Optimization of impacts parameters on the equipment of electrical networks during operation according to the technical condition

V M Levin¹, N P Guzhov², N A Chernenko³ and N F Cheganova³

¹Department of Automated Electrical Power Systems, Novosibirsk State Technical University, Karl Marx ave., 20, Novosibirsk, 630073, Russia
²Department of Power Supply Systems Enterprises, Novosibirsk State Technical University, Karl Marx ave., 20, Novosibirsk, 630073, Russia
³Department of High Voltage Engineering and Electrophysics, Novosibirsk State Technical University, Karl Marx ave., 20, Novosibirsk, 630073, Russia

E-mail: levin@corp.nstu.ru

Abstract. Scheduled operation of power grid facilities is regulated by the relevant regulations based on a system of scheduled preventive maintenance. Maintenance and repair (M&R) of power grid facilities due to their technical condition increases demands for planning methods and models. In these conditions, the goals of the M&R management are aimed at improving the efficiency of the operation of electrical networks. They differ depending on the purpose and form of ownership of the latter. The article suggests a combined approach to planning maintenance of electrical networks using strategy depending on their technical condition based on optimization of impact parameters such as frequency and labor intensity under specified constraints and variability of management goals. To implement the proposed planning procedure, the authors developed and verified models of process maps. Each of them represents a local database including the information about the composition and complexity of operations, depending on the type of equipment and the type of corrective actions. In addition, a set of operational algorithms, that solve the issues of process automation in the maintenance system of electrical network equipment, has been developed. The analysis and discussion of the developed models and algorithms are carried out on a specific example illustrating the possibilities of improving the efficiency of equipment operation in the electrical networks on the oil fields.

1. Introduction
Long-lasting safe operation of electrical network equipment is ensured by compliance with a set of statutory and technical requirements, according to which the main corrective actions are maintenance and repair. Scheduled maintenance and repair (M&R) of electrical equipment (EE) imply advance scheduling for the introduction of corrective actions with the registration of their type, volume, and cost in the planning interval $\Delta T$ (year). Depending on the type of EE, an M&R strategy is identified. It determines the planning approaches (Rules for organization of electric power facilities maintenance and repair. Approved by order No. 1013 dated 25.10.2017 of the Ministry of Energy of the Russia).

Until recently, the strategy "by periodicity, operating time", which regulates planning and implementing corrective actions for M&R of EE at certain precisely fixed time intervals, was recognized as practically the only one [1]. This strategy, along with its advantages, has a significant disadvantage. It
assigns to each unit of EE the implementation of a full set of operations as part of a certain corrective action as it reaches its planned period, regardless of whether there is an actual need for it. This determines the unjustified redundancy of the strategy "by periodicity, operating time" with respect to the total time spent, labor and material resources involved in technical M&R of EE. In addition, increasing the frequency and duration of planned outages of EE reduces the reliability of power supply to consumers, and thus the efficiency of electrical network operation [2, 3].

With the introduction of methods for condition index (CI) calculation for units and/or groups of single-type EE in operating practice of electrical networks the scope of M&R application with the strategy "by technical condition" expanded (Methodology for assessing the technical condition of the main technological equipment and power lines of power plants and electrical networks. Approved by Order of the Ministry of Energy of Russia dated July 26, 2017 No. 676) [4]. This strategy prescribes the implementation of corrective actions with an arbitrary frequency, precisely as necessary, and the necessity is determined as a result of monitoring and diagnosing the status parameters of EE with a quantitative assessment of the CI.

The mass switch of EE to the strategy "by technical condition" opens up new opportunities for improving the operating efficiency of power distribution networks for various purposes. This will require formalization of the description and solution of a set of tasks to justify the performance criteria in accordance with the priority control goals of the M&R, developing models, methods and scheduling algorithms, updating the parameters of technical impacts on the main EE, taking the influence of key risk factors into account, and so on. Many of these tasks have been brought to acceptable practical results, promising methods and approaches to solving them are discussed, but the process of finding the best scientific-based solution is still far from complete [5-12].

Electrical networks of oil-production industries, in contrast, for example, to the facilities of JSC Rosseti, supply power only to technological consumers of oil-field facilities (OFF). This determines the difference in the target priorities and performance criteria of such facilities operation. Thus, for general-purpose electrical networks a long-term strategic priority is to ensure the maximum level of reliability of power supply to consumers, which is regulated by reliability indexes such as SAIFI (System Average Interruption Frequency Index) - the index, which shows the average frequency of interruptions in the system, SAIDI (System Average Interruption Duration Index) - the index of the average duration of interruptions in the system, etc. [13]. For electrical networks, providing electricity for oil fields, the strategic target priority is the continuity of technological processes and minimum total damage from underproduction (loss of oil production). Thus, there are obvious differences in optimization approaches to planning M&R and choosing parameters of corrective actions on EE in frequency and volume. It is necessary to point out, that the solution of the optimization problem is usually performed under various restrictions, for example, on available material, labor, and financial resources (costs for M&R of EE), as well as taking the influence of numerous risk factors into account.

For the electrical networks of oil fields, a key risk event is the failure of the EE that supplies energy to the OFF. Failure of EE, considered as an accident, is characterized by parameters such as probability $Q$ and frequency $\omega_i$, depending on a number of factors. There are gradual and sudden failures of EE [14]. Gradual failures can usually be predicted. They are caused by aging (worsening of the material properties and construction elements) of EE. Sudden failures cannot be predicted. They occur due to the influence of internal and external occasional factors in relation to electrical equipment, such as environmental influences, operating errors, etc. Thus, the probability (frequency) of EE failure is directly related to its technical condition. CI is its integral characteristic. Is determined on the basis of technical documentation data and diagnostic results. The relationship for the i-th unit of electrical equipment is taken into account in the following formula:

$$Q_i = 1 - \exp(-\omega_i) \cdot J_i,$$

where $\omega_i$ (year$^{-1}$) and $J_i$ (relative units) - the values of the average failure rate and the CI of the i-th unit of EE.
In addition to the probability, an accident is characterized by the severity of the consequences (damage from technology violations, equipment failures, threats to the environment and personnel safety, product underperformance) [15]. The components of total damage (Dam) can be ranked and quantified for each typical OFF [16]. For these purposes, the author of the article enumerated in the references uses the term "criticality", which serves as an integral estimative probability and severity of the consequences of a key accident for each type of OFF (GOST 27.310-95 Reliability in technology. Analysis of types, consequences, and criticality of failures). Thus, the criticality or risk function of EE failure can be shown as follows:

$$ R = Q \cdot M[Dam], $$

where:

- $M[Dam] = P_{load} \cdot \Delta t \cdot D \cdot c$ - damage expectation value;
- $P_{load}$ (kW) - load power;
- $\Delta t$ (hour) - power supply interruption;
- $D$ (tons/kWh) - specific capacity of the OFF consumer;
- $c$ (USD/ton) - unit cost of losses.

The total number and scope of corrective actions for M&R of EE serve as optimization parameters on the planning interval $\Delta T$ since they ultimately determine one of the main components of the integrated production resources ($C_{M&R}$) of the network enterprise, which are always limited [17].

Taking this into account, the minimum of the risk function $Min (R)$ should be taken as the optimization target function, and the following relations should be taken as restrictions:

$$ C_{M&R} \leq C_{lim}, \quad C_{I} \geq C_{Ilim}, \text{при } i = 1, N, $$

where:

- $C_{lim}$ - an available integrated resource of a network enterprise for M&R of EE for the planning year (for example, in man-hours or rubles);
- $C_{lim}$ - $C_I$ acceptable limit values for each equipment unit of a certain type;
- $N$ - number of units EE to be M&R for the planning year (number of units).

The parameters for corrective action optimization will be the following:

1) frequency of M&R activities for each unit of EE in the planned interval $T_{M&R}$;
2) total labor intensity of a set of operations to eliminate defects ($\Sigma L_I^j$) as part of each i-th corrective action of a certain type for each j-th unit of N units of EE to be scheduled M&R.

Considering the information mentioned above, it is obvious that there is a need for a decision-making methodology that would take into account and combine the scenario approach, the variety of influencing factors, and the variability of management goals. This article presents and discusses the core components of the developed methodology.

2. Materials and Methods

2.1. Planning model for M&R of EE

EE operation with the "by technical condition" strategy implies the initial formation of the scheduled plan of the work execution plan (WEP) for a calendar year. The principles of its formation are based on the concept of a repair cycle – the time interval between two consecutive overhauls (OH), which are designed to restore partially lost functional capabilities of EE. During the repair cycle interval, $T_{rc}$ of EE with a fixed standard rate, other types of corrective actions are scheduled. They include:

- inspection (I) - visual testing of EE;
- detailed inspection (DI) - instrumentation control with the use of facilities of technical diagnostics and nondestructive testing (TD&NT) of EE;
- maintenance (M) - complex of operations to maintain the EE working condition during operation without disconnecting it;
- routine maintenance (RM) - a set of operations to guarantee the operability of EE with its withdrawal from the operation.
When the scheduled plan of the WEP for the current calendar year is being prepared, the year of the previous OH and/or RM is taken into account \(T_{WEP}\). The plan drawn up in a similar way is fixed and represents a "basic grid" for obtaining a scheduled plan for M&R of EE "by technical condition". The M&R scheduled plan "by technical condition" is not static. It is periodically adjusted by shifting the timing of repair works in accordance with the actual need, which is determined by the technical condition of the EE. Also CI am an integral characteristic of the technical condition.

Thus, obtaining information about the value of the CI of an EE unit is a necessary and sufficient condition for making a decision on adjusting the overhaul period in the scheduled interval. The practice of operating EE in the distribution networks of oil-fields has proved the validity of the following rules:

1) If for an EE unit \(25\% \leq CI < 50\%\), the repair is scheduled for the next calendar month with the date fixed in the M&R schedule. This makes it possible to exclude possible failures of electrical equipment, including those with serious consequences.

2) If the value is \(CI \geq 50\%\), then the adjustment of the overhaul period of the RM is made according to the mathematical expression (4):

\[
T_{op} = k \cdot T_{stand},
\]

where:
- \(T_{op}\) - estimated duration of the overhaul period;
- \(T_{stand}\) - standard duration of the overhaul period for the WEP strategy;
- \(k\) - correction factor, that takes values within the range \(1 \leq k \leq 1.5\).

The specified range is set by an expert method based on an analysis of the functioning of EE with a "by technical condition" strategy. After receiving the adjusted value of the overhaul period, the date of repair is determined:

\[
T_r = T_{rWER} + T_{op},
\]

where: \(T_{rWER}\) - date of the previous repair from the scheduled plan of the WEP.

Table 1 shows the values of standard overhaul periods for some types of EE 6(10) kV by type of main corrective action.

| Name of equipment                              | Periodicity, months |
|-----------------------------------------------|---------------------|
|                                               | M  | RM | OH |
| Overhead line on metal and reinforced concrete supports 6(10) kV | 6  | 24 | 120 |
| Cable line 6(10) kV                           | 6(3)| 26 | 60 |
| Power transformer 6(10) kV                    | 3  | 12 | 144 |
| Oil breaker 6(10) kV                          | 1  | 12 | 96 |
| Vacuum breaker 6(10) kV                       | 6  | 24 | 120 |
| Disconnecting switch 6(10) kV                 | 1  | 12 | 96 |

The value of the correction factor \(k\) is determined using Table 2 in accordance with the values of the EE CI calculated on the basis of data obtained as a result of I, IDI and diagnostic examinations.

| CI, %          | 50 – 70 | 70 – 85 | 85 – 100 |
|----------------|---------|---------|----------|
| \(k\), relative units | 1.0     | 1.25    | 1.5      |
2.2. Adaptive model of the EE process map

The process map (PM) serves as the main organizational and technological document in the management of M&R EE. It contains a set of measures for human engineering using the most effective modern means of mechanization, processing equipment, tools, and devices. As a rule, the PM includes the most advanced and rational methods and technologies of M&R that help to increase labor productivity, improve the quality of work, and reduce their cost. The standard model and methodology for creating an MP WEP of electric power facilities are approved by the regulation (Organization standard STO 56947007-29.240.55.168-2014 "Methodological guidelines for the development of flow charts and projects for the maintenance and repair of overhead lines". Approved by the Order of JSC FGC UES dated 02.04.2014 No 165). In accordance with requirements, MP is divided by types of impacts on the object (I, DI, M, RM, OH) and contain the following information:

1) characteristics of the facility;
2) the standard list of required operations;
3) the labor intensity of each operation in man-hours;
4) the number of employees involved in accordance with the functions (brigade staff);
5) processed materials, equipment, tools, special mechanisms, including means of transport.

Management of M&R of EE with "by technical condition" strategy based on the minimum risk criterion relies on making decisions under the influence of random factors, such as damage to EE, power failure to OFF, the severity of the consequences of failure, the availability of the necessary resource, etc. Under these conditions, the standard model of the PM is unsuitable for planning EE M&R due to its redundancy and determinism. We need an adaptive model of the PM that allows us to adjust the total labor intensity of EE repair work based on the minimum set of operations necessary and sufficient for high-quality restoration and verification of the serviceability of the maintained facility (MF) in compliance with standard measures and safety rules.

The adaptive model of the PM of MF repair is based on the typical division of the complete list of operations into two blocks: organizational and technological ones. The organizational block cannot be corrected and it includes operations connected with logistics, workplace preparation, compliance with health standards, access to the MF, reporting documents, and it cannot be corrected. The technological block includes operations aimed at MF fault repair, adjustment and functionality test. It allows the necessary adjustment. The formation of an adaptive process map model should follow the following key principles:

1) full identification of possible malfunctions (defects) of the EE functional units and determination of appropriate corrective operations;
2) objective assessment of each corrective operation labor intensity under the conditions of its execution on the MF;
3) ranking of defects in terms of criticality (from the point of view of extending the operation of the MF), determined by TD&NT, for example, as a non-critical defect (NCD) or a critical defect (CD). Compliance with these principles ensures that the resulting labor intensity is determined not as the sum of labor costs for the full list of operations contained in the standard technological map for the repair of an object, but by a reduced list of corrective operations requiring actual performance in specific conditions. Table 3 shows a fragment of the corrected PM for the repair of an overhead line 6(10) kV, derived from the developed adaptive model.

2.3. The algorithm of formation the discrepancy list for MF

A discrepancy list is one of the most popular tools for planning repairs of electrical equipment with the "by technical condition" strategy. A discrepancy list is formed for each MF and contains information from the inspection sheets [18]. In fact, this is a list of defects identified on MF during and I or DI, but not eliminated at the current time, indicating the criticality extent for each defect and assigning a certain type of corrective action to it. As a rule, such types of impacts as M and RM are assigned as corrective actions of M&R. If it is necessary to monitor the extent of EE failure and clarify the scope of repairs, and DI is scheduled, identifying a specific method of TD&NT. Figure 1 shows the structure of the discrepancy list of the generalized MF.
Table 3. Corrected process map of repair overhead power lines 6(10) kV (fragment).

| Sr. No | Block of operation | Working sequence | Equipment | Number, man | Time of operation, minute | Labor costs, man-hours | NOTATION (Defect code) |
|--------|--------------------|-----------------|-----------|-------------|--------------------------|-----------------------|-----------------------|
| 1      | Organizational / start of operation | MF testing for the previously detected defects and the amount of operating time. If there are defects, determining the necessary mechanisms, components, materials, etc. Implementation of administrative procedures ensuring work safety in electrical installations, including the implementation of additional measures when working at height, conducting fire-hazard work, etc. | Overhead power line 6(10) kV Repair | 1 | 30 | 0.50 | Analysis of the of the previous DI and M results, discrepancy list, inspection sheets, operating hours, thermovision inspection, controlled parameters, etc. Registration of works by order, instruction, list of works. Getting permission to prepare the workplace. Getting work permission, supervision |
| 2      | Organizational / operation completion | Cleaning of the workplace, removal of grounding clusters of the brigade, posters, etc. | | 2 | 30 | 1.00 | |
| 3      | Registration of operation completion | Filling in the passport of an overhead power line | | | | | |

Depending on the type of EE, each defect is assigned its personal identity code, which is used to define a specific method of TD&NT to the defect. The defect code is also used when forming an adaptive PM of MF repairs to identify the detected defect and the related list of corrective operations. To illustrate this, Table 4 shows a fragment of the discrepancy list for the overhead power line 6(10) kV.
Figure 1. Structure of the discrepancy list.

Table 4. Discrepancy list for overhead power lines 6(10) kV (fragment).

| Functional unit | Defect code | Name (characteristic) of the defect | Controlled parameter | Level of criticality | Corrective action |
|-----------------|------------|-------------------------------------|----------------------|---------------------|-------------------|
| Right-of-way    | T01        | The presence of objects not accounted for in the project | $L < 10$ metre       | + – M –             |
|                 | T03        | The presence of trees on the edge of the forest corridor threatening to fall on the overhead power line wires |                        | + – M –             |
| Support         | C01        | Deformation of the metal grating elements of support structure |                        | + + RM IDI         |
|                 | C02        | Break of elements construction supports |                        | + + RM M           |
|                 | C08        | Absence or loosening of mounting nuts on the anchor bolts |                        | + – M –             |
| Span            | П07        | Changing the slacks and distances from the overhead line wires to the ground, to intersecting objects, between phases to values other than acceptable |                        | + – RM –           |

3. Results
As an example illustrating the developed methodology for managing EE repairs in oilfield distribution networks, let's consider two identical objects operating in similar conditions. Both network objects have 2 and 3 km long double-circuit overhead transmission line (OTL), made on metal supports with AS-95 wire. The first object (OTL-1) provides power supply to process load of a booster pipeline pumping station with a device for initial reservoir water separation (BPPS with DIRWS) with a power $P_{load}=1000$ kW, a supply interruption time $\Delta t=1$ hour and a specific throughput $D=0.01$ tons/kWh. The
second object (OTL-2) supplies energy to consumers of the oil multiple-well platform with a total power $P_{load}=1000$ kW, $\Delta t=0.015\, h$, $D=10$ tons/kWh. Let the condition of OTL-1 and OTL-2 be characterized by the presence of defects in the discrepancy list (Table 5).

**Table 5. Structure of defects OTL-1 and OTL-2.**

| Functional unit | Defect code | Name (characteristic) of the defect | Controlled parameter | Level of criticality | Corrective action |
|-----------------|-------------|-------------------------------------|----------------------|---------------------|-------------------|
|                 |             |                                     | $L < 10$ metre       | CD                  | NCD               |
| OTL-1 Right-of-way | T09       | Presence of object not accounted for in the project | $L < 10$ metre       | +                   | M                 |
| Support         | C02        | Metal support                       |                      | +                   | RM                |
| Span            | П07        | Break of elements construction supports |                          | +                   | RM                |
| OTL-2 Support   | C08        | Lack of perpendicularity            |                      | +                   | RM                |
| Span            | П01        | Wire repair, bandaging with lowering the wire |                  | +                   | RM                |

Table 6 provides a list of processing steps of the adaptive PM for the repair of each MF (OTL-1 and OTL-2), and shows differences in the total labor costs for their implementation, considering the correction factors that take into account natural and climatic conditions and transport accessibility.

**Table 6. List of processing steps of the adaptive PM for the repair of OTL-1 and OTL-2.**

| Defect code | Corrective operations | OTL-1 | $L \overline{I}_i^{+}$, man/hour | OTL-2 | $L \overline{I}_i^{+}$, man/hour |
|------------|-----------------------|-------|---------------------------------|-------|---------------------------------|
| T09        | Clearing the right-of-way from scrubs, eliminating foreign objects, cutting down trees that threaten to fall. | 10.0  | C08 Checking the condition of the supports and their installation (lack of perpendicularity, skewing elements), if necessary, supports alignment | 9.3   |
| C02        | Anchor bolt tightening, restoration of corners of the cross brace | 10.0  |                                |       |
| П07        | Pulling separate segments of wires, tightening and adjusting the wire sag. | 10.0  | П01 Wire repair, bandaging with lowering the wire | 9.3   |

The calculations of the CI OTL using method [4] are shown in Table 7. The calculations used scorecard groups of separate functional units status parameters of the item within the range from 10
(best) to 1 (worst). Based on the results of the calculations for CI functional units, the CI score for each object as a whole is calculated:

$$J_{\text{OTL-1}} = (0.91 \cdot 0.334 + 0.1 \cdot 0.666) \cdot 100\% = 37\%;$$

$$J_{\text{OTL-2}} = (1 \cdot 0.334 + 0.37 \cdot 0.666) \cdot 100\% = 58\%.$$ 

As follows from the calculations, the condition of the OTL-1 by the CI value falls into the category $\geq 25\%$ and $< 50\%$ (unsatisfactory), in which the repair must be planned directly for the next calendar month after the calculated one, with the date fixed in the Maintenance schedule M&R. For OTL-2 the correction factor $k$ of the repair frequency adjustment takes value 1.0 (Table 2), i.e. the overhaul period is not adjusted in the M&R schedule. Thus, based on the assessment of the technical condition, the repair of OTL-1 is of a higher priority than the repair of OTL-2 and should be planned according to the M&R schedule at an earlier time.

### Table 7. Calculations results of CI OTL-1 and OTL-2.

| Defect code | Parameters group | Scorecard of parameters group OTL-1 / OTL-2 | "Weight" of a parameters group in the node estimation | CI of functional units |
|-------------|------------------|-------------------------------------------|--------------------------------------------------|-----------------------|
| Support     | Fixing support, stand, traverse, hitch, insulator on the support stand, wire | 10 | 0.3 | OTL-1 $(0.3 \cdot 10 + 0.1 \cdot 1 + 0.2 \cdot 10 + 0.1 \cdot 10 + 0.3 \cdot 10)/10 = 0.91$ |
|             | Attachment, stand, strut | 1/10 | 0.1 |                     |
|             | Traverse, hitch, insulator on the traverse | 10 | 0.2 | OTL-2 $(0.3 \cdot 10 + 0.1 \cdot 10 + 0.2 \cdot 10 + 0.1 \cdot 10 + 0.3 \cdot 10)/10 = 1$ |
|             | Grounding connection | 10 | 0.1 |                     |
|             | Switching units, surge arrester | 10 | 0.3 |                     |
| Span        | Right-of-way OTL | 1/10 | 0.3 | OTL-1 $(0.3 \cdot 1 + 0.7 \cdot 1)/10 = 0.1$ |
|             | Wire, intermediate cable | 1/1 | 0.7 | OTL-2 $(0.3 \cdot 10 + 0.7 \cdot 1)/10 = 0.37$ |

When calculating the probability of an MF failure, taking into account their actual technical condition, formula (1) uses the value of the average failure rate for an OTL 6 kV with a length of 2-3 km, equal to $\omega = 0.202$ year$^{-1}$ [19, 20]:

$$Q_{\text{OTL-1}} = 1 - \exp(-0.202) \cdot 0.37 = 0.698;$$

$$Q_{\text{OTL-2}} = 1 - \exp(-0.202) \cdot 0.58 = 0.526.$$ 

Calculations of the risk function (optimization target function) for each of the OTL are performed using formula (2) when the value of the incremental cost of oil production losses $c = 200$ USD/ton. Obtained results:

$$R_{\text{OTL-1}} = 1000 \cdot 1 \cdot 0.698 \cdot 200 = 1396$ USD;$$

$$R_{\text{OTL-2}} = 1000 \cdot 0.526 \cdot 200 = 15780$ USD,
indicate that the risk of interruption of consumer power supply of OFF in the OTL-2 is well above than the risk of OTL-1 failure.

Thus, according to the minimum risk criterion, the highest priority in planning is given to the repair of OTL-2, the failure of which leads to the most severe consequences. From the point of view of checking the fulfillment of conditions (3), we will limit ourselves to general considerations. As the most likely situation, we assume that the total cost of equipment maintenance does not exceed the specified value \( C_{\text{lim}} \), and \( C_{\text{lim}} = 25\% \). This situation will allow us to recognize the optimal solution to the problem of planning the repair of OTL-2 within a calendar month from the estimated date, and to shift the repair of OTL-1 a month after OTL-2. This, in turn, will increase the index of its technical condition and reduce the probability of failure, and therefore the amount of total risk.

4. Conclusion

1. Improving the methodology for managing M&R of EE with a "by technical condition" strategy on risk-based models and decision-making algorithms contributes to improving the efficiency of electrical networks and industrial process complexes.

2. The original methodology proposed by the authors is focused on the application of OFF in distribution networks and power supply systems. The methodology allows for a formal description and solution of a set of M&R planning tasks for selecting and adjusting the type, volume, and frequency of technical impacts on the EE with a "by technical condition" strategy. The target function of optimizing the parameters of technical impacts is to minimize the total risk from interruptions of power supply to consumers of OFF. The main restrictions on the scope of acceptable solutions are the available resources of the enterprise (total M&R costs) and reliability (the maximum allowable value of the EE CI). The calculation of the total risk involves the determination of oil production loss from each process consumer, taking into account the individual characteristics of its power supply, as well as determining the probability of EE failure, paying attention to its actual technical condition.

3. One of the main options in the methodology is an adaptive model of the PM for the repair of EE with the strategy "by technical condition". The basis of its modeling is featured by a number of key pillars, such as complete identification of possible defects of EE functional units and relevant corrective operations, an objective assessment of the labor intensity of each correcting operation in the conditions of its implementation on the MF, ranking defects by the extent of criticality, defined by the TD&NT. This ensures that the amount of corrective action on electrical equipment is determined only by a reduced list of corrective operations requiring actual performance under certain conditions.

4. Certain example illustrates the logical and computational-analytical advantages of the developed methodology. Unfortunately, the scope of the article limits the ability to demonstrate the proposed set of solutions to the full, but the example clearly shows an accurate sequence of calculations, the reliability of the results, provided by the correctness of the models’ application, verified by practice, the logic of excluding contradictions when choosing priorities and evaluating the effectiveness of the results obtained. It should be noted that the presented components of the developed methodology have found practical application in the terms of real operation of EE OFF.

References

[1] Sinyagin N N 1984 Sistema planovo-predupreditel'nogo remonta elektrooborudovaniya promyshlennykh predpriyatij [System for preventive maintenance of electrical equipment of industrial enterprises] (Moscow: Energiya) [In Russian]

[2] Korotkevich M A 2003 Osnovnye napravleniya sovershenstvovaniya eksploatacii elektricheskikh setej [Main directions for improving the operation of electric networks] (Minsk: Tekhnoperspektiva)

[3] Grabchak E P 2017 Otsenka tekhnicheskogo sostoyaniya energeticheskogo oborudovaniya v usloviyah tsifrovoy ekonomiki [Assessment of the technical condition of power equipment in the digital economy] Nadezhnost' i bezopasnost' energetiki [Reliability and Safety of Energy] 10(4) 268-74 [In Russian]
[4] Nazarychev A N 2002 *Modeli i metody optimizatsii remonta elektrooborudovaniya ob”ektov energetiki s ucheton tekhnicheskogo sostoyaniya* [Models and methods for optimizing the repair of electrical equipment for energy facilities, taking into account the technical condition] (Ivanovo: ISEU) [In Russian]

[5] Wang M, Vandermaar A J and Srivastava K D 2002 Review of condition assessment of power transformers in service IEEE Electrical Insulation Magazine **18**(6) 12-25

[6] Gavrilovs G 2011 Technical condition asset management of power transformers *2nd IEEE PES Int. Conf. and Exhibition on Innovative Smart Grid Technologies* (Manchester: IEEE) 6162762

[7] Aladon M B 2018 *RCM3: Risk-Based Reliability Centered Maintenance* (NY: Industrial Press)

[8] Levin V M 2018 Methodological Aspects of Assessing State of HPP Transformers in Monitoring Mode *XIV Int. Scientific-Technical Conf. on Actual Problems of Electronics Instrument Eng.* (Novosibirsk: NGTU) pp 238-43

[9] Petrosenko A V and Tulsky V N 2019 Primenenie mnogokriterial'nogo podkhoda i kombinirovannogo analiza pri formirovanii proizvodstvennoy programmy organizatsiy [Application of the multicriteria approach and combined analysis in the formation of the production program of organizations] *E`lektroe`nergiya. Peredacha i Raspredelenie* **56**(5) 38-49 [In Russian]

[10] Grabchak E P, Medvedeva E A et al. 2019 O metodologii rascheta tekhnicheskogo riska na osnove veryatnosti i posledstviya otkaza funkcional'nogo uzla i edinicy osnovnogo tekhnologicheskogo oborudovaniya [On the methodology for calculating technical risk based on the probability and consequences of failure of a functional unit and a unit of main technological equipment] *E`lektroe`nergiya. Peredacha i Raspredelenie* **52**(1) 22-9 [In Russian]

[11] Antonenko I N 2019 Metodologiya RCM: retrospektiva i perspektiva nadezhnostno-orientirovannogo analiza pri formirovanii proizvodstvennoy programmy organizatsiy [RCM methodology: a retrospective and perspective of reliability-oriented maintenance] *E`nergiya Edinoj Seti* **1**(43) 34-46 [In Russian]

[12] Rychagova E A and Levin V M 2019 Improving the efficiency of electric network equipment operational service *E3s Web of Conf.* **11** 03001

[13] Saharova I V 2013 Ob uchete kachestva uslug v tarifnom regulirovanii raspredelitel'nych elektroseteykh kompanij v rossijskoj i zarubezhnoj praktike [About accounting of quality of services in tariff regulation of distribution electric grid companies in the Russian and foreign practice] *Sovremennaya E`konomika: Problemy` i Resheniya* **5** 43-51 [In Russian]

[14] Levin V M and Sekretarev Yu A 2019 Ocenka vliyanija na nadezhnost` sistemny elektronsnabzheniya razlichnogo roda defektov ee osnovnykh elementov [Assessment of the impact on the reliability of the power supply system of various types of defects in its main elements] *Vestnik KGEU* **44**(4) 55-63 [In Russian]

[15] Nordgärd D E, Welte T M and Heggset J 2010 Using life curves as input to quantitative risk analysis in electricity distribution system asset management *Proceedings of the Institution of Mechanical Engineers, Part O: J. of Risk and Reliability* **224**(2) 63-74

[16] Lesnyh V V, Timofeeva T B and Petrov V S 2017 Problemy ocenki ekonomicheskogo ushcherba, vyzvannogo pereryvami v elektronsnabzhenii [Problems of assessment of economic damage caused by interruptions in the power supply] *Regional'naya Ekonomika* **3** 847-58 [In Russian]

[17] Antonenko I N 2020 Risk-orientirovannoj podhod k upravleniyu proizvodstvennymi aktivami energetiki [Risk-based approach to managing energy production assets] *Energoexpert* **1** 26-33 [In Russian]

[18] Voronin V V and Davydov O A 2019 Relative Equivalence of Defects *2019 Int. Multi-Conf. on Ind. Eng. and Modern Technologies* (Vladivostok: IEEE) 8933857
[19] Napoleone A, Roda L and Macchi M 2016 The implications of condition monitoring on asset-related decision-making in the Italian power distribution sector *IFAC-PapersOnLine* 49(28) 108-13

[20] Levin V M 2020 Innovacionnye resheniya v upravlenii remontami energeticheskogo oborudovaniya neftedobyvayushchestogo kompleksa [Innovative solutions in the management of repairs of power equipment of the oil production complex] *Glavny’j Energetik* 1 30-9 [In Russian]