Configuration management of electricity distribution grids 6-35 kV according to the criteria of reliability

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Abstract. Questions of a choice of criteria for definition of places of opening of electric networks 6-35 kV are considered in this paper. Recommendations are given on the configuration management of distribution electrical networks based on the hierarchy analysis method.

1 Introduction

In most Distribution Grid Organizations, the task of optimizing the configuration of the distribution grid (6/10-35 kV) is solved only if there are damages to its individual elements participating in power transmission normal mode. Post-accident configuration management, as a rule, is carried out by the criterion of a minimum number of switching operations to eliminate damage and restore power supply to consumers (installation and coordination of relay protection devices is simplified). Automation of the normal mode, reacting to a change in the flow distribution, in grids of 6-35 kV is practically not represented.

The current legislation in the field of tariff formation (loss standard and transport tariff for Distribution Grid Organizations do not depend on grid mode but are determined based on the unit output per unit length of the electric line) practically excludes the account of electric power losses as the main factor in determining the disconnection points in the normal mode of the distribution grid. At best, in practice, the approach is to maximize the reliability of grid due to the use in the normal mode of electrical components with the best reliability. At the same time, for various reliability indices, the optimal open-loop configurations of the 6 - 35 kV electric grid are not the same in the general case.

The actual task is to develop a universal approach to determining the most efficient distribution grid configuration for Distribution Grid Organizations and end consumers, considering the following factors:

- compliance of the parameters of the mode with grid solutions (voltage in the nodes of connection of consumers and long-tolerated power line currents);
- value of the load losses of electric power in the normal steady-state grid mode;
- reliability of the main power transmission elements.

Its implementation will lead to both a reduction in electricity losses during power transmission, and an increase in the reliability of electricity supply to individual consumers and the electric grid. As a mathematical tool of the approach being developed, it is proposed to use the hierarchy analysis method proposed by T. Saati [1].

2 Application of the hierarchy analysis method to assess the reliability of open-loop configurations of a 6-35 kv distribution grid

The hierarchy analysis method allows obtaining a multi-criteria evaluation of the ways of power transmission from the power centers to the end users of the 6-35 kV grid based on pairwise comparisons of both possible configurations and single reliability indicators. Its application allows to include in the analysis all available indicators and characteristics of the elements of the power supply system.

In the problem of assessing the reliability of open-loop configurations of an electrical grid, it is advisable to use this method to determine the optimal path to each consumer individually and the overall configuration of the entire power supply system. To do this, it is necessary to determine the list of criteria by which to evaluate the properties of the object. When comparing the reliability of power transmission lines for such criteria, the following are accepted:

- time of failure-free work (t_{fw}, year);
- parameter of the flow of restoration (ω_r ,1 / year);
- the inverse of the recovery time (recovery rate - $\mu = 1 / t_r$, 1 / hour).

The choice of such reliability indicators is since their influence on each other is insignificant and the maximum values of these indicators are used in further calculations.

The practical implementation of this approach begins with the use of the algorithm for constructing all the

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trees in the graph of the grid area [2] to determine the possible open configurations of a distribution grid of arbitrary type. Additionally, a complete list of transmission paths from each of the power centers to all load nodes can be obtained.

After this, the transition to the alternate calculation of the selected reliability indicators of all possible paths of electricity transmission to each consumer (load node) of grid under investigation is carried out. For simplicity, all branches of the graph of grid area are set by blocks (for example, electric line element is considered together with the switching equipment at both ends). This approach allows you to better navigate the elements of the simulated grid, determine the reliability of the blocks, and, to a large extent, reduce the number of objects in the future calculation.

For the automation of calculations, an algorithm for transforming an arbitrary configuration grid scheme has been developed, which compares two elements and determines their form of connection among themselves. Then the circuit is converted into one equivalent element and, depending on the type of connection, the new end element is assigned the values of the beginning and the end. This procedure runs through the entire grid and repeats until the last element remains [3].

The hierarchy of choosing the optimal transmission of electricity to a consumer with eight possible options for electricity supply is shown in Fig. 1.

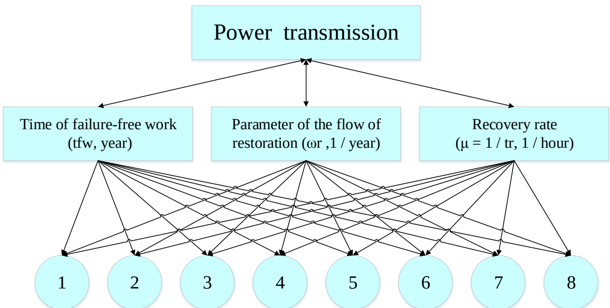

Fig. 1. Hierarchy of choice of transmission path

To select the optimal power transmission, it is necessary to compare the elements of the third level in pairs by the force of their influence on the element of the second level, i.e. put numbers that reflect a pairwise comparison of possible transmission paths in the matrix and find the eigenvector (EV) with the largest value.

When comparing the paths of transmission of electricity to the consumer by one criterion, for example, the time of failure-free work, the matrix is filled with the relations between the values of this reliability index. The next step is to calculate the priority vector for the given matrix. From a mathematical point of view, the EV after normalization will be the vector of priorities. Its value can be obtained by extracting the root of the n-th degree from the product of n elements (B_i) of each row by the expression:

$$\mathrm{EV} - \sqrt[n]{B_1 \cdot B_2 \cdot \ldots \cdot B_n} \qquad (1)$$

The numbers obtained are normalized. The sum of the values of the eigenvector is divided by the sum of the corresponding column of the matrix. By adding the products of the obtained normalized values to the sum of each column of the matrix, the main eigenvalue λ_{max} is determined. The closer λ_{max} to n, the more consistent the result.

The deviation from consistency is expressed by the consistency index (CI), which is defined as:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \qquad (2)$$

To assess the consistency of the resulting matrix and, correspondingly, to check the adequacy of the comparisons of the variants given in [1], the consistency relation (CR) is used, which is defined as the ratio of the CI to the average random index (RI) of the matrix of the same order. CR $\leq$ 0,1 for the solution of the tasks is considered acceptable [1].

In the presence of statistical or reference information on single indicators of the reliability of grid elements, a complete consistency of the matrix of comparisons of the transmission paths of electricity (CR= 0) should be observed. This is due to the fact that in each comparison the same reliability indicators (time of failure-free work, recovery flow parameter or intensity of recovery) participated.

Since the chosen criteria characterize different reliability properties, in calculating its resulting estimate, it becomes necessary to consider the "weight" of each criterion and the path of electricity transfer. The "weight" of the criterion is determined based on expert assessments by the personnel of the Distribution Grid Organizations electrical service. To obtain a matched matrix, weighting coefficients based on expert estimates are assigned in the range from 1 to 9 in accordance with the scale of relative importance of the criteria [1].

The last step is to calculate the overall reliability estimate for all possible ways of transmitting electric power N for each consumer of grid area in question. For this purpose, the sum of the products of the "weight" of the estimate according to the accepted criterion k_i (i is the number of selected reliability indicators) is found on the normalized value of this criterion. For the selected reliability indicators, the estimation of the j-transmission path to the consumer is determined by the expression:

$$N_j = k_1 \cdot t_{\mathrm{fw.norm}j} + k_2 \cdot \omega_{\mathrm{Bnorm}j} + k_3 \cdot \mu_{\mathrm{norm}j} \qquad (3)$$

where are the normalized estimates of the corresponding reliability index of the j-transmission path to the consumer in question.

The calculation algorithm is implemented for each consumer (load node) of the distribution grid under study.

3 Determination of the places of disconnection in distribution electric grids

Determination of the optimal transmission path to each load node does not guarantee the construction of an optimal configuration for the entire grid area. This is due to the fact that the choice of a certain path for the first consumer, in general, significantly reduces the possible number of configurations for the next in order. It is necessary to specify the priority hierarchy of the load nodes themselves, which are chosen as:

- reliability category of load receptors;
- total installed capacity of consumers (S, MVA).

Based on the results of the ranking of load nodes by their importance, two options are possible for choosing the optimal open distribution grid configuration for reliability:

1) Begin the construction by choosing the optimal configuration from the most significant consumer to the next in order, until all consumers are connected to the power centers;

2) Calculate the reliability estimates of all possible grid configurations considering the priority of load nodes and choose among them the configuration with the maximum value of the obtained index.

Additionally, the configurations obtained by these methods are checked for the possibility of the existence of a stable transmission mode at the maximum and minimum grid loads. The second option allows you to find the configurations that most satisfy the requirements of optimality, but at the same time is more labor-intensive and voluminous from the point of view of the calculations. The total number of options for the solutions under consideration will also be the largest. At the same time, this variant of searching optimal locations for the distribution grid allows obtaining the best configurations not only by the criterion of ensuring the maximum reliability of electricity supply to consumers, but also taking into account the energy losses in the steady-state grid mode.

In general, the sequence for determining the locations of the spread in the distribution grid 6-35 kV is as follows:

1) Based on the algorithm for constructing all the trees in grid area graph [2], a complete list of open grid configurations is defined, as well as possible ways of power transmission for each load node.

2) Calculation of steady-state grid conditions for all configurations (at minimum, maximum and medium loads) is performed, configurations that do not provide conditions for the existence of a long-tolerated regime are excluded from further consideration.

3) Load losses for the medium load regime are calculated and their normalized values are determined.

4) Reliability rating (R_{Σ}) is carried out for each configuration [5]:

$$R_{\Sigma} = \sum_{k=1}^{n} R_k \cdot A_k \qquad (4)$$

where R_k is the estimates of the reliability of the transmission path to the k-customer, A_k is the estimate of the priority of the k-consumer, n is the total number of consumers in grid area.

Summation of the numerical values of the reliability estimates of the transmission paths to all consumers in grid area, considering their hierarchy, is mathematically acceptable [4], since for all configurations the reliability indicators of individual elements and node loads are unchanged.

5) The obtained reliability estimates for all considered grid configurations are normalized.

6) The optimal configuration of the distribution grid is calculated considering the weight coefficients of the reliability and loss estimates determined individually for each distribution grid organizations.

4 Implementation of the algorithm for choosing the open configuration of the 6-35 kV power grid region

Approbation of the developed algorithm for locating faults was carried out using the example of a 35 kV electric grid section of the Nizhny Novgorod energy system (Fig. 2).

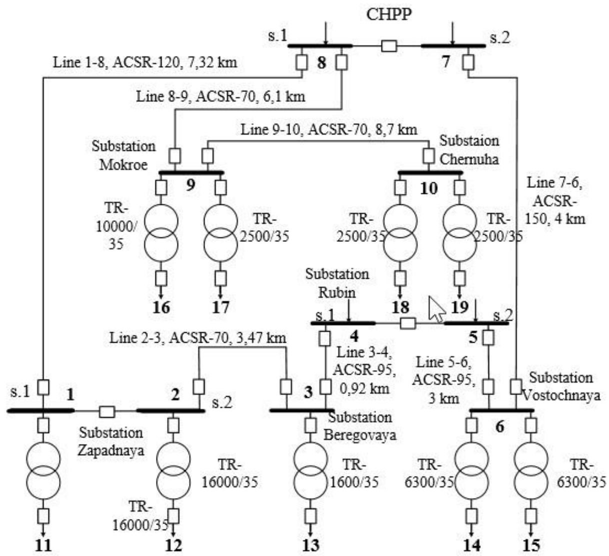

Fig. 2 Single-line scheme of a 35 kV grid section

Under the nodes of grid area is meant the distribution device of high-voltage substations (35 kV) and low (6-10 kV) voltages. Distribution device low-voltage are nodes for connecting the load. The load on the substation side of substations is absent. Under the branches, three types of electrical equipment are understood: transformers and overhead transmission lines in conjunction with the Switch-gear equipment, as well as sectional switches. The power centers of grid section under consideration are the Novogorkovskaya CHPP and the Rubin substation. Data on the average loads of nodes on the annual interval, used in calculating the load losses, are given in Table. 1. Initial data on indicators of reliability of electrical equipment and transmission lines were adopted based on materials of JSC "Firm ORGRES". According to the analysis results, 14 possible grid configurations were obtained, only 12 of them meet the requirements (Table 2)

Table 1. Grid node load

S11=4,318+*j*2,149 MVA	**S12**=2,569+*j*1,158 MVA	**S13**=0,485+*j*0,175 MVA
S14=2,363+*j*1,951 MVA	**S15**=2,35+*j*0,796 MVA	**S16**=1,218+*j*0,406 MVA
S17=1,197+*j*0,577 MVA	**S18**=0,945+*j*0,456 MVA	**S19**=0,397+*j*0,219 MVA

Table 2. Characteristics of possible open grid configurations

№ configuration	Disabled branches	Load losses, MW	Characteristic of the transmission mode
1	7-8, 4-5, 1-2, 5-6	0,141	Meets the requirements
2	7-8, 4-5, 1-2, 7-6	0,143	Meets the requirements
3	7-8, 4-5, 2-3, 7-6	0,181	Meets the requirements, heavily loaded line 1-8 (0,180 kA)
4	7-8, 4-5, 2-3, 5-6	0,174	Meets the requirements, heavily loaded line 1-8 (0,180 kA)
5	7-8, 4-5, 3-4, 5-6	0,192	Meets the requirements, heavily loaded line 1-8 (0,195 kA)
6	7-8, 4-5, 3-4, 7-6	0,193	Meets the requirements, heavily loaded line 1-8 (0,195 kA)
7	7-8, 4-5, 1-8, 5-6	0,182	Meets the requirements, heavily loaded line 3-4 (0,194 kA) и 2-3 (0,183 kA). It is not desirable to work continuously in the maximum load mode (Load line 2-3 is close to the limit)
8	7-8, 4-5, 1-8, 7-6	0,184	Meets the requirements, heavily loaded line 3-4 (0,194 kA) и 2-3 (0,183 kA). It is not desirable to work continuously in the maximum load mode (Load line 2-3 is close to the limit)
9	7-8, 1-8, loss power center 4 и 5	0,320	Meets the requirements.
10	7-8, 4-5, loss power center 4 и 5	0,194	Meets the requirements
11	7-8, 2-3, loss power center 4 и 5	0,184	Meets the requirements
12	7-8, 1-2, loss power center 4 и 5	0,173	Meets the requirements, heavily loaded line 7-6 (0,139 kA),
13	7-8, 4-5, loss power center 7 и 8	0,320	Doesn't match requirements, heavily loaded line 3-4 (0,299 kA) и 2-3 (0,285 kA, overloaded in the maximum mode)
14	7-8, loss power center 4, 5 и 8	0,73	Doesn't match the requirements. voltage decreases below acceptable, overloaded lines 7-6, 3-2

For each consumer of grid region in question (nodes 11-19), single reliability indicators of all possible options for power transmission from the power center were calculated. To obtain the resulting reliability estimates, a pairwise comparison of single indicators was performed (Table 3).

Table 3. "Weighing characteristics" of single reliability indicators

	t_{fw}, year	ω_r 1/y	1/t_r, 1/h	EV	Norm. value
t_{fw}, year	1,000	9,000	7,000	3,97905	0,792757363
ω_r 1/year	0,111	1,000	0,500	0,38157	0,076021412
1/*tr*, 1/h	0,143	2,000	1,000	0,65863	0,131221225
Summ	1,254	12	8,5	5,01926	1
λmax	3,0217				
CI	0,0109				
CR	0,0187				

The relative importance of the criteria is chosen by the Distribution Grid Organization's staff, which ensures the operation of distribution networks. The results obtained are acceptable in terms of CR size and are the same for all load nodes of the network area.

Estimates of reliability indicators of possible options for electricity transmission to each consumer. node 11 (Zapadnaya substation, n.1) are given in Table. 4.

Similar estimates were obtained for the remaining load nodes of the network under consideration. Criteria for assessing the priority of consumers are determined from the condition that the total capacity of the node is 3 times less important component than the maximum category of reliability of consumers in the node. This ratio is chosen based on expert assessments of Distribution Grid Organization's personnel, for which the priority is minimal damage to consumers from disruption of electricity supply. Calculation of the priority of load nodes of the network region is presented in Table 5.

Table 4. Evaluation of the distribution of reliability of transmission paths by electric power distribution for node 11

№ s/p	Path to nodes from CP	t_{fw}, year	ω_r 1/y	1/t_r, 1/h	Crite-rion	Weight	Rating
1	8-1-11	0,15	0,14	0,16	t_{fw}, year	0,7927	0,1544
2	8-7-6-5-4-3-2-1-11	0,09	0,11	0,09	ω_r 1/y	0,0760	0,0884
3	7-8-1-11	0,15	0,14	0,17	1/t_r, 1/h	0,1312	0,1534
4	7-6-5-4-3-2-1-11	0,08	0,11	0,09			0,0810
5	4-3-2-1-11	0,180	0,044	0,126			0,1626
6	4-5-6-7-8-1-11	0,075	0,206	0,120			0,0911
7	5-4-3-2-1-11	0,203	0,045	0,137			0,1822
8	5-6-7-8-1-11	0,072	0,205	0,106			0,0865

Table 5. Comparison of the criteria for assessing the priority of consumers

№ Load node	Category	S, p.u.	Criterion	Weight	Rating
11	0,273	0,271	Category	0,75	0,272220
12	0,273	0,158	*S*, MVA	0,25	0,244084
13	0,030	0,029			0,029961
14	0,152	0,172			0,156632
15	0,152	0,139			0,148449
16	0,030	0,072			0,040741
17	0,030	0,075			0,041371
18	0,030	0,059			0,037449
19	0,030	0,025			0,029088

The obtained results show that the simplest variant of determining the places of disconnection in the considered network is to ensure the maximum reliability of power transmission to the key consumer of the network (node 11), with the subsequent selection of connections to the remaining consumers that are not connected power center.

By this principle, the most rational 7th or 8th network configurations are selected (Table 2). For a more detailed search for optimal locations, a comparative evaluation of the reliability of all possible configurations taking into account the priority of consumers is calculated (expression 4) (Table 6)

Table 6. Evaluation of reliability of all possible network area configurations

Configuration	Node									R_Σ
	11	12	13	14	15	16	17	18	19	
1	0,086	0,106	0,136	0,078	0,078	0,083	0,083	0,083	0,083	0,089543
2	0,086	0,106	0,136	0,094	0,094	0,083	0,083	0,083	0,083	0,094471
3	0,086	0,080	0,136	0,094	0,094	0,083	0,083	0,083	0,083	0,088031
4	0,086	0,080	0,136	0,078	0,078	0,083	0,083	0,083	0,083	0,083103
5	0,086	0,080	0,031	0,078	0,078	0,083	0,083	0,083	0,083	0,079939
6	0,086	0,080	0,031	0,094	0,094	0,083	0,083	0,083	0,083	0,084867
7	0,091	0,106	0,136	0,094	0,094	0,083	0,083	0,083	0,083	**0,095703**
8	0,091	0,106	0,136	0,078	0,078	0,083	0,083	0,083	0,083	0,090775
9	0,045	0,049	0,030	0,078	0,078	0,083	0,083	0,083	0,083	0,061278
10	0,086	0,080	0,031	0,078	0,078	0,083	0,083	0,083	0,083	0,079939
11	0,086	0,080	0,031	0,078	0,078	0,083	0,083	0,083	0,083	0,079939
12	0,086	0,049	0,030	0,078	0,078	0,083	0,083	0,083	0,083	0,072412

According to the results obtained, according to the criterion of ensuring maximum reliability of consumers in the network area in question, configuration 7 is preferable. The final choice of the optimal solution, according to the authors, should be taken considering the load losses in the normal transmission mode.

The priority of losses and reliability is determined by Distribution Grid Organization’s personnel, depending on the likely failure to supply electricity (in the example considered, 0.4 to 0.6).

The results of the calculation are given in Table 7.

Table 7. Complex multi-criteria evaluation of reliability and efficiency of all possible network area configurations

Configuration	Reliability rating	Load losses, MW	The reciprocal of losses	Normalized losses	Resulting configuration rating
1	0,089543	**0,141**	7,092	0,107	0,096597
2	0,094471	0,143	6,993	0,106	**0,098955**
3	0,088031	0,181	5,525	0,083	0,086216
4	0,083103	0,174	5,747	0,087	0,084603
5	0,079939	0,192	5,208	0,079	0,079448
6	0,084867	0,193	5,181	0,078	0,082241
7	**0,095703**	0,182	5,495	0,083	0,090636
8	0,090775	0,184	5,435	0,082	0,087318
9	0,061278	0,32	3,125	0,047	0,055657
10	0,079939	0,194	5,155	0,078	0,079123
11	0,079939	0,184	5,435	0,082	0,080817
12	0,072412	0,173	5,780	0,087	0,078389

Configuration No. 2 is the most optimal for long-term power transmission mode. In addition, the obtained estimates allow to determine the preferred solutions for controlling switching equipment in post-emergency and recover mode of the network.

5 Conclusions

The developed control algorithm for the configuration of 6-35 kV distribution networks based on Saati hierarchy analysis method makes. It possible to take multi-criteria solutions for the selection of optimal opening locations. It is recommended to choose the optimal network configurations when jointly considering the losses of electricity in the steady mode of the network and complex estimates of ensuring the reliability of electricity supply to individual consumers.

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