Estimation of acceptable failure rates for equipment of power distribution network

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Abstract. Regulatory requirements for reliability indexes of power distribution networks are considered. The dynamics and structure of the reliability indexes of electricity distribution companies are analyzed. Criteria for determining the acceptable number of outages of power network equipment are proposed to calculate the acceptable frequency of outages. The proposed approach is illustrated by calculation of acceptable values of reliability indexes for the power distribution network of Moscow Region.

1 Introduction

Power distribution networks are very diverse in terms of areas covered, network structure, consumer composition, length and other characteristics. Therefore, it is impossible to develop uniform standards for the reliability level of power distribution networks. Both in Russia and in most countries of the world, the planned values of reliability indexes are set for each electricity distribution company separately. Reliability indexes *SAIDI* and *SAIFI* are used as standard indicators.

In the most countries, there is usually a regulatory body at the legislative level, which sets distribution network reliability targets, develops a methodology for their calculation, sets penalties and incentives for each electricity distribution company. In the UK, OFGEM sets targets and incentive rates for each network operator [1]. In Italy, the AEEG sets SAIDI and SAIFI targets for electricity distribution company, as well as penalties and bonuses [2]. In the Netherlands, the Netherlands Competition Authority is an independent government agency responsible for supervising compliance with general competition law and laws related to energy and transport [2]. In the USA, the electricity distribution companies are regulated by The Public Service Commission [3].

The reliability of different distribution networks can vary a lot. Many countries divide power distribution networks depending on the type of territory served, climatic conditions, load density and other factors [4]. Reliability standards are set for each type of network separately, based on historical data for the previous 3-5 years. In many countries, the maximum permissible duration of one power outage at the consumer level is set by law. This standard takes values from 4 to 24 hours.

In Russia, the methodology for calculation planned values of reliability indexes is determined by the order of the Ministry of Energy of the Russian Federation № 1256 dated 29.11.2016 [5]. For this purpose, the basic values of reliability indexes are calculated for groups of territorial power distribution networks with comparable characteristics and operating conditions. The base values of reliability indexes are given in the order of the Ministry of Energy of Russia № 976 dated 18.10.2017 [6]. Annual planned values of reliability indexes are determined based on the rate of improvement, which is determined in such a way that the power distribution network achieves the basic indexes in the long-term regulation period (5 years). For electric distribution companies whose reliability level is better than the baseline, the minimum rate of improvement (1.5% per year) is applied. The planned reliability indexes are achieved if the actual reliability indexes for the calculation period do not exceed them by more than 30%. Tariffs and company's profit directly depend on the fulfillment of the reliability standards [7].

2 Analysis of the reliability indexes of electric distribution company, case of Moscow Region

Figure 1 shows the planned reliability indexes of Moscow and Moscow Region for two long-term regulation periods with their allowable ranges [8-11]. Actual indicators for the first long-term regulation period are also shown.

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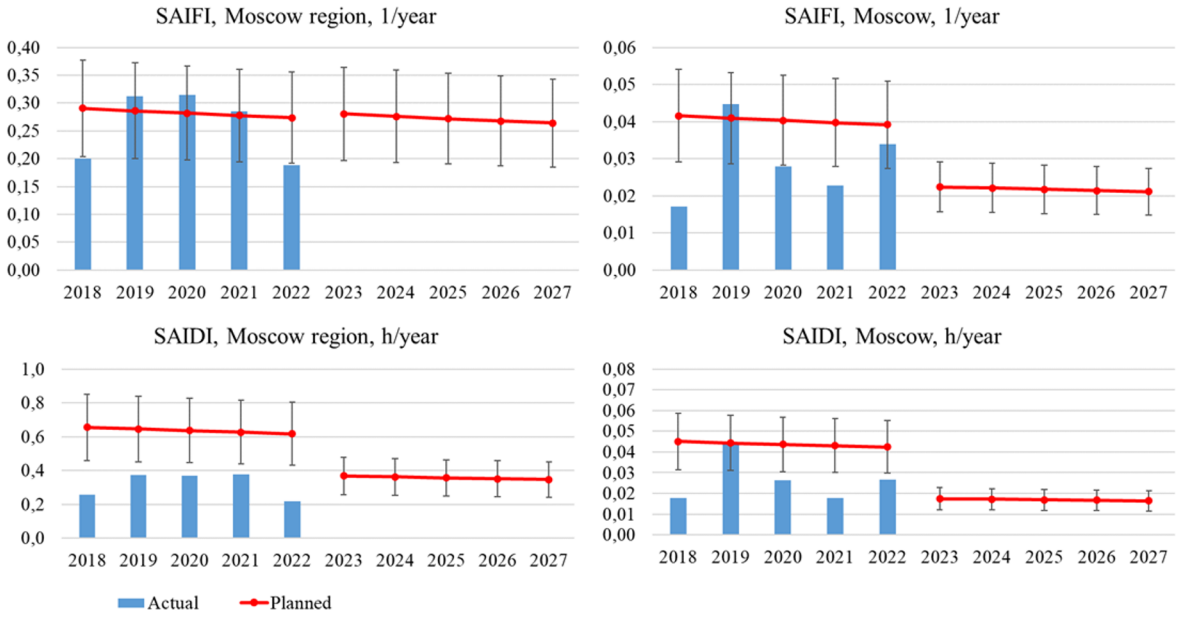

Fig. 1. Actual reliability indexes of Moscow and Moscow region for 2018-2022 and planned indicators for 2018-2022 and 2023-2027.

Figure 1 shows that current standards reduce reliability targets annually. At present, there are no regulatory limits for reduction the reliability planned indexes. Obviously, it is economically impractical and technically unfeasible to reduce reliability indexes to zero. Hence, there is an acceptable reliability level, when achieved, which should be further maintained without requiring improvement.

The reliability level of power distribution networks depends on the structure, composition of the network and reliability of equipment. The structure of the distribution network is determined by location and reliability category of the majority of consumers on served territory. The structure of the network in long-term operation does not change, therefore, reliability indexes are determined by the reliability of the equipment of this network.

Since the reliability indices *SAIFI*, *SAIDI* have additive character, they can be represented as a sum of components from failures of different equipment groups caused by various reasons:

$$SAIFI = \sum_{i=1}^{I}\sum_{j=1}^{J} SAIFI_{ij};$$
$$SAIDI = \sum_{i=1}^{I}\sum_{j=1}^{J} SAIDI_{ij} \quad (1)$$

where I – set of equipment types, J – set of failure causes.

Figure 2 shows the distribution of contributions to the reliability indexes of Moscow and Moscow region of different types of equipment: overhead line (OHL), cable line (CL), substation equipment, relay protection and automation devices (RPA). Figure 3 shows the contributions from different failure causes.

The most significant contribution to the reliability indexes is made by failures of overhead and cable transmission lines caused by inappropriate technical status, insufficient fault detection and effect of trees and vegetation.

3 Criteria for determining the acceptable frequency of equipment outages

Acceptable reliability indicators of the distribution network can be calculated based on the sample of acceptable failures. First of all, failures should be considered in accordance with the order of the Ministry of Energy of the Russian Federation № 1256 dated 29.11.2016 [5]. Intermittent failures eliminated by successful action of automatic reclosing and emergency repairs without power supply interruption are excluded from consideration.

Failures caused by personnel errors and non-compliance with the timing and scope of maintenance and repairs are excluded from the set of acceptable failures.

When calculating the frequency of acceptable failures, equipment with systematic failures are not taken into account. Overhead lines for which the number of failures per year caused by poor technical state or state of route is more than 3 is excluded [12]. Overhead lines are excluded for which the number of outages per year due to one meteorological phenomenon or another external factor is more than 3 [13]. Cable lines are excluded, for which failure rate caused by electrical breakdown is 30 or more failures per 100 km per year [14].

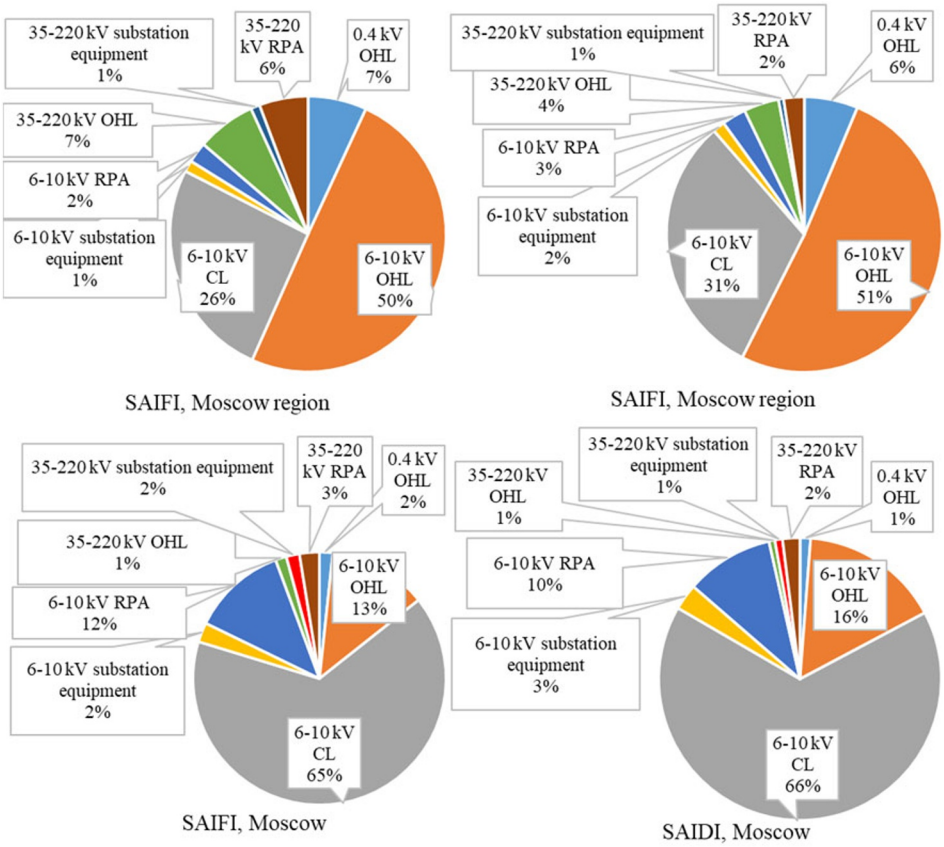

Fig. 2. Contribution of different equipment types to reliability indexes of Moscow and Moscow region

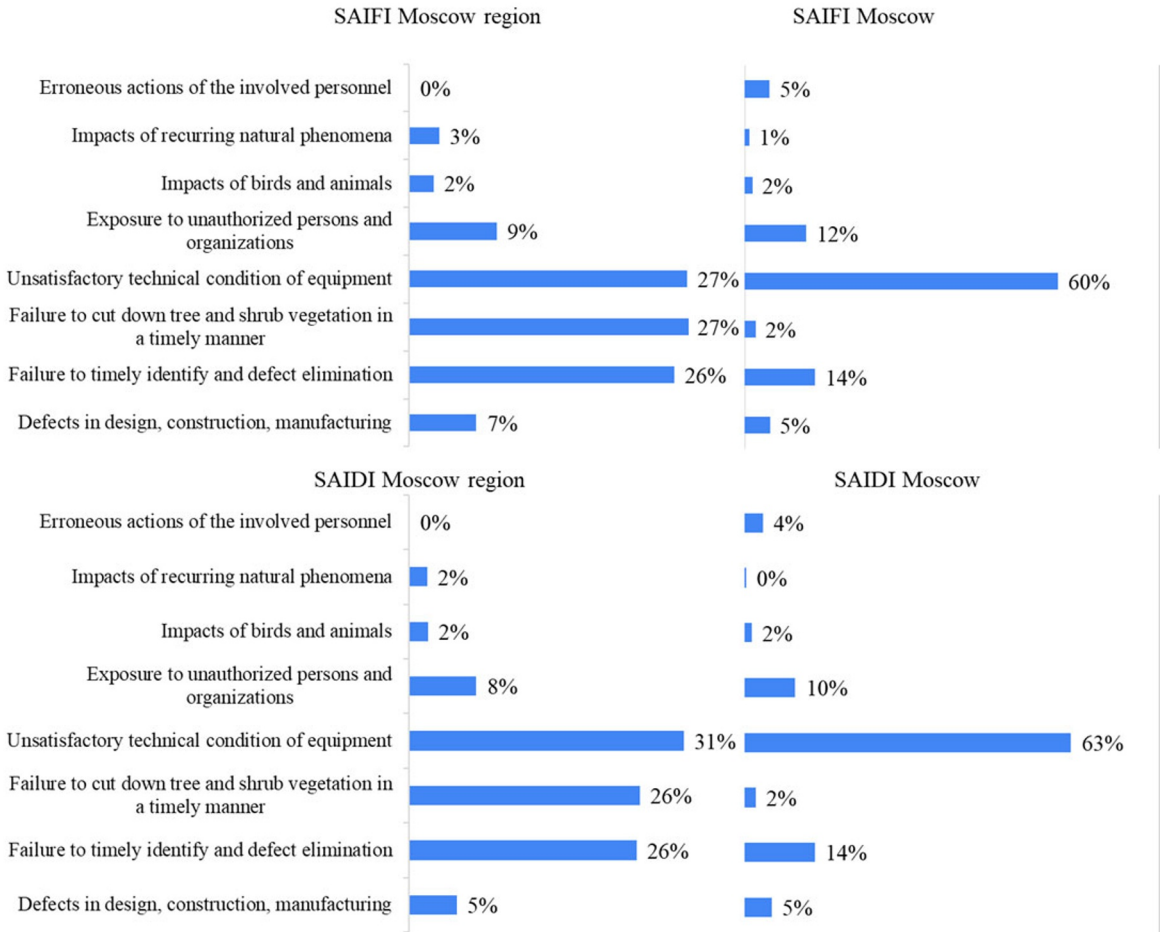

Fig. 3. Contribution of different failure causes to the reliability indexes of Moscow and the Moscow Region

Also excluded cable lines, which failures are caused by violation of cable laying requirements: violation of cable laying depth requirements, backfilling of the trench with soil with large elements of construction debris [15].

The remaining failures caused by external factors considered as an acceptable.

Failures caused the technical state or route condition (for OHLs), are further checked in compliance with the scope and regularity of maintenance.

The majority of OHL failures caused by undetected faults in the form of wire sagging, damage or contamination of insulators, heating and weakening of contact connections. Such defects may appear during the period between repairs, therefore, if the frequency of OHL inspections is observed, the failures are classified as acceptable. The standard frequency of inspections is at least once a year [12].

OHL failures due to falling branches or trees are usually associated with missing the detection of threatening trees outside the line route, therefore the frequency of inspections is also checked for these failures. Failures due to untimely cutting of trees and shrub vegetation within the OHL route should be classified as unacceptable, since the growth of vegetation under the OHL is observable and controllable.

For failures caused by the wear and tear of OHL elements, the regularity of major repairs is checked, which is 12 years for OHL on concrete, metal and composite poles and 6 years for OHL on wooden poles [16].

For 6-20 kV cable lines, the main type of maintenance is testing of insulation with increased voltage of ultra-low frequency 0.1 Hz [14]. The regularity of testing is once every 5 years for CL with paper insulation and once every 9 years for CL with cross-linked polyethylene insulation.

For 35-220 kV cable lines there are tests of cable sheathing with increased rectified voltage and infrared inspection once in 3 years [14].

Failures of circuit breakers are most often associated with defects of the actuator (misalignment, deformation, jamming) and defects of insulators (microcracks, chips, contamination). In accordance with [17], circuit breaker tests are carried out at least once every 5 years.

A significant factor of equipment failures at transformer substations 6-10 kV is a violation of the leak proofness of the roof with the subsequent ingress of moisture. For the equipment located in transformer substations 6-10 kV the periodicity of inspections is checked, which should be at least once every 6 months [14].

For power transformers, the requirements for failure-free operation are also specified as a standardized MTBF (Mean Time Between Failures). The acceptable failure rate caused by technical state is determined based on the standard MTBF.

In standards [18, 19], the probability of failure-free operation within the specified MTBF γ for transformers is not explicitly specified. In [20], the requirement is specified: the probability of failure-free operation over an operating time of 8800 h is at least 0.995. This probability corresponds to a probability of failure-free operation within the MTBF of 25,000 hours of operation of at least 0.985.

For the exponential distribution of operating hours, the expression for the acceptable failure rate is valid:

$$\omega_{ac} = \frac{-\ln(\gamma)}{MTBF / 8760} \tag{2}$$

Then for oil transformers with standard MTBF of at least 25000 hours, the permissible outage frequency is 0.005 1/year; for dry-type transformers with standard MTBF of at least 43800 hours, the permissible outage frequency is 0.003 1/year.

When calculating the acceptable number of failures, incorrect operation of relay protection systems associated with deficiencies and errors of operation are not taken into account. For the rest of cases, a check of compliance with the periodicity of maintenance in accordance with [21] is performed: preventive restoration or preventive inspection, technical inspection, testing - once every 4 years; technical inspection - once every 8 months; test inspection - once every 12 months.

For equipment failures due to workmanship and installation defects, the warranty periods for the equipment and electrical installation work are checked. The failures are classified as acceptable if the service life exceeds the warranty period.

4 Estimation of acceptable values of reliability indexes

The acceptable values of reliability indicators of electric distribution companies can be determined based on historical values through the ratio of acceptable and actual failure rates for each group of equipment and causes:

$$\begin{aligned} SAIFI_{perm} &= \sum_{i=1}^{I}\sum_{j=1}^{J}\frac{\omega_{perm\ ij}}{\omega_{ij}} SAIFI_{ij}; \\ SAIDI_{perm} &= \sum_{i=1}^{I}\sum_{j=1}^{J}\frac{\omega_{perm\ ij}}{\omega_{ij}} SAIDI_{ij} \end{aligned} \tag{3}$$

Based on the proposed criteria, acceptable failure rates for Moscow and Moscow Region equipment were determined.

The average values of SAIFI and SAIDI reliability indexes for the period 2021-2022 for each group of equipment were determined and the acceptable values were calculated. The final values of actual and acceptable reliability indexes SAIFI, SAIDI for Moscow and Moscow region are shown in Figure 4. Taking into account the probabilistic nature of equipment failure rates for the distribution network, confidence intervals of acceptable reliability indexes are also assessed. For most of the equipment the permissible frequency of outages is insignificantly less than the actual value. Figure 4 shows that current reliability indexes for Moscow are within the confidence intervals of acceptable values, for Moscow region current reliability indexes slightly exceed acceptable values. For Moscow and Moscow Region

there is practically no potential for reducing the frequency of power equipment failures. Therefore, it is reasonable to fix the planned reliability indicators for Moscow and Moscow Region at the current level.

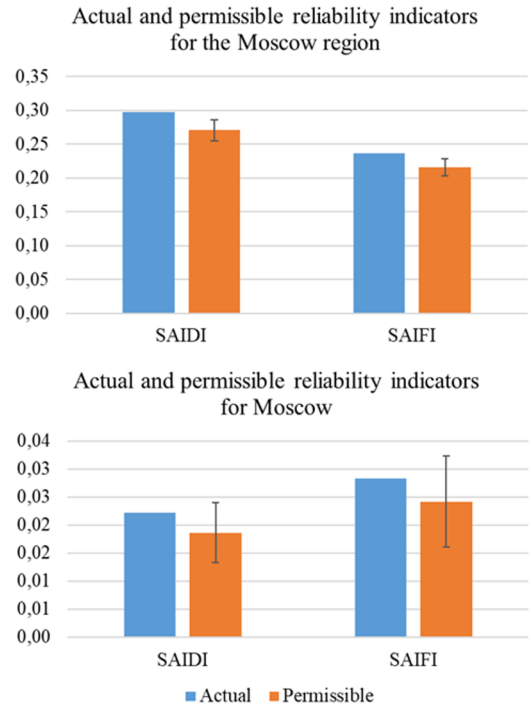

Fig. 4. Actual and acceptable values of reliability indexes for Moscow and the Moscow region

5 Conclusion

It is shown that currently there is a regulatory requirement for electric distribution companies in Russia to improve the level of reliability annually, while the limit level of improvements is not set. Based on the current standards for the power equipment were developed the criteria for determining the acceptable number and frequency of failures. On the example of power distribution network of Moscow region, the acceptable values of reliability indexes were calculated.

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