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The selection of a priority package of measures for technical re-equipment and reconstruction of the district of electrical grids

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Abstract. Making decisions on the technical re-equipment and reconstruction of electrical grids needs analyzing a large amount of information, comparing a variety of options, evaluating the impact of a decision in the long term. Therefore, the process of formation of the package of measures is complicated. In this regard, it is necessary to develop an automated decision support system for selecting a priority package of measures for the technical re-equipment and reconstruction of the electrical grid district. The article presents the structure of the decision-making process for the technical re-equipment and reconstruction of the district of electrical grids, the model of formation and the method for selecting a priority package of measures. It is proposed to use graph theory for compiling a decision tree and methods of combinatorial optimization for the formation and selection of a priority package of measures. A two-level structural scheme of the decision-making process for the selection of a priority package of measures for the technical re-equipment and reconstruction of the electrical grids at the local and global levels has been developed.

1. Introduction

The variety of features of the technical re-equipment and reconstruction (TR&R) of electrical grids: many goals of functioning with the uncertainty of growth of load; increase in the number of estimated parameters; modern socio-economic requirements, leads to an increase in the number of development options and the amount of information processed. This necessitates not only the automation of information processes but also the introduction of intelligent decision support systems (DSS)[1]. Currently, DSS are being actively developed for analyzing, modeling, planning, operating and servicing customers in the electricity distribution system from alternative sources [2-3], creating microgrids and connecting them to the Smart Grid [4-5], optimizing investment management for power grid companies [6], projects on the repair of electrical grids [7], the reconfiguration of the energy distribution system [8], the regulation of the hydro-power plant's operating mode [9], managing of the generating company [10]. However, there is no modern DSS research in the field of decision making on the technical re-equipment and reconstruction of electrical grids; therefore, the topic of paper is relevant and significant.

For electrical grids characterized by a hierarchical structure, multiply connected and nested objects. As noted in [11], "the emergence of a hierarchical structure was due to the increasing complexity of

the technology of controlled objects, which creates great difficulties for centralized management. Therefore, it has become necessary to divide the entire decision-making process into such a number of levels so that the solution to the optimization problem at each of them is not difficult."

In the article district of electrical grids is a set of technologically interconnected objects, located on the same territory and served by one structural unit. An electrical grid object (EGO) is a collection of substation and power lines that supplying it. The study proposed to consider a two-tier decision-making structure: at the first (local) level, the selection of preferred alternatives for the technical re-equipment and reconstruction of electrical grid facilities is made, and at the second (global) level – the selection of a priority package of measures for the technical re-equipment and reconstruction of the district of electrical grids, formed from the preferred alternatives for EGO.

2. Two-Level Decision-Making Structure, Mathematical Model of the Formation and the Method of Selecting a Priority Package of Measures for the Technical Re-Equipment and Reconstruction of Electrical Grid District

2.1. Two-level decision-making structure for the technical re-equipment and reconstruction of electrical grid district

Analysis of the literature in the field of decision-making on the technical re-equipment and reconstruction has revealed the following main stages of decision-making [12]: the formation of alternatives; evaluation of alternatives; selection of a preferred alternative. Based on the proposed two-level decision-making structure, the authors adapted the classical decision making steps in accordance with the purpose of the study.

Stages of the decision-making process for the technical re-equipment and reconstruction of electrical grid object at the local level:

1 Determining the need for a solution: formalization of the problem of making a decision on the technical re-equipment and reconstruction of the EGO by assessment the technical state of the equipment;

2 Generation of possible solutions: the formation of alternatives depending on the type of nomenclature work in the framework of technical re-equipment or reconstruction of EGO;

3 Selection of decision criteria: justification and development of mathematical models of criteria for evaluating alternatives for the technical re-equipment and reconstruction of EGO;

4 Comparison and selection of preferred EGO technical re-equipment and reconstruction alternatives;

5 Evaluation of results and feedback.

Stages of the decision-making process for the technical re-equipment and reconstruction of electrical grid district at the global level:

1 The selection of the district of the electrical grids, limiting the number of objects, limiting the number alternatives;

2 Generation of solutions: the formation of the possible package of measures from the preferred alternatives for the technical re-equipment and reconstruction of electrical grid objects;

3 Evaluation of alternative package of measures by decision criteria;

4 Ranking and selection of a priority package of measures for the technical re-equipment and reconstruction of the district of electrical grids;

5 Evaluation of results and feedback.

Based on the above, the authors have developed a structural decision-making model for the technical re-equipment and reconstruction of the district of electrical grids. It is presented in Figure 1.

The local level of decision making was considered in detail by the authors in [13]. This article describes the second stage of decision making at the global level. At this stage, it was proposed to select the priority package of measures for the technical re-equipment and reconstruction of the district of electrical grids as a solution to the optimization problem.

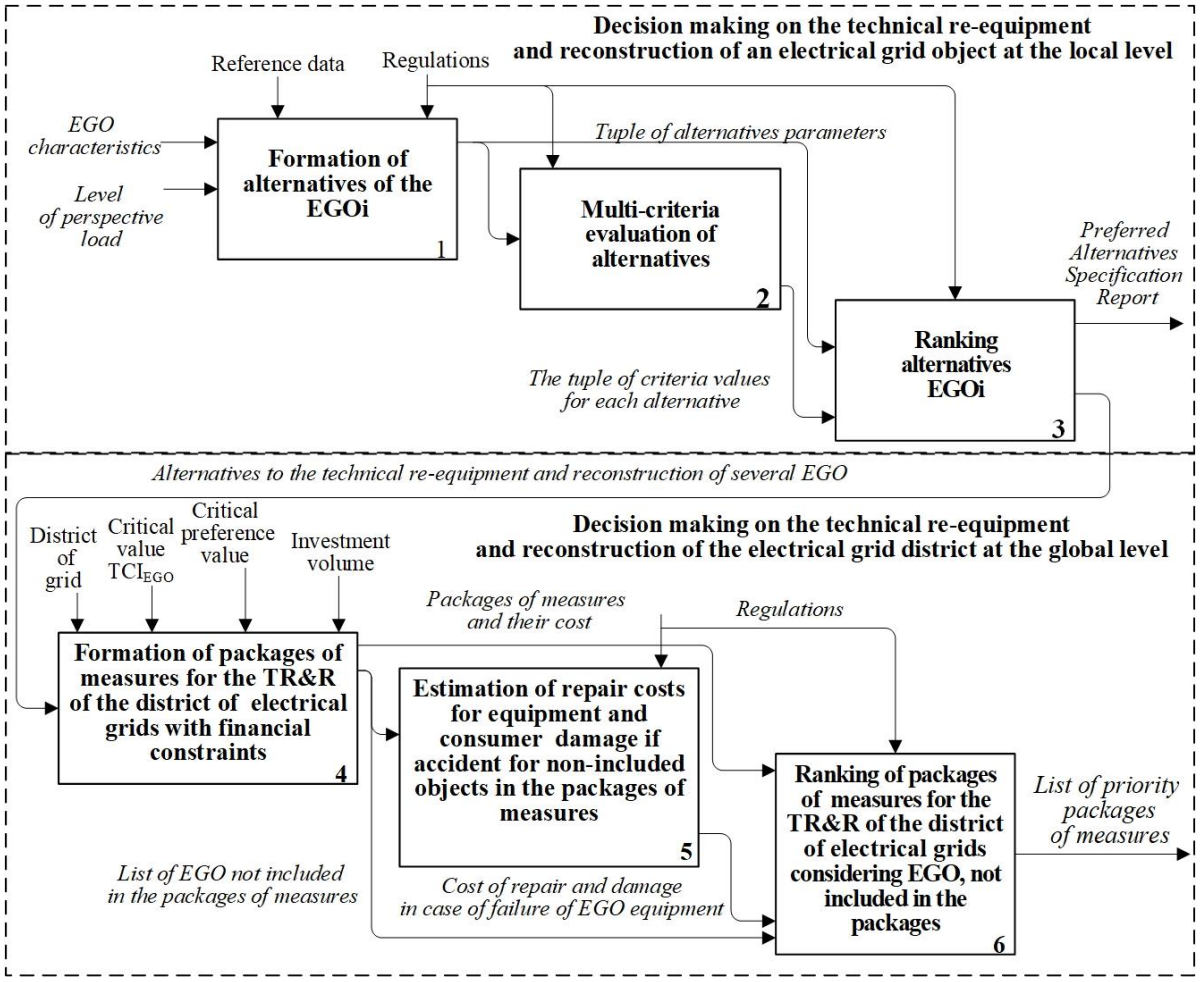

Figure 1. Structural model of decision-making on the selection of the priority package of measures for the technical re-equipment and reconstruction of the district of electrical grids.

2.2. Mathematical model of the formation of a package of measures for the technical re-equipment and reconstruction of the district of electrical grids

The selection of a package of measures for the technical re-equipment and reconstruction of the district of electrical grids is the problem of combinatorial optimization. To solve it, the authors identified and formalized:

1 Objective function: minimization of repair costs and consumer damage from interruptions in power supply if the equipment fails:

$$\sum_{j=1}^{n}(M_j + F_j) \to \min \quad (1)$$

where M_j is operating costs for the refurbishment of the j-th equipment that is not included in the equipment replacement program;

F is damage from undersupply of electricity in case of failure of worn-out equipment of the *j-th* EGO.

2 Constraints:

2.1 Critical value of the technical condition index. The EGO should be included in the package of measures, having a technical state index less than the threshold value. It is set by the decision maker (DM):

$$TCI_{EGOi} \le TCI_{cr} \tag{2}$$

where TCI_{EGOi} is the index of the technical condition of the *i-th* EGO [14];
TCI_{cr} is the threshold value of the technical condition index, set by the decision maker.

2.2 The critical value of the coefficient of preference for alternatives. The EGO should be included in the package of measures, having a preference coefficient is greater than the threshold value. It is set by DM:

$$T_i \ge T_{cr} \tag{3}$$

where T_i is the value of the preference coefficient of the *i-th* alternative for the technical re-equipment and reconstruction of EGO. The calculation of this coefficient is described by authors in detail in [13];
T_{cr} is the critical value of the coefficient of preference for alternatives, set by the decision maker.

2.3 Financial volume of the investment program:

$$\sum_{i=1}^{n} C^{EGOi} \le C_{\max} \tag{4}$$

where C^{EGOi} is the costs of new construction, technical re-equipment or reconstruction for the i-th alternative of EGO;
C_{max} is the size of the investment.

The costs for the i-th alternative of EGO are proposed to be defined as:

$$C^{EGO} = \sum_{t=0}^{3} (C_{Lt} + C_{St} + C_{dt} - C_{rest}) \cdot (1 + E_н)^{-t} \tag{5}$$

where C_L is capital investment for the power line;
C_S is capital investments for substations;
C_d is dismantling costs;
C_{res} is residual value of the equipment.

3 Boundary conditions: the considered quantities must be positive, and the sequence numbers of the objects must belong to the natural numbers:

$$\begin{aligned} &M_j, F_j, C_i, C_{\max}, TCI_{EGOi}, TCI_{cr}, T_i, T_{cr}, > 0 \\ &\text{i, j} = 1, 2...n \end{aligned} \tag{6}$$

2.3. The method of selecting a priority package of measures for the technical re-equipment and reconstruction of the electrical grids

All measures should use modern technical solutions and a comparative analysis of options, ensure the achievement of strategic development goals and fulfill key performance indicators, but exclude redundant technical solutions. If the volume of the investment program is not enough for the implementation of the whole package of measures, the objects are ranked according to the degree of prioritization. So, it is necessary to search for combinations of alternatives for the technical re-equipment and reconstruction of objects corresponding to typical technological solutions with financial constraints. The authors developed a method with the following stages for the formation of a package of measures for the technical re-equipment and reconstruction of the district the electrical grids.

Stage 1. Reduction of the number of elements used in the formation of a package of measures The reduction is carried out by considering the EGO, located on the territory of only one of the districts of electrical grids, as well as the constraints defined by (2-4).

Stage 2. Determining the priority of adding the EGO to the package of measures for the technical re-equipment and reconstruction of the districts of electrical grids. An analysis of internal regulations of electrical grid companies on investment programs was conducted. On its basis, the division of the EGO into three groups of prioritization depending on the technical condition, level of prospective load was developed and implemented in software.

The rationales for the first group of objects included implementation were:

- restoration of the power supply scheme and the achievement of the standard parameters of the damaged object as a result of the accident;
- the need to reduce the risks of a power failure caused by weather conditions;
- the need to comply with the requirements of supervisory and regulatory authorities;
- the need to replace objects in pre-emergency condition.

The second group of objects has measures to fulfill obligations under concluded and forward-looking contracts for technological connection.

The third group of objects has measures, which are necessary for technical re-equipment: an increase in the capacity of the electrical grid and the capacity of substations.

Stage 3. Formation of a preliminary package of measures for the technical re-equipment and reconstruction of the district the electrical grids. To find all the possible combinations of measures generated decision tree [15]. Its nodes contain combinations of EGO numbers and alternatives for each of them. The tree has a root – a zero node without designation.

Pre-determined the sequence of adding EGO_i in the branches of the tree according to their group prioritization. First, an EGO from the first group is added to the branch, then an EGO from the second group is added, and at the end, an EC EGO from the third group is added. The authors explain the process of forming a decision tree by the example of three objects (Figure 2).

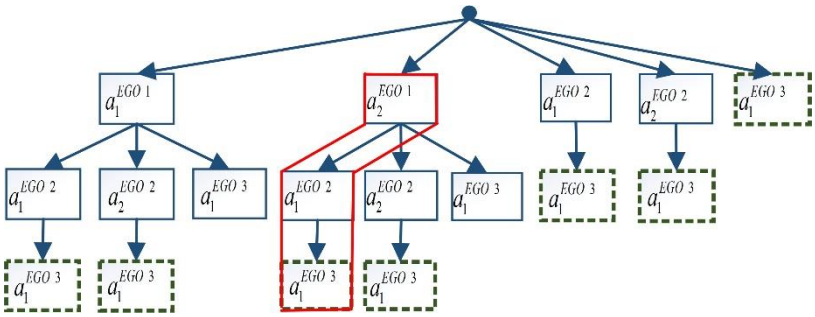

Figure 2. Decision Tree for 3 EGO.

Possible solutions for the technical re-equipment and reconstruction of the district of electrical grids are the branches of this tree. For example, the solution may contain for the first object a second alternative A_2^{EGO1}, for the second object – the first alternative A_1^{EGO2}, for the third object – the first alternative A_1^{EGO3}. In Figure 2, an example of the solution is highlighted with a broken line.

To find all potentially realizable combinations, the tree is traversed in direct order by a depth-first search. The tree is traversed down as much as possible on each child, before moving on to the next related branch. The tree is traversed in direct order: each of the parent nodes is viewed before its child.

The transition to the child node is carried out if the total cost of alternatives for all EGO in the branch is less than the volume of the investment program (4). If the volume of the investment program for $i + 1$ node is exceeded:

$$\sum_{i=0}^{n} C^{EGO_{i+1}} > C_{\max} \tag{7}$$

this node-parent *i* (with respect to the considering node *i + 1*) was the final vertex of the branch - a leaf.

At this stage, the formation of the branch is completed. All EGO and their alternatives a_m^{EGOi} in the branch nodes were added to the list of the preliminary package of measures for the technical re-equipment and reconstruction of the electrical grids:

$$A^{EGO_i} = \{a_1^{EGO_1}, a_3^{EGO_2} ..., a_m^{EGO_i}\} \quad (8)$$

4 stage. Determination of the list of point-replaceable equipment. Formation of the list of equipment of electrical grids objects not included in the package of measures. Compiled a list of equipment objects that do not fall into the branch of the decision. It was ranked by technical condition index:

$$E = \{e_1^{EGO'_1}, e_2^{EGO'_2} ... e_k^{EGO'_j}\}, TCI_{e_k} < TCI_{e_{k+1}} \quad (9)$$

where e_k is a unit of equipment installed on EGO'_j.

For each piece of equipment, a list of alternatives A^{ek} was compiled. It ranked by a coefficient of preference T_{am}:

$$A^{e_k} = \{a_1^{e_k}, a_2^{e_k} ..., a_m^{e_k}\}, T_{a_m} > T_{a_{m+1}} \quad (10)$$

The unspent funds of the investment program were determined for each package of measures:

$$C_{res} = C_{\max} - \sum_{i=1}^{n} C^{EGO_i} \quad (11)$$

If the unspent funds of the investment program were sufficient for a point replacement of one or several units of worn-out equipment:

$$C_{res} - \sum_{m=1}^{k} C_{a_m^{e_k}}^{EGO'_j} \to 0 \quad (12)$$

then a cost-effective alternative to the replacement of equipment a_m^{ek} was added to the package of measures.

5 Determination of the list of equipment not included in the package, and subject to repair.

The equation (12) determines the list of the equipment to be repaired by the EGO, which is not included in any package of measures for the technical re-equipment and reconstruction of the district of electrical grids:

$$V^{EGO'_j} = \left\{ v \middle| \; v \notin A^{EGO_i} \wedge v \notin A^{e_k} \right\} \quad (13)$$

The equipment included in this set cannot be replaced within the investment program. It is recommended for him to conduct repairs at the expense of operational costs.

3. Results

The result of the formation of the package of measures for the technical re-equipment and reconstruction of the district of electrical grids are:

1 Objects with equipment replacement alternatives included in the A^{EGOi} solution branch;

2 List of pointwise replaceable worn equipment a_m^{ek};

3 For each package a list of EGO'_j with equipment $V^{EGO'j}$ not included in the investment program, subject to repair at the expense of operating resources.

The selection of the priority package was carried out by ranking the packages of measures according to the value of the objective function. The objective function was determined by (1) by calculating the amount of operating costs *M* associated with the repair of equipment $V^{EGO'j}$ not included in the

package of measures, and the damage *F* from an interruption in the power supply in case of accidents. The ranking was carried out by a selection sort algorithm. As a result, an ordered sequence of packages was created by attaching one package after another in order of increasing costs. Thus, a priority package of measures was determined for the most responsible and worn-out object with limiting the investment program.

Priority package of technical re-equipment and reconstruction measures for the Central district of electrical grids without financial constraints is presented in Table 1. Financial volume of the investment program consist 653159.9 ths rubles.

Table 1. Priority package of technical re-equipment and reconstruction measures for the Central district of electrical grids without financial constraints.

Number of EGO	Power Transformer MVA	Circuit Breaker HV	Circuit Breaker MV	Circuit Breaker LV	Cost ths rubles
1	Change to 2x40	Change to SF6	Change to VCB	Change to VCB	292817.7
2	Change one to 40	No change	-	No change	84127.4
3	Change to 2x10	Change to VCB	-	Change to VCB	49743.3
4	Change to 2x25	Change to SF6	Change to VCB	Change to VCB	226471.5

Priority package of technical re-equipment and reconstruction measures for the Central district of electrical grids with financial constraints in 610000 ths rubles is presented in Table 2. Financial volume of the investment program consist 607220.3 ths rubles.

Table 2. Priority package of technical re-equipment and reconstruction measures for the Central district of electrical grids with financial constraints.

Number of EGO	Power Transformer MVA	Circuit Breaker HV	Circuit Breaker MV	Circuit Breaker LV	Cost ths rubles	Repair costs and consumer damage ths rubles
1	Change to 2x40	Change to SF6	Change to VCB	Change to VCB	292817.7	9377.1
2	Change one to 40	No change	-	No change	84127.4	
3	No change	Change to VCB	-	Change to VCB	3804.3	
4	Change to 2x25	Change to SF6	Change to VCB	Change to VCB	226471.5	

4. Discussion

Software implemented method in an automated decision support system. Testing of DSS and approbation on the example of EGO of the Central District of electrical grids of the Orenburg region was carried out. The obtained results do not contradict the proposals for the substations of the Central District of electrical grids indicated in the documents on the development of the power industry of the Orenburg region.

5. Conclusion

A two-level structural scheme of decision making on the technical re-equipment and reconstruction of the district of electrical grids has been developed. It contains the local level of decision making on the selection of preferred alternatives for the technical re-equipment and reconstruction of electrical grid object; the global level of decision-making on the selection of a priority package of measures for the

technical re-equipment and reconstruction of the EC region, formed from the preferred alternatives to the technical re-equipment and reconstruction of the EGO, taking into account financial constraints.

A mathematical model for the formation of a package of measures for the technical re-equipment and reconstruction of the district of electrical grids is proposed. It consists of a set of equations:

- the objective function to minimize the cost of repairs and damage from interruptions in power supply in case of equipment failure;
- three constraints to take into account the threshold values of the technical condition index, the preference coefficient of alternatives and the financial volume of the investment program;
- the boundary condition for considering only positive values of quantities.

A method for selecting a priority package of measures for the technical re-equipment and reconstruction of the district of electrical grids has been designed. It is based on graph theory and combinatorial optimization. To implement the method proposed the following steps:

- reduction of the number of elements in the formation of a package of measures for the technical re-equipment and reconstruction of the district of electrical grids;
- determination of the sequence of adding electrical grid objects to the package of measures;
- formation of a preliminary package;
- determination of the list of point-replaceable equipment;
- definition of the list of repaired equipment, not included in the packages.

The developed model and method are implemented in a decision support system that has been tested. The results of the DSS are consistent with the schemes and energy development programs for the electrical grids of the Orenburg region.

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