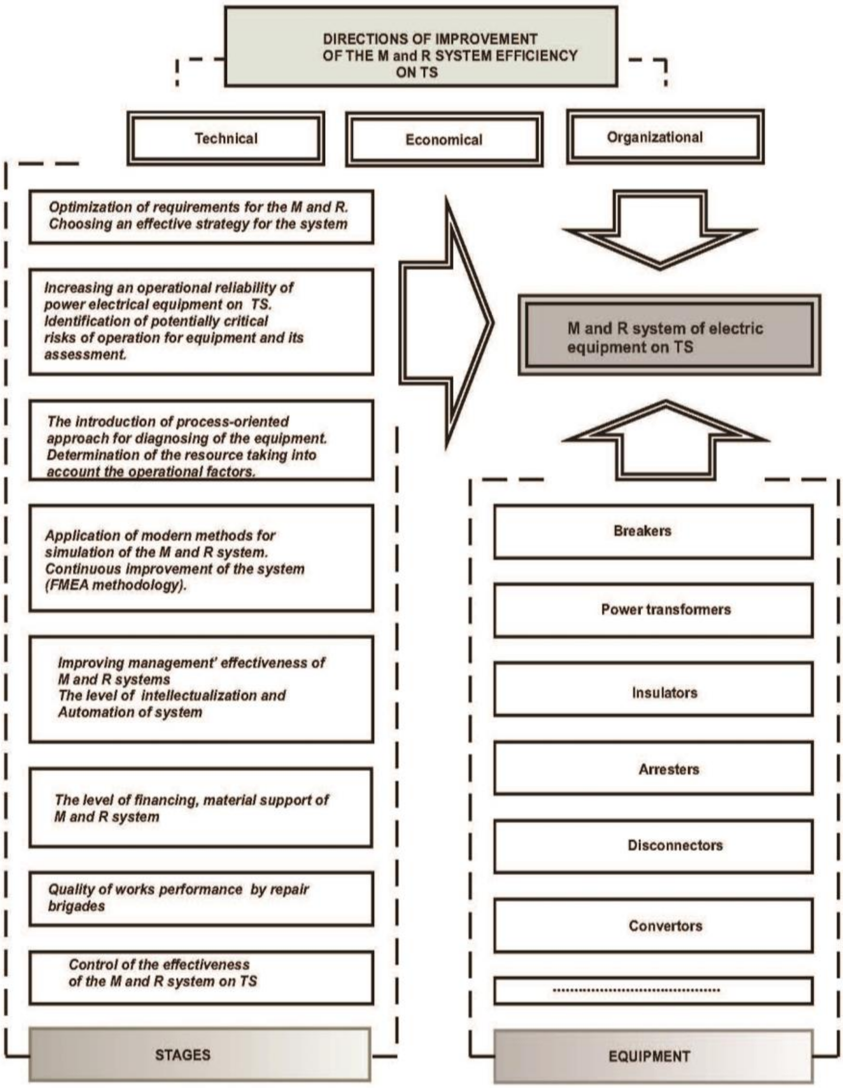

Fig. 1. Model of complex improvement and increase of M and R system effectiveness for power electric equipment on TS

The effectiveness of the M and R system of the power equipment on TS of electrified railways can be evaluated in terms of different indicators (individual, group, integrated), each of which has a quantitative or qualitative character. The relationship between the indicators, in terms of which the process of organizing and conducting of the M and R is described, has a complex structure. In general, some indicators can be expressed through other models placed at same or different level of the operational and diagnosing process. As the theory and practice of diagnostic shows, a common approach to analysing equipment diagnostics data is the transition from a set of indicators (often single ones) whose values can be easily measured (calculated) to a small number of integrated indicators functionally associated

with the output. The main goal of the transition from a set of individual indicators to a group one, and later to a complex one is to obtain the values of indicators characterizing the achieved efficiency of the system and (or) its individual components.
The basis for assessing the effectiveness of the system is the initial expert data regarding the level of a complex indicator of effectiveness. An expert group can be created to carry out the expertise and to make recommendations. In expert studies, as a rule, three types of questions are used: closed, open and semi-open. When answering closed questions, it is possible to choose only from the answers formulated in advance . In the answer to an open question it is explained the expert's opinion in free form. Semi-open questions occupy an intermediate position - in addition to choosing among the options listed in the map, one can add his own thoughts and recommendations.
The determination of indicator's level of the effectiveness of the M and R system can be carried out on the basis of ballistic, linguistic and interval assessments of experts that are expressed in quantitative and / or qualitative form. The task of the expert commission is to select the optimal strategy for M and R system. There are two fundamentally different approaches to solving this task.
The first approach based on a comparison of existing M and R systems. For example, each of the experts selects the system in accordance with his own considerations. The ranking obtained from experts is processed by some mathematical methods with the aim of calculating the final thought of the expert commission.
The second approach has the purpose to compare the importance of various quality indicators of the M and R system and to build an integral quality index (rating evaluation), through which it is possible to streamline the M and R systems regarding quality (calculate the rating of systems).

In this case, in order to process the results of expert assessments and determine the resulting indicators for increasing the efficiency of the M and R system, additive, multiplicative or maximin result indicators can be applied.
For example, the additive indicator is the sum of weighted normalized partial indicators of increasing the efficiency of the M and R system (Π_e) and has the following form:

$$\Pi_e = \sum_{i=1}^{m} a_i q_i \quad , \tag{1}$$

where
q_j - the actual value of the level indicators of the requirements for improving the quality of the M and R system of power equipment on TS ;
a_i - coefficient of relative importance of the direction of improving the quality of the M and R system for power electrical equipment on TS; $0 \le \Pi_e \le 1$ and $0 \le a_i \le 1$ and $\sum_{i=1}^{m} a_i = 1$.
The larger the value is, the more it affects the improvement of the system's quality $\sum_{i=1}^{m} a_i q_i = 1; a_i > 0$ and $i = 1, m$.
According to the proposed components of the definition of the complex efficiency index of the M and R system of power equipment on TS, can be constructed the system efficiency matrix (Table 1), taking into account the stages and directions of improving the operational reliability of the electrical power equipment of the TS (Fig. 1).

Table 1. M and R system's effectiveness matrix for power electric equipment on TS

Sequence of increasing of the efficiency (stages)	Equipment and directions of enhancement of the M and R system's effectiveness									
	Equipment 1 (010)			Equipment 2 (020)			…… (…)	Equipment N (0n0)		
100	Ie 111	Ie 112	Ie 113	Ie 121	Ie 122	Ie 123	……	Ie 1n1	Ie1n2	Ie 1n3
200	Ie 211	Ie 212	Ie 213	Ie 221	Ie 222	Ie 223	……	Ie 2n1	Ie 2n2	Ie 2n3
……	……	……	……	……	……	……	……	……	……	……
M00	Ie m11	Ie m12	Ie m13	Iem21	Iem22	Ie m23	……	Iemn1	Iemn2	Iemn3

On the basis of offered model of improvement and increasing of M and R system's effectiveness one can compose a matrix of system's effectiveness (table 1) taking into account stages and directions (fig. 1).

On the basis of interrelations of components of a matrix, which are presented in table 1, it is created equations for complex indicators of M and R system effectiveness for the equipment (1, 2... N) and systems in general:

1. $I_{e111} = q_{111} \cdot k_{111}$ - a complex indicator of M and R system's effectiveness at service *of the equipment 1 on TS*, at implementation of requirements of a stage 1 and the technical direction 111, q - real value of indicators of requirements for increasing of efficiency of power electric equipment on TS; k - coefficients of relative importance of the directions and stages.

2. $I_{e22} = q_{221} \cdot k_{221} + q_{222} \cdot k_{222} + q_{223} \cdot k_{223}$ - a complex indicator of M and R system's effectiveness at service *of the equipment 2 on TS*, at implementation of requirements for increasing of the efficiency of the equipment at a stage 2 regarding directions: technical, economic, organizational.

3. $I_{eN} = q_{1n1} \cdot k_{1n1} + ... + q_{mn3} \cdot k_{mn3}$ - a complex indicator of M and R system's effectiveness at service of the equipment N on TS, at implementation of requirements for increasing of the efficiency of the equipment at a stages 1 ÷ M regarding directions: technical; economic; organizational.

4. $I_{e.systemMandR} = I_{e1} \cdot k_{\text{eq}.1} + I_{e2} \cdot k_{\text{eq}.2} + ... + I_{eN} \cdot k_{\text{eq}.N}$ - a complex indicator of the M and R system's efficiency at service of the equipment 1 ÷ N on TS, at implementation of requirements at a stages 1 ÷ M regarding directions: technical; economic; organizational.

According to the proposed equations, one can calculate the complex indicators of M and R system's effectiveness at service for the equipment 1 ÷ N on TS regarding any given direction and stage; for the equipment 1 ÷ N on TS regarding all directions and at given stage; for the equipment 1 ÷ N on TS in all directions and stages; for M and R system for all power electric equipment on TS at all stages and directions -111÷ mn3.

On the basis of the proposed method was chosen an optimum option for maintenance of electric equipment on TS (for power transformer TDTN-25000/150-70).

Assume, there is a set A option for increasing of the M and R system's effectiveness on TS:

$$A = [a_1, a_2, ..., a_n] \tag{2}$$

According to (Dolin et al., 2000) for some indicator of increasing of the efficiency the fuzzy set can be considered:

$$I_{ec} = \{\mu_c(a_1)/a_1; \mu_c(a_2)/a_2; ..., \mu_c(a_n)/a_n\} \tag{3}$$

where $\mu_c(a_i) \in [0,1]$ - expert assessment of increasing of the M and R system's efficiency for option (a_i) regarding indicator I_{ec}.

For power transformer were considered by experts four options for increasing the M and R system's effectiveness - a_1, a_2, a_3, a_4. Options were estimated regarding three directions - C_1- technical, C_2 - economical, C_3- organizational, which are mentioned above (fig. 1).

For example, for power transformer TDTN-25000/150-70 U1 that is in service on DC TS (Sychenko et al., 2014) experts estimated the following options that characterize the extent to which the M and R system's effectiveness could be raised according to the requirements for the specified three directions of alternative options:

$$\begin{aligned} I_{ec_1} &= \{0.7(a_1); 0.65(a_2); 0.9(a_3); 0.8(a_4)\}, \\ I_{ec_2} &= \{0.6(a_1); 0.9(a_2); 0.6(a_3); 0.8(a_4)\}, \\ I_{ec_3} &= \{0.9(a_1); 0.8(a_2); 0.8(a_3); 0.8(a_4)\}. \end{aligned} \tag{4}$$

According the extent to which the efficiency of maintenance system's functioning could be increased can be calculated as

$$I_e = I_{ec_1}\omega_1 + I_{ec_2}\omega_2 + I_{ec_3}^{\omega_3}\omega_3 = \prod_{i=1}^{3} I_{ec_i}^{\omega_i} \tag{5}$$

where: I_{ec_i} - value of $i-th$ indicator of system; ω_i – weight coefficient of $i-th$ indicator of system regarding directions $(0<\omega_i<1)$.

Making a decision regarding the best option for improving the effectiveness of system one could face a problem of determining the weights for directions. The review of the main methods for determination of weight coefficients was carried out in (Anokhin et al., 1997). For the practical tasks authors suggest to define weight coefficients as the average geometrical ratio:

$$\omega_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}\ , \qquad (6)$$

where a_{ij} - coefficient of a matrix of pair comparisons, n-number of options, $j=\overline{1,n}$, $\omega \geq 0$, $\sum_{i=1}^{3}\omega_i = 1$.

Determination of weight coefficients could be made on the basis of a method of pair comparisons (Saati' method). The scale for an assessment of relative importance for indicators is given in table 2.

Table 2. A scale for an assessment of relative importance of indicators

Intensity of relative importance	Definition
0-0.10	Equal importance of the compared requirements
0.11-0.30	Moderate (weak) advantage of one over another
0.31-0.50	Strong (essential) advantage
0.51-0.70	Obvious advantage
0.71-0.90	Absolute advantage

As a result of an expert assessment of the relative importance of indicators for improvement the quality of M and R system's functioning for power transformer TDTN-25000/150-70 U1 (Sychenko et al., 2014), the experts offered the following matrix of pair comparisons:

$$\omega = \begin{vmatrix} 0.38(a_{11}); 0.5(a_{12}); 0.36(a_{13}); 0.42(a_{14}) \\ 0.36(a_{21}); 0.34(a_{22}); 0.34(a_{23}); 0.38(a_{24}) \\ 0.26(a_{31}); 0.16(a_{32}); 0.3(a_{33}); 0.2(a_{34}) \end{vmatrix} \qquad (7)$$

According to (5) and data of a matrix of pair comparisons (7) one can define relative the importance of the directions for increasing the maintenance system's effectiveness I_{ec_1}, I_{ec_2}, I_{ec_3}:

$$\omega_1 = \sqrt[4]{\omega_{a11}\cdot\omega_{a12}\cdot\omega_{a13}\cdot\omega_{a14}} = 0.413$$
$$\omega_2 = \sqrt[4]{\omega_{a21}\cdot\omega_{a22}\cdot\omega_{a23}\cdot\omega_{a24}} = 0.356$$
$$\omega_3 = \sqrt[4]{\omega_{a31}\cdot\omega_{a32}\cdot\omega_{a33}\cdot\omega_{a34}} = 0.231$$

Results of the calculated coefficients of relative importance of indicators regarding directions for increasing M and R system's effectiveness is shown on (fig. 2).

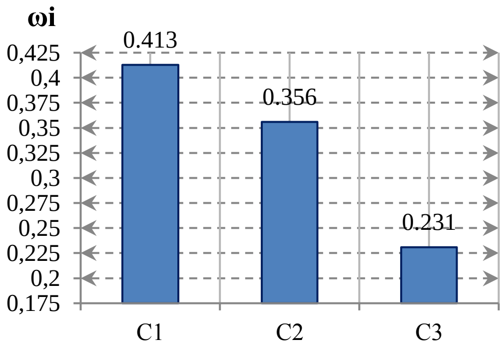

Fig. 2. Weight coefficients of indicators

Fig.2 shows that the most important indicator for increasing of the M and R system's effectiveness in the given case is indicator regarding direction C1.

In the case when the indicators of increasing the efficiency have different relative importance, the weight is attributed to each of them (higher importance correspond to higher ω_i) and the general rule for calculating the indicator is

$$I_e = I_{ec_1}^{\omega_1} \cap I_{ec_2}^{\omega_2} \cap \ldots \cap I_{ec_n}^{\omega_n} \qquad (8)$$

On the basis of fuzzy sets characterizing alternative options for increasing the efficiency of service for power transformer TDTN-25000/150-70 U1 equations (3) could be modified taking into account the relative importance regarding directions ω_1, ω_2, ω_3

$$I_{ec_1}^{0.413} = \{0.7^{0.413}(a_1); 0.65^{0.413}(a_2);$$
$$0.9^{0.413}(a_3); 0.8^{0.413}(a_4)\} =$$
$$= \{0.825(a_1); 0.824(a_2);$$
$$0.954(a_3); 0.904(a_4)\};$$

$$I_{ec_2}^{0.356} = \{0.6^{0.356}(a_1); 0.9^{0.356}(a_2);$$
$$0.6^{0.356}(a_3); 0.8^{0.356}(a_4)\} =$$
$$= \{0.858(a_1); 0.969(a_2);$$
$$0.858(a_3); 0.935(a_4)\};$$

$$I_{ec_3}^{0.231} = \{0.9^{0.231}(a_1); 0.8^{0.231}(a_2);$$
$$0.8^{0.231}(a_3); 0.8^{0.231}(a_4)\} =$$
$$= \{0.974(a_1); 0.946(a_2);$$
$$0.946(a_3); 0.946(a_4)\}.$$

On the basis of (2) and (4) was calculated a set I_e:

$$I_e = \{0.712(a_1); 0.775(a_2); 0.744(a_3); 0.8(a_4)\}$$

Fig.3 shows the comparison of results for alternative options for power transformer TDTN-25000/150-70 U1 (taking into account relative importance of directions).

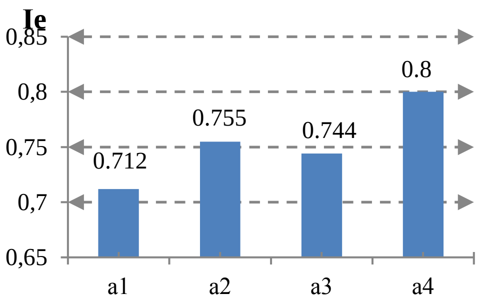

Fig. 3. Alternative options for increasing the M and R system's efficiency for power transformer TDTN-25000/150-70 U1

According to fig.3 the maximum value of efficiency of M and R system I_e for power transformer TDTN-25000/150-70 U1 is for an alternative a_4. This option can be chosen for operation, as a more rational option for increasing the efficiency of M and R system for power transformer that is in service on TS-18 "Sinelnikovo" on Pridnieprovskaya Railway.

5. Conclusions

The analysis of modern methods of increasing the efficiency of the equipment's functioning on railway enterprises shows that effective mean for increasing the reliability of electric equipment, a continuation of its resource, decreasing the repair expenses is improvement of M and R system taking into account risks of possible failures and accidents.

The proposed method for improving the M and R system for equipment in traction power supply system allows – to react quickly to changes of operating conditions of power electric equipment on traction substations; to define the most effective strategy for M and R under the conditions of uncertainty of functioning; to set (to imitate) different service conditions of the equipment on TS for a choice of optimum option of service and achievement of necessary level of M and R system's effectiveness; to control a condition of system's improvement ; to determine the level of the real integrated indicator of efficiency of the M and R system in general or separately regarding each type of the equipment, direction and stage of system's improvement.

It is also proposed the complex indicator for an assessment of the efficiency of service taking into account various directions and stages for various power equipment for traction power supply system. Currently, such indicator is absent in standards regulating M and R system.

Proposed method for increasing the M and R system's effectiveness for power electric equipment on traction substations allowed to choose the most rational option for operation of the power transformer TDTN-25000/150-70 U1 on traction substation "Sinelnikovo" on Pridnieprovskaya Railway that raised an instantaneous availability, steady state availability factor, service expenses are reduced by 7 - 8%. This effect was achieved by the transition from the normative system of maintenance and repair to the prospective system of maintenance and repair on the basis of actual technical state, which allowed to exclude unnecessary types of maintenance and decrease the operation costs. The calculation was made according to normative documents, on the basis of which is organized the technical maintenance and repair of electric power supply devices on Ukrainian railways.

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