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Features of the functional reliability of 0.4-10 kV distribution networks

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Abstract. The article is devoted to the study of the influence of regime restrictions on the functional reliability of distribution networks of 0.4-10 kV. This level of the network is largely determining the values of indicative indicators of reliability of power supply. In the work, by the example of the analysis of the reliability of power supply of two energy regions, the significance of the influence of the regime factor on the uninterrupted power supply is proved. Due to the complexity of the topology and the variability of the flow distribution, it is proposed to use the decomposition method for calculating the reliability and recoverability of network nodes. The expediency of calculating indicative indicators of the reliability of electricity supply at the stage of network design is shown, since today, in Russia, the economic efficiency of the functioning of territorial network companies is largely determined by the level of reliability due to the existing relationship between reliability indicators and the tariff for the transmission of electric energy.

1. Introduction

The mission of the electric grid complex is the long-term provision of reliable, high-quality and affordable power supply to consumers. Distribution electric network is an important and extended link, to a greater extent determining the level of reliability and quality of power supply. Failures in networks of 6 - 10 kV are the cause of about 70% of all power supply disturbances of consumers [1], [2] which reduces the technical efficiency of these networks [3], which actualizes the tasks of studying the reliability of networks.

At the same time, the level of the tariff for the provision of services for the transmission of electric energy by network organizations in Russia depends, inter alia, on the level of functional reliability of electricity supply, estimated by indicative indicators of reliability of electricity supply. These indicators, according to the current legislation (Government Decision of the Russian Federation 2002, Dec. 31 №1220 "On the determination of the reliability and quality indicators of the delivered goods and services provided when establishing long-term tariff"), are used in Russia to stimulate an increase in the level of reliability and quality of services provided by network organizations, and are used in the mechanism of setting tariffs for electric power transmission. Upon reaching certain values of the indicators, it is possible to increase the tariff for the transfer of electric energy to 2%, and decrease to -3%.

However, when designing electric networks of low and medium voltage classes, when deciding on the maintenance and repair, reconstruction and re-equipment, calculation of indicative indicators of reliability is not provided. However, the economic efficiency of network companies will subsequently depend on their values. What explains the relevance of research and the scientific novelty of the work.

The goal is to assess the impact of operational restrictions on the functional reliability of the distribution network. Achieving this goal contributes to the solution of the formulated tasks:

- to analyze and evaluate functional reliability using the example of a distribution network section without taking into account operational restrictions on the performance of the mutual reservation function;
- to analyze and evaluate the functional reliability of the distribution network, taking into account the identified operational restrictions on the performance of the mutual reservation function.

2. Materials and Methods

2.1. Relation of reliability and tariff

In Russia, according to Government Decision № 1220 and the relevant guidelines, the level of reliability of services for the transmission of electric energy to consumers provided by territorial grid organizations that have networks not related to the Unified National Electric Grid is determined by two indicative indicators calculated based on the duration and frequency of interruptions of power supply, the number of connection points of consumers:

- The average duration of the termination of the transfer of electrical energy to consumers at the point of delivery (SAIDI);
- The average frequency of the cessation of the transfer of electrical energy to consumers at the point of delivery (SAIFI).

$$SAIDI = \frac{\sum_{j=1}^{J} T_j \cdot N_j}{N_t} \quad (1)$$

$$SAIFI = \frac{\sum_{j=1}^{J} N_j}{N_t} \quad (2)$$

where:

T_j - the duration of the j-th termination of the transmission of electric energy in relation to points of supply to consumers of services of a network organization within the framework of a technological violation, hour;

N_j - the number of points of supply to consumers of the services of the network organization, in relation to which the j-th cessation of transmission of electric energy occurred within the framework of a technological violation, pcs;

N_t - the maximum number of points of supply for consumers of services of a network organization for the t-th settlement period of regulation for a year, pcs.

These indicators largely coincide with some used abroad, but the set of indicators used there is much wider [4, 5].

Average Service Availability Index, Energy Not Supplied and Average Energy Not Supplied [6] are widely used, which are used for demand management tasks [7].

2.2. Calculation of indicators based on the structure and topology of the network

The calculation of the expectation of indicative reliability indicators can be based on information about:

- network structure,
- topology,
- individual reliability indicators of the main network equipment,
- presence of redundancy,
- automation,
- the number of connected consumers.

Using the methodology of reliability analysis of a regional electric network [8], equivalent reliability indicators of load nodes are calculated and then indicative indicators of reliability of power supply of the analyzed network are calculated. The following are investigated in the work:

$$SAIDI = \frac{\sum_{i=1}^{m} \omega_i \, t_i N_i}{\sum_{i=1}^{m} N_i} \tag{3}$$

$$SAIFI = \frac{\sum_{i=1}^{m} \omega_i \, N_i}{\sum_{i=1}^{m} N_i} \tag{4}$$

where:
N_i - the number of points of supply to consumers of the services of the network organization, in respect of which there was an i-th termination of the transmission of electric energy as part of a technological violation, pcs.;
m is the number of load nodes in the analyzed network;
ω_i, - failure rate of power supply for node i of the network;
t_i - average recovery time of power supply for node i of the network.

The assumption of the methodology [8, 9], which is true for 110-220 kV supply networks, is that power supply interruption occurs only when all branches (equipment) that come to the node fail due to a significant amount of redundancy.

In 0.4-10 kV networks, mode studies conducted by the authors confirm the insolvency of this restriction as applied to distribution networks. To determine the reliability indicators of power supply to consumers using the above methodology, it is proposed to determine the nodes, disconnecting the load in which allows for complete mutual redundancy between the energy regions of the network.

It is worth noting that some criteria could be considered in defining the network structure, such as reliability improvement [10], [11] as well as minimization of power losses [12], [13] When choosing nodes that, based on the conditions of the regime, will be turned off under certain conditions (to keep the rest of the supply points in working condition).

We will be guided by the principle of turning off the required power (determined by operating restrictions for inter reservation), with a minimum number of disconnected consumers:

$$P \quad \to \min N_j \tag{5}$$

where N_j - is the number of points of supply to consumers of the services of a network organization that are disconnected for inter-reservation of energy areas.

Therefore, for the selected nodes when calculating the average duration of the termination of the transfer of electric energy to the supply point, the average frequency of the termination of the transfer of electric energy to the delivery point, two components are necessary: reflecting the level of structural and functional reliability.

As a scientific novelty of this work, it should be noted the proposal to use the decomposition method for calculating the reliability indicators of nodes in energy regions, taking into account the existing functional redundancy in the distribution network of 0.4-10 kV.

The essence of the method is to separately calculate the indicators for each energy region, taking into account possible redundancy from a neighboring power center, followed by superimposing the results of two calculations to determine the indicators of the structural and functional reliability of the load nodes. For this, in accordance with the methodology for reliability analysis of the regional electric network [8], matrices are compiled for the distribution network section in normal operation, as well as in the case of reserving the section supplying power from the neighboring energy region. Next, the matrix is superimposed on each other. Figure 1 shows an overlay of matrices reflecting:

- equipment failure rate;
- equipment recovery time;
- possible power distribution between network nodes.

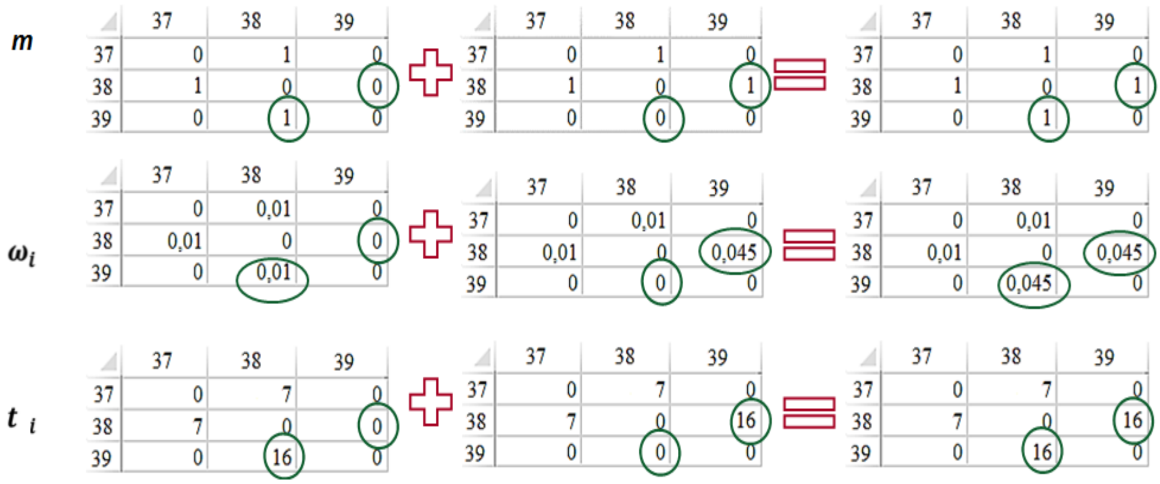

Figure 1. Implementation of the decomposition method for calculating the reliability indicators of nodes.

3. Results of a distribution network reliability analysis

The study was conducted on the example of a 10 kV network section, consisting of two energy areas. Possible operational restrictions in the conditions of redundancy and their influence on the functional reliability of the network are revealed.

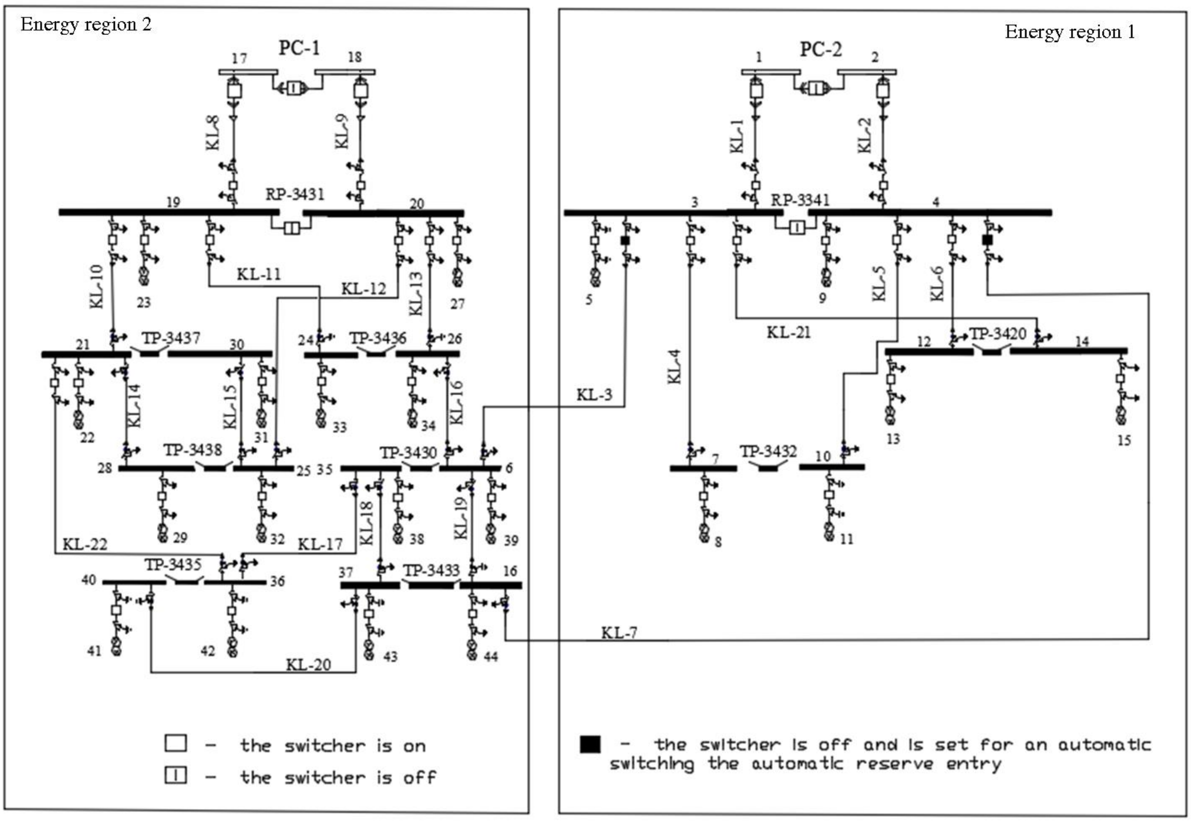

Figure 2. Schematic diagram of the electrical connections of the studied network section.

Power supply to consumers of the analyzed 10 kV network is carried out from two independent power centers (PC - 1, PC - 2). The schematic diagram of the electrical connections of the distribution network is shown in figure 2.

The distribution network section is represented by ten load nodes with a total number of connected consumers equal to 925 pcs. By load nodes we mean consumer connection points – transformer points (TP), the state of which allows characterizing the reliability of power supply. The total power of the connected load of the first energy region is 7.3 MVA, and the second 3.6 MVA.

Mutual reservation of energy areas in the network is carried out by backup lines KL-3 and KL-7, the inclusion of which is due to the action of automatic switching on the reserve.

Calculations of the electrical modes made it possible to identify the existing regime restrictions on the implementation of the function of mutual reservation between energy regions. In the event of a power failure of the PC-2, the available redundancy in the network is sufficient to maintain power supply to all consumers of both energy regions, while maintaining at least one of the two backup lines in working condition.

However, in case of power failure of the PC-1 and the failure of one of the backup lines, the power supply of the local energy district of the PC-1 will be interrupted due to a mismatch of the operating parameters - exceeding the maximum allowable current on the backup line.

To determine the indicative indicators of the reliability of power supply using the method presented in [8], [9], the nodes are determined, disconnecting the load in which allows for complete mutual redundancy. Therefore, for the selected nodes, equivalent reliability indicators will be determined not only by structural reliability, but also by functional reliability, which will lead to a change in the failure frequency and recovery time of these nodes.

Based on the criterion of minimizing the number of disconnected supply points (which is consistent with the incentive mechanism in Government Decision № 1220) and the need to reduce the reserve line load by 2.05 MW, the following points were selected:

- TP-3431;
- TP-3436;
- TP-3438.

The failure rates and recovery time of power supply in these nodes will be affected by the reliability indicators of the backup lines, depending on the backup path. The above is taken into account when compiling the incident matrix [8], [9], which reflects the topology and possible direction of power flows, determined as a result of the analysis of the circuit and calculation of electrical modes.

Due to the complexity of the topology that determines the flow distribution, the decomposition and superposition of the correlation matrices is used to determine the structural and functional reliability of the load nodes.

Table 1 presents the equivalent reliability indicators of the load nodes, where it is necessary to disconnect the load for inter-reservation in case of power failure from the PC-1.

Table 1. Equivalent reliability indicators of nodes.

Lode node		Excluding the regime factor		With the regime factor	
Nomination	Number	ω_i, 1/year	ti, h	ω_i, 1/year	ti, h
TP-3431	71	$4.259\cdot 10^{-6}$	19.272	$5.168\cdot 10^{-5}$	7.999
TP-3436	47	$3.575\cdot 10^{-6}$	21.684	$5.168\cdot 10^{-5}$	7.999
TP-3438	56	$3.575\cdot 10^{-6}$	21.680	$5.168\cdot 10^{-5}$	7.999

Based on the equivalent reliability indicators of the load nodes, indicative indicators of the reliability of power supply are determined, both without taking into account and in the presence of operational restrictions on the performance of the function of mutual reserving of energy regions, table 2.

Table 2. Indicative indicators of reliability of power supply.

Energy region	Excluding the regime factor		With the regime factor	
	SAIDI, h	SAIFI, r.u.	SAIDI, h	SAIFI, r.u.
The First	0.6658	0.0294	0.6658	0.0294
The Second	0.6847	0.0322	1.9400	0.2119
All over the network	0.6791	0.0313	1.5577	0.1571

4. Discussion

As a result of the calculation of indicators, in the case of the assumption that there are no regime restrictions on the performance of the mutual reservation function, we can state a high level of reliability, since the values of the indicators did not exceed 1, which corresponds to 1 shutdown per year for no more than 1 hour, and an average level reliability of power supply when taking into account the influence of the regime factor, since the values of SAIDI and SAIFI indicators do not exceed 4, which corresponds to 1 shutdown per quarter for no more than 1 hour [14].

However, the influence of the regime factor is great. When considering the regime factor, an increase in both indicators is observed. SAIDI increased 2.83 times, and SAIFI increased 6.59 times for the second energy region. For the network as a whole, SAIDI increased 2.29 times, and SAIFI increased 5.02 times.

The load nodes identified as a result of the study, the disconnection of which allows ensuring the mode when backing up on one cable line - these are actually “bottlenecks” of the network where measures for ensuring reliability are necessary. These nodes can be considered as points of connection of micro generation or installation of energy storage systems [15, 16] which may be the subject of further research.

5. Conclusion

In the work, the possibility of mutual reservation of power supply of two energy region of a 10 kV network was investigated. The presence of operational restrictions in case of interruption of power supply from one power center and the failure of one backup line is revealed.

Due to the complexity of the topology and possible flow distribution, it is proposed to use the decomposition method to calculate network reliability indicators.

Comparison of indicative indicators of reliability, taking into account operating restrictions and without, showed the importance of operating restrictions on the functional reliability of the distribution network, which confirms the hypothesis that it is necessary to take into account operating factors in distribution networks 10-0.4 kV.

The necessity of taking into account indicative reliability indicators at the stage of designing distribution networks and making decisions on measures aimed at improving reliability, which will improve the technical and economic efficiency of the network, is shown.

Acknowledgments

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