Ensuring the consumer reliability based on retrospective analysis

R V Klyuev¹, O A Fomenko², O A Gavrina¹, A A Sokolov¹, O A Sokolova¹, M T Plieva¹, A A Kabisov¹ and E Yu Ikoeva³

¹North-Caucasian Institute of mining and metallurgy (State Technological University), 44, Nikolaeva St., Vladikavkaz, 362021, Russia
²Southern Federal University, 105/42, Bolshaya Sadovaya Str., Rostov-on-Don, 344006, Russia
³Gorsky State Agrarian University, 37, Kirova St., Vladikavkaz, 362040, Russia

Abstract. The article discusses the research methods of indicators of structural and functional reliability for electricity consumers based on a retrospective analysis, which makes it possible to evaluate the causes of under-supply of electricity to consumers and to develop measures to eliminate these causes. The analysis of the reliability of overhead power lines of the power system. The analysis of the causes of failures for 2012–2018 showed that about half of the causes of failures are not established at all, other causes of failures are approximate. The exceptions are the causes of failures due to a malfunction of the relay protection and automation devices, the proportion of which in the total number of failures does not exceed 2–3%. In order to obtain an objective assessment of the influence of climatic factors on the reliability of the electric power system, a special technique has been developed. This technique allows quantifying the average values of the correlation coefficients between the failure rates of overhead power lines and climatic factors.

1. Introduction
The reliability of power supply is understood as the reliable supply of consumers with electricity of the required quality with possible economic performance indicators. The interruption of power supply is possible in case of failure of a certain group of elements (complete failure), however such cases are rare, more often there is a decrease in the transmitted power due to power shortage, as well as overloading of the remaining elements in operation (partial failure).

Under the conditions of operation of electric power systems (EPS), the reliability of power supply is quantitatively evaluated by the parameters of circuit and operating reliability. Under the reliability of the circuit the probability of providing electricity to consumers of EPS is meant. In particular, during the energy analysis at the enterprises of non-ferrous metallurgy of the Republic of North Ossetia-Alania: Electrozinco OJSC (lead-zinc production), Pobedit OJSC (hard-alloy production), reliability indicators were investigated.

2. Key indicators structural reliability
For a quantitative assessment of structural reliability, single and complex indicators are used. The life (tlifei) and restoration time (trest.timei) are taken as single indicators of the reliability of recoverable elements of EPS. The failure means the termination of an element's performance (full or partial). The operational
condition of the equipment between the two failures determines the life. The complex indicator represents a generalized assessment of the reliability of an element and is characterized using the availability rate:

\[ k_{\text{av.rate}} = \frac{t_{\text{life}}}{t_{\text{life}} + t_{\text{rest.time}}}, \]  

(1)

The failures of elements are considered as rare events, therefore, for practical calculations, average reliability indices of the same type of elements are used. These indices are calculated on the basis of statistical data for a certain period of time:

\[ \bar{T} = \frac{1}{N} \sum_{i=1}^{N} t_{\text{life}}. \]  

(2)

\[ \bar{T}_{\text{rest.time}} = \frac{1}{N} \sum_{i=1}^{N} t_{\text{rest.time}}. \]  

(3)

The failure flow of EPS elements is the simplest Poisson flow, thus the probability of failures can be quantified:

\[ q = \lambda \cdot e^{-\lambda t}. \]  

(4)

where \( \lambda = 1/t \) – is the rate of the failure flow.

The probability of equipment failure-free operation can be quantified by the availability rate:

\[ p = 1 - q \approx k_{\text{av.rate}}. \]  

(5)

Investigating the change in reliability indicators by years, it is possible to estimate the expected values for the future, i.e. to perform a retrospective analysis of the elements reliability. This provides the basis for the development and adjustment of the timing of the withdrawal of equipment in scheduled preventive maintenance or conducting preventive tests.

The failure of an element or its withdrawal for repair may break the power supply circuit of consumers, but this is mainly determined by the power supply circuit and the level of redundancy. In case of failure of one element, the power is supplied through the other, and the probability of failure of both elements (active resistance, R and inductance, L) is equal to the product of the failure probability of each element. The situation is similar when the element is brought in for repair, but in this case the situation of the second element failure and, accordingly, the formation of a power supply interruption are possible. In this case, the probability of interruption of the power supply of a specific consumer will be determined by the sum of the probability of successive chains of elements of the electrical network:

\[ Q = \sum_{i=1}^{k_h} q_{i} + \sum_{i=1}^{k_h} \left( q_{k} \cdot q_{i} \right) + \sum_{i=1}^{k_h} q_{\text{plan.out}} + \sum_{i=1}^{k_h} \left( k_{h.f.1} \cdot q_{k} \cdot q_{\text{plan.out}} + k_{h.f.2} \cdot q_{\text{plan.out}} \cdot q_{i} \right). \]  

(6)

where \( q_{i} \) is probability of accidental failure of elements;  
\( q_{k} \cdot q_{i} \) is the probability of a crash at the same time of two elements;  
\( q_{\text{plan.out}} \) is the probability of planned outage.  
\( q_{k} \cdot q_{\text{plan.out}} \) is the probability of failure of the element \( k \) at the time of repair of the element \( l \);  
\( k_{h.f.1}, k_{h.f.2} \) is the coefficient of hardware failure of an element of type \( k \) at the time of repair of an element of type \( l \), if they are of the same type, then \( k_{h} = k_{f}. \)

The retrospective analysis of the structural reliability of the power supply system allows developing measures not only to improve the reliability of the elements of the electrical network, but also to change the power supply circuit.

Assessing the probability of interruption of power supply, it is necessary to take into account that the failure of elements usually does not lead to a complete interruption of the power supply to consumers,
but the resulting overload of the remaining elements forces to limit the transmission of electricity, which is equivalent to a partial interruption of the power supply. Therefore, the reliability of power supply is additionally evaluated by functional or operating reliability using the capacity factor of the elements:

$$k_{cap\text{.factor}} = \frac{P \cdot \tau}{P_{inst\text{.power}} \cdot 8760}.$$  \hspace{1cm} (7)

where \(P\) is the actual loading of elements;
\(P_{inst}\) is the installed power of the element or the maximum transmitted power;
\(\tau\) is the number of hours of elements use.

The combined use of indicators of structural (6) and functional (7) reliability makes it possible to more fully assess the reliability of electricity supply to consumers for the development of measures to improve it. In this case, for the purposes of forecasting, it is necessary to combine them functionally with one generalized indicator, for example, the coefficient of providing consumers with electricity service:

$$k_{el\text{.serv}} = \frac{W_{inc\text{.energy}} - W_{act\text{.cons}}}{W_{inc\text{.energy}}}.$$  \hspace{1cm} (8)

where \(W_{inc\text{.energy}}\) is increment of energy determined by the declared power for the year;
\(W_{act\text{.cons}}\) is actual electricity consumption.

When forecasting the reliability of power supply to consumers, a mathematical model is compiled based on the multiple regression equation:

$$P = b_0 + b_1 \cdot Q + b_2 \cdot k_{cap\text{.factor}}.$$  \hspace{1cm} (9)

where: \(b_0, b_1, b_2\) are regression coefficients.

Based on the statistics of failures and operating modes, the average indicators of structural and functional reliability (6-8) are determined and the regression coefficients are calculated using the least squares method. Based on the compiled model (9), projected indicators for the future are calculated. The evaluation of the projected reliability indicators allows assessing the degree of change in the reliability of power supply.

In order to improve reliability, the measures are usually taken to upgrade the reliability of components (preventive tests, repairs, replacement of obsolete equipment). In order to improve the circuit reliability, a redundancy circuit (including parallel elements) and modal (replacement with a line of a higher bandwidth) are provided. Similarly, the transformers are replaced with more power, and also provide the inclusion of additional power sources. Planned measures are evaluated quantitatively based on changes in the parameters of the circuit and operation reliability, i.e. the effectiveness of these measures is evaluated.

Conducting a retrospective analysis of the reliability of power supply allows assessing the causes of under-supply of electricity to consumers and developing measures to eliminate these causes [1–7].

### 3. Analysis of failures of overhead power lines in electric power systems

The main task of the electric power systems (EPS) is the reliable supply of consumers with electrical energy. In turn, the reliability of EPS can be assessed by two main components: structural and functional reliability. The first is determined by both the reliability of individual elements and the circuit of their connection. The second is determined by the operation mode of the system.

One of the largest EPS of the North Caucasus is the North Ossetian branch of IDGC of the North Caucasus.

The analysis of the reliability of EPS elements showed that the least reliable element of the system is power lines, which account for more than 70% of all failures. As a system-forming distribution
network, JSC Sevkazenergo mainly considers 110 kV overhead lines (VL-110). At present 81 VL-110 kV overhead lines with a total length of 1009 km are in operation. These air lines operate in difficult, widely varying conditions, and are exposed to a number of external factors, the main of which are: changes in wind speed, icy rime deposits, daily and seasonal changes in air temperature, chemical elements and their compounds (for example, salt, alkali, acid).

Using the database of element failures of the North Ossetian branch of Sevkavkazenergo, the curves of the distribution of the frequency of failures over the years were constructed. Figure 1 shows the regression models of failures of 110 kV overhead lines.

![Figure 1. Regression model of failures for VL-110 kV overhead lines](image)

The main indicators of the structural reliability of the electrical network are indicators of the reliability of the elements of the EPS under study. Currently, there are 81 110 kV overhead lines and 33 substations in operation, in which 61 transformers are installed.

The distribution of the frequency of failures among them is unequal, so about 20% of the lines were disconnected on average 2–3 times a year for various reasons and for different durations, including the response time of the automation. Over 30% of overhead lines for the entire study period 2012–2018 shut off no more than 2–3 times. The disconnection of transformers during this period, on average 2–3 times a year. Therefore, the focus on improving the reliability of EPS elements should be given to overhead power lines.

To analyze the causes of failures of 110 kV overhead lines, typical causes are selected from the database and new tables are formed for them, where elements that failed due to similar features are entered. As it is known that the causes of element failures can be divided into two types: non-objective and objective. Objective reasons include the effects of climatic conditions (thunder, wind, flood, ice, etc.). Non-objective reasons include a violation of the operating mode (personnel errors, failure of relay protection and automation) and a culture of operation and maintenance (violation of preventive test schedules for the destruction of elements by unauthorized persons, etc.). A special position is occupied by unidentified causes of failures, according to the records in the dispatch service logs.

The distribution of causes of failures for 2012–2018 found that about half of the causes of failures was not defined. This indicates a lack of control over the maintenance of operational logs and the responsibility of personnel to account for the causes of failures. The main share of failures accounted for urban electrical networks. Thus they account for about 40% of failures. According to the number of failures, some lines fail 5-6 times a year for a period from a few minutes to 2–3 hours. The distribution due to failures after unspecified reasons is due to outages, unsatisfactory operation of automation devices (APV, AVR, MTZ, etc.). Under climatic conditions, the share of failures for urban electrical networks is insignificant, but for mountainous and rural areas it acquires a stronger impact.
The distribution by district is also unequal. In comparison with urban electrical networks, the failure rate for other areas is much less and the proportion of unidentified causes is smaller [8–12].

The main share of failures, more than 40%, is accounted for by urban electrical networks; the emergency downtime of transmission lines varies from a few minutes to 2–3 hours. The distribution of the main climatic factors by months for zone I is shown in Figure 2.

![Graph showing distribution of precipitation and temperature by months](image)

**Figure 2.** Average monthly precipitation and air temperature

The analysis of the causes of failures for 2012–2018 showed that about half of the causes of failures are not established at all, other causes of failures are approximate. The exceptions are the causes of failures due to a malfunction of the relay protection and automation devices, the proportion of which in the total number of failures does not exceed 2–3%.

In order to obtain an objective assessment of the influence of climatic factors on the reliability of 110 kV overhead lines, the special technique has been developed. This technique allows quantifying the average values of the correlation coefficients between the failure flows of 110 kV overhead lines and climatic factors.

For the correlation analysis, the samples were made for the main climatic factors based on the data presented in the reports of the Hydro-meteorological Center of the RNO-Alania for 2012–2018. The main climatic factors, the probability of which influence on the reliability of 110 kV overhead lines is obvious, include: air temperature from 0 to −5 °C (ice deposition condition on overhead lines), wind speed (from 3 m/s and more), cloudiness (in points from 8 to 10 and above), snow rain, thunderstorm, hail - all in conventional units, as the relative frequency of occurrence per unit of time. The distribution of climatic factors by months of the year is given in Table 1.

| Climatic factors | Frequency of factor recurrence by months, times/month |
|------------------|-----------------------------------------------------|
|                  | 1        | 2        | 3        | 4        | 5        | 6        | 7        | 8        | 9        | 10       | 11       | 12       |
| temperature      | 4.75     | 4.25     | 2        | 0.25     | -        | -        | -        | -        | -        | 0.255    | 0.5      | 6.25     |
| wind             | 0.25     | -        | 1        | 0.5      | 0.5      | 1.5      | 0.25     | 0.5      | 0.25     | 0.25     | 0.75     | 1        |
| Cloudiness       | 3.25     | 1.5      | 4.5      | 4.75     | 2.25     | 1.25     | 2.5      | 4        | 2.5      | 3        | 2.5      | 4.75     |
| Snow             | 1        | 1        | 1.75     | 0.75     | -        | -        | -        | -        | -        | -        | 1.25     | 4.25     |
| Rain             | -        | -        | 0.75     | 4.5      | 4.75     | 5.5      | 3.75     | 2.25     | 4.5      | 1.25     | 1        | -        |
| Thunderstorm     | -        | -        | -        | 0.75     | 3.25     | 3.5      | 3        | 1.25     | 1.5      | -        | -        | -        |
| Hail             | -        | -        | -        | 0.25     | 1.25     | 1.25     | 1.25     | -        | 0.25     | -        | -        | -        |

The average values of paired correlation coefficients are shown in Table 2.

**Table 2.** Assessment of the significance of selected climatic factors
Weather factors

| Weather factors | Temperature | Wind | Cloudiness | Snow | Rain | Thunder storm | Hail |
|-----------------|-------------|------|------------|------|------|---------------|------|
| Average correlation values | 0.674 | 0.58 | 0.68 | 0.767 | 0.714 | 0.75 | 0.436 |

4. Conclusion

Based on the conducted research, the following recommendations can be made in order to improve the reliability of EPS.

1. In areas with significant wind load from 3 m/s and above, vibration dampers must be installed to prevent wire vibration and mechanical damage to the wires.

2. In areas with intensive icing, it is necessary to organize monitoring of the icing process on the overhead lines, review and shorten the time for inspection of transmission lines and improve network utilization, develop and introduce ice melting to prevent the destruction or swinging of wires.

3. In urban areas, it is necessary to increase the level of operation of power transmission lines, strengthen preventive inspection and cleaning of insulators that are subject to intensive pollution by industrial emissions into the atmosphere. This will reduce the flow of failures in heavy fog, drizzle and snow.

4. In areas of intense lightning discharges, it is imperative to install lightning protection cables on the overhead lines, to increase the level of preventive measures to ensure the required ground resistance value of overhead lines.

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