Intelligent control support for reconstruction of electrical circuits of stations and substations

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Abstract. The article deals with the application of expert systems and the theory of fuzzy sets for decision-making in the reconstruction of electrical connections of power plants and substations. Multicriteria optimization problems are characterized by the uncertainty of a part of the initial information with the boundaries of the range of values from the minimum to the maximum. This theory allows us to compare the options of scheme of power distribution power plants according to different criteria in the conditions of uncertain information, as well as in the conditions of conflicting rules and criteria. For fuzzy sets, the membership function becomes the only possible means of describing them.

1. Introduction
When considering options for the reconstruction of circuits electrical circuits of power plants and substations, the optimal solution for minimizing the reduced costs and reliability is not always the only one. The impossibility of unambiguously determining the optimum causes uncertainty in solving the problem of choosing an effective technical solution. To reveal the uncertainty and make a reasonable choice of an option, it is proposed to use a multicriteria approach based on expert systems and the fuzzy set theory [1-4].

Multicriteria optimization problem of the reconstruction of scheme of power distribution power plants are resolved based on the scheme of power distribution complex system, which is characterized by multiple objectives. Based on the analysis of the goals of the system functioning, the choice of particular criteria (criteria properties) for evaluating options should be made, based on the concept of effectiveness. The effectiveness of the scheme of power distribution can be identified with its economic efficiency, estimated by the value of the reduced costs for the electric energy transferred to consumers. Also, the main objectives of the scheme of power distribution are to provide consumers with electricity with a high level of reliability.

When solving the problem of choosing the optimal scheme of power distribution, specific criteria may include: reliability indicators, damage from undersupply of electricity, capital investments, reduced costs, as well as ease of maintenance, visibility, maintainability, etc.

Multicriteria optimization problems are characterized by the uncertainty of a part of the initial information with the boundaries of the range of values from the minimum to the maximum.

2. Fuzzy decision-making methods for the reconstruction of electrical installations
The theory of fuzzy sets allows you to compare the options of scheme of power distribution power plants according to various criteria: calculable and uncountable. For calculable criteria, you can use the
membership functions to determine whether you belong to the optimal option. For uncountable criteria, a table of accessories is compiled with the help of experts. The solution of optimization problems based on multi-criteria models consists in the convolution of several particular criteria (criterion properties) into a single (complex efficiency criterion). Particular criteria are described by the essential characteristics of the system, which can be represented by both quantitative and qualitative indicators.

Currently, various forms of convolution are used for multi-criteria evaluation: arithmetic mean, linear, multiplicative, additive, and harmonic mean [3].

The arithmetic mean linear convolution form has the form

$$ F_{ar}^* = \sum_{i=1}^{n} v_i e_{ij} \quad \text{at} \quad \sum_{i=1}^{n} v_i = 1; \quad (1) $$

the multiplicative convolution method has the form

$$ F_{M}^* = \prod_{i=1}^{n} (e_{ij})^{v_i} \quad \text{at} \quad \sum_{i=1}^{n} v_i = 1; \quad (2) $$

the additive uniform scalar criterion is defined from the expression

$$ F_{A}^* = \left[ \sum_{i=1}^{n} v_i e_{ij} \right]^{-2} \quad \text{at} \quad \sum_{i=1}^{n} v_i = 1; \quad (3) $$

the average harmonic convolution form

$$ F_{h}^* = \left\{ \sum_{i=1}^{n} \frac{v_i}{e_{ij}} \right\}^{-1} \quad \text{at} \quad \sum_{i=1}^{n} v_i = 1, \quad (4) $$

where $F$ – evaluation functional represented by a single complex (scalar) criterion; $e_{ij}$ – evaluation of the $i$ partial criterion in the $j$ variant; $n$ – the number of particular evaluation criteria in the problem under consideration; $v_i$ – weight of a particular criterion.

Justification of the structure of the complex efficiency criterion $F^*$ it is an independent task. The value of the target function $F_j^*$ for each $j$ variants the scheme of power distribution is a comprehensive assessment of its quality and makes it possible to order options according to their effectiveness.

Range of possible values $F$ it is convenient to choose a single segment. Then any inefficient option corresponds to $F^*=0$, and the perfect one $- F^*=1$. The required regulation range $F^*$ it should be provided by the structure of the objective function and the corresponding scaling of the weight coefficients. As the optimal variant of the scheme of power distribution, the one with the highest efficiency score is selected according to the expressions (1-4).

For the formation of estimates of the relative weighting of individual criteria $v_i$ various methods of expert assessments can be used: methods of direct assessment, rank correlation, sequential comparisons, modifications of partial and paired comparisons, etc. [2-3]. Practical experience in the use of expert assessments has shown the feasibility of using the rank correlation method, which has advantages in assessing the coordination of experts.

The evaluation of the effectiveness of the $e_{ij}$ variants for each property is based on the determination of the property indicators associated with the variants by certain dependencies. When assigning $e_{ij}$ estimates, you can use possible economic and technical calculations, as well as expert estimates.

Since the property indicators have a different physical nature and therefore a different dimension, it is necessary to eliminate it by normalizing it using the membership function.

For fuzzy sets, the membership function becomes the only possible means of describing them. The numerical value of the membership function $\mu^A(x)$ characterizes the degree of membership of the
element \( x \) to a certain fuzzy set \( A \), which in the expression of natural language is usually some elementary characteristic of the phenomenon (the degree of reliability of the electrical installation, cost, etc.).

The specific type of membership function is determined on the basis of various additional assumptions about the properties of these functions (symmetry, monotonicity, continuity of the first derivative, etc.), taking into account the specifics of the existing uncertainty, the real situation on the object and the number of degrees of freedom in the functional dependence. The following methods of constructing the membership function described in the literature [5-8] are known: on the basis of paired comparisons; expert assessments, using statistical estimates; the method of interval estimates; semantic differential, etc.

3. Selecting the scheme of power distribution hydroelectric plant (HEP)

As an example of using the expert system and fuzzy set theory, we will consider the choice of the optimal option for the reconstruction outdoor switchgear with a voltage of 500 kV HEP. The existing scheme of the outdoor switchgear -500 kV is shown in figure 1. In the practice of operating the outdoor switchgear -500 kV, the following shortcomings of the "four switches for three connections" scheme were identified: in repair modes, a large number of elements are taken out of operation; a complex system of relay protection and control; limited power output when performing remote work; the scheme does not have visibility and can provoke errors of operational personnel.

![Figure 1. The existing scheme of the outdoor switchgear -500 kV.](image)

In accordance with the number and type of connections (five power units and four power lines), the size of the site (the impossibility of increasing the area of outdoor switchgear 500 kV and the construction of a new switchgear nearby), as well as the shortcomings of the existing scheme identified during operation and the proposals made by specialists operating this electrical installation, possible options for the reconstruction of the outdoor switchgear – 500 kV scheme are considered as alternatives. Three technically feasible reconstruction options were proposed for the outdoor switchgear 500 kV scheme with nine connections at the existing site:

- Reconstruction of outdoor switchgear with the connection of the middle chain of the existing connection scheme according to the scheme two switches per connection - "combined circuit" (figure 2, a);
- Reconstruction of outdoor switchgear with connection connections according to the scheme three switches for two connections (figure 2, b);
- Reconstruction of outdoor switchgear with connection connections according to the scheme two switches per connection (figure 2, c).
These schemes are technically feasible and meet the requirements. When switching from the existing scheme to the proposed options, there is no need to disable the entire switchgear. When comparing these options using the reduced cost method (table. 1) it was not possible to identify the best option, as two of them fell into the zone of uncertainty. Therefore, we used a method based on expert systems and fuzzy set theory, which allowed us to determine the optimal option for the reconstruction of outdoor switchgear – 500 kV.

![Diagram of Variants](image)

**Figure 2.** Variants of schemes proposed for the reconstruction of outdoor switchgear – 500 kV.

The experts determined the following list of criteria for the properties to be evaluated in order to select the option for the reconstruction of outdoor switchgear -500 kV:

- minimum undersupply of electricity from the station buses;
- minimum capital investment;
- minimum reduced costs;
- minimum frequency of accidents with the loss of one generator;
- minimum frequency with loss of one generator and one aerial line;
- minimum duration of an accident with the loss of one generator;
- minimum duration of an accident with the loss of one generator and one aerial line.

Expert estimates of the weights of these properties obtained by the rank correlation method: $v_I =$
0.21; \(v_2 = 0.17; \ v_3 = 0.16; \ v_4 = 0.12; \ v_5 = 0.15; \ v_6 = 0.10; \ v_7 = 0.09\).

As a result of calculations of technical and economic indicators, frequencies and durations of accidents (the Reliability program for calculating the reliability of electrical installations based on the probabilistic method of calculating reliability [3]), the following criteria were obtained for the compared options (Table 1)

Table 1. Criteria proposed for comparison of open switchgear schemes -500 kV.

| Variant | Undersupply of electricity from the station buses, megawatt-hour/year (1) | Capital investment, ths. of rubles (2) | Reduced costs, ths. of rubles (3) | Frequency of accidents, 1/year (4) | Duration of an accident, hour (5) | 1G* | 1G1A** |
|---------|---------------------------------------------------------------------------------|---------------------------------------|----------------------------------|---------------------------------|---------------------------------|------|---------|
| №1      | 12374                                                                          | 15347.2                                | 176450.7                         | 1.27                            | 0.938                           | 73.2 | 0.5     |
| №2      | 12371                                                                          | 48789.4                                | 177106.5                         | 1.27                            | 0.983                           | 73.2 | 0.5     |
| №3      | 12575                                                                          | 58098.6                                | 244106.9                         | 1.87                            | 0.193                           | 51.7 | 0.5     |

*1G – loss of one generator;
**1G1A – loss of one generator and one power line.

The membership function \(m(x)\) was chosen so that it shows the degree of belonging to the optimal solution for a particular criterion, and this can be a function of the minimum or maximum belonging to a certain range or number. As a result of calculations based on a specific criterion, \(m(x)\) becomes equal to 1 for the most optimal criterion and equal to 0 for the non-optimal criterion.

In this case, the choice of the form of the accessory function was made by an expert method by setting the rules of behavior of the accessory function and was carried out for groups of factors:

- reliability indicators (frequency and duration of accidents, power underflow);
- cost indicators (capital investment, reduced costs).

A mathematical expression describing the membership function

\[
\mu(x) = \begin{cases} 
1, & X_i \leq X_{\min} \\
1 + \left( \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \right)^{2^2} & \text{if } X_i > X_{\min}
\end{cases}
\]

where \(X_i\) – the criterion for which it is calculated \(\mu(x)\); \(X_{\min}, X_{\max}\) – the minimum and maximum values of the criterion.

To compare the options based on fuzzy set theory, a computer program called Fuzzy was developed, which was used to normalize particular ej criteria by membership functions.

Table 2 shows the results of calculating the numerical values of the membership function for each of the seven optimal criteria.
Table 2. Normalized values of particular $e_{ij}$ criteria

| Variant | Undersupply of electricity from the station buses, megawatt-hour / year (1) | Capital investment, ths. of rubles (2) | Reduced costs, ths. of rubles (3) | Frequency of accidents, 1/year (4) | Duration of an accident, hour (5) | (6) | (7) |
|---------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|-----|-----|
| №1     | 0.99                           | 1                               | 1                               | 1                               | 0.38                            | 0.89| 1   |
| №2     | 1                               | 0.55                            | 0.99                            | 1                               | 0.36                            | 0.89| 1   |
| №3     | 0.99                           | 0.42                            | 0.91                            | 0.87                            | 1                               | 1   | 1   |

Table 3. A comprehensive assessment of the options of scheme of power distribution.

| Variant | Evaluation of private criteria $e_{ij}$ | The convolution form | $F_{ar}$ | $F_{h}$ |
|---------|---------------------------------|----------------------|----------|---------|
|         | Evaluation of weights of the criterion properties |                        |          |         |
|         | $v_1=0.21$ | $v_2=0.17$ | $v_3=0.16$ | $v_4=0.12$ | $v_5=0.15$ | $v_6=0.10$ | $v_7=0.09$ | $F^*_{ar}$ | $F^*_{h}$ |
| 1       | 0.99 | 1 | 1 | 1 | 0.38 | 0.89 | 1 | 0.90 | 0.80 |
| 2       | 1   | 0.55 | 0.99 | 1 | 0.36 | 0.89 | 1 | 0.81 | 0.70 |
| 3       | 0.99 | 0.42 | 0.91 | 0.87 | 1 | 1 | 1 | 0.87 | 0.78 |

As a result of comparing the options using the method based on fuzzy set theory, a complex criterion was calculated (table 3), which shows that the reconstruction option, when the middle chain of the existing circuit is converted into a circuit of two busbar systems (two switches per connection), is optimal under seven criteria.

4. Conclusions

Expert systems and the fuzzy set theory information allow solving various applied problems in the electric power industry. These include managing the reconstruction of power facilities, choosing a strategy for restoring power supply after an accident, carrying out diagnostic operations, etc.

The use of fuzzy sets when choosing technical solutions for the reconstruction of power distribution schemes for power plants makes it possible to formalize this operation with a lack of information, as well as under conditions of conflicting rules and criteria.

The results obtained at the end of the considered calculation lead to the conclusion that the first option during the reconstruction of the 500 kV outdoor switchgear HEP will be optimal.

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