On the Rural Electric Networks Reliability Level Issue

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Abstract. The structure study, condition and 10 kV electric networks reliability level in the Irkutsk region for the period from 2016 to 2020 is carried out. The analysis is based on real data on the studied electric networks published in the open press. The Interactive Matlab system libraries and interfaces were used to calculate and analyze the studied indicator. The considered electric networks structure has investigated, algorithms and computer programs for the Matlab graphic editor are compiled with the help which changes time diagrams in the failures number, the interruptions time and the under-output electricity amount for each year months are constructed. The year months in which the highest damage occurs were determined. The electrical networks wear is considered, as well as the repair plan implementation for the main equipment. The reliability level according to the established indicators has analyzed, the main reasons for equipment failure are considered. The characteristics of improving considered electrical networks functioning are presented. Based on the conducted studies, it was found that the most damaged the considered overhead lines elements are: wires, supports, insulators, and switching devices. The characteristic reasons that lead to their damage are: wind load, damage to switching devices. The greatest damage is the Angarsky and Irkutsky branches networks characteristic (the average annual value all failures are 26.4 and 23.9%). The Kirensky and Cheremkhovsky branches networks are the least damaged annually. The obtained data probabilistic-statistical and correlation analysis, as well as the emergency outages risks analysis for the future, taking into account the seasonal component, is carried out.

1. Introduction

Overhead power transmission lines (overhead lines) are the least rural electric networks reliable elements; about all violations 85-90% in the networks are accounted for by them. At the same time, rural power 10 kV lines are recognized as the most damaged, which account for up to all damage 70% [1]. The damage main causes to the overhead lines are: surface and other insulation breakdowns; icy-frost deposits on the wires; loads from wind and ice; vibration, "dancing" and wires clashing; the support parts mechanical strength weakening; damage caused to the line by transport, mechanisms, etc. Icy-wind impacts are the most severe in their consequences, sometimes leading to mass accidents with a large consumers number being disconnected for a long time, the backup power availability regardless. It is believed that the damage to the overhead line is distributed evenly along the line length, therefore,
based on static data, the specific failure rate (intentional disconnections) is determined, attributed to the one-line kilometer. In fact, long rural power transmission lines with a 10 kV voltage are quite heterogeneous in their length, due to the territorial features area along which they are extended. It is well known that the power lines reliability, as an electrical network element, should be laid down during design, observed during installation and carried out during operation [2]. The vast rural 10 kV power lines majority were built more than 40 years ago, by the mobile mechanized columns forces, in which student detachments often worked. The overhead line wires Installation was carried out manually and very often the wire sag arrows, determined "by eye", already had different values in different spans. That is, the reliability requirements violation was carried out already at the installation stage. In the end, during the operation, in the territorial natural and climatic features conditions is additional line extensions. Therefore, most of the emergency shutdowns when exposed to wind and icy-wind loads are associated with various the wires fluctuations, causing their convergence to dangerous distances in insulation terms, short circuits and breaks. Another important rural 10kV networks feature is the weak post-emergency switching automation, which is understood as switching aimed at isolating the damaged element from the circuit (localization) and restoring the all loads ES that were disconnected (limited) when this element was damaged. Therefore, improving the rural 10 (6) kV overhead lines reliability by reducing their emergency shutdowns under the wind influence and icy-wind loads is an urgent problem. The electricity consumption level is continuously increasing. For example, the projected electricity consumption in the Irkutsk region is expected from 55.141 million kWh in 2019, up to 64967 million kWh in 2024 [3]. At the same time, one of the main conditions for the effective enterprises any economic orientation operation, as well as ensuring normal living the population conditions, is to maintain the required electricity supply reliability level. Therefore, measures related to obtaining detailed information about the main damage causes, its analysis and drawing up certain recommendations based on this analysis is an important aspect in improving the power supply reliability in all levels electric networks [4-6].

According to experts, the damage caused by planned and unscheduled interruptions in electricity supplies in developed countries is several times greater than the damage caused by natural disasters [7]. The most damaged elements are overhead power lines, which account for up to all failures 90% in power supply systems. The total power lines length along electric circuits under the Federal Grid Company "Russian Networks" control at the 2019 end was 148.3 thousand km, and for the 2020-2024 period it is planned to put into operation another 8.71 thousand km [8]. The current state existing electrical networks leaves much to be desired. The electric networks equipment is average age is 34 years. And, even though at the 2017 end, emergency failures were reduced by 20 % over the past 5 years due to the network infrastructure renewal [9], and by the 2019 end, the specific accident electric networks rate decreased by another 12% [8], the equipment aging problem is still very acute. Low-voltage electrical networks are often called low-observability networks, since they are characterized by an insufficient equipment degree with control means. In addition, there is a very low power quality in these networks. As a result, the wear increases from year to year. Therefore, annual monitoring and repair is necessary to maintain the electrical networks in a working condition.

In many the European Union countries, the United States, some Russian Federation regions and some CIS countries (for example, Belarus), to assess the power supply reliability level, the International Electrical and Electronics Engineers Institute (IEEE) sets special indices that characterize the relationship between the failures number (duration) and the consumers number connected to the power centers buses. According to experts, the average this indicator value for a European country ranges number from 0.2 to 4.35. For example, the energy system reliability index in the following countries has average values: Austria – 0.73; Great Britain – 0.53; Germany – 0.51; Norway – 1.59; Finland – 1.42 [10, 11].

The article purpose is to study the Irkutsk region electric networks existing state in the real operating conditions. The achieving result this goal is the tasks number solution: 1) the existing electric networks structure analysis, their condition for the period under study; 2) damage assessment, forced downtime
and the electricity under-supply amount; 3) recommendations development for improving the power supply efficiency.

**The research object characteristics.** The distribution electric Irkutsk region "Oblkommunenergo" (OKE) 10 kV networks were selected as the research object. The main Irkutsk region feature is the largest hydroelectric power plants presence on the territory, which is all power plants capacity 5.7% in the country [12].

2. Results and discussion

The regional state Energy Enterprise "Power Supply Company for the electric networks operation "Oblkommunenergo" (OKE) is a network organization that provides operation and electric grid facilities repair on the Irkutsk region territory. The overwhelming consumers receiving electricity number through the OKE networks belongs to rural areas. Therefore, it is safe to say that the OKE networks are rural purposes electric networks. According to experts, these networks average wear is 87%. But, despite this, these networks were included in the network companies rating in Russia for 2016-2017 energy efficiency. At the same time, OKE took the 85th place 184 organizations out participating in the assessment in the integrated, generalized OKE organization rating. According to the loss reduction index, the Irkutsk regional enterprise took the 42nd place out 184 [13]. The studied networks structure includes 10 branches: 1 – Angarsky, 2 – Cheremkhovsky, 3 – Sayansky, 4 – Nizhne-Udinsky, 5 – Taishetsky, 6 – Ust-Kutsky, 7 – Kirensky, 8 – Mamsko-Chuisky, 9 – Ust-Ordynsky, 10 – Irkutsky. The power transmission lines length (PTL) in general for 10 branches at the 2020 beginning was 11437.2 km. The overhead power lines share accounts for more than 83%. From 2013 to 2020 27 388 095.04 thousand kWh electric energy were transferred to the OKE network, including: on high-voltage networks – 14 003 456.5 (from network to consumers – 5 403 921.293) th.kWh; midle-voltage – 14003456.5 (5403921.293) th.kWh and low-voltage – 2 365 134 (14 238 592.59) th.kWh. At the same time, the electricity total loss from the transmitted volume was 18.53% (Figure1).

**Figure 1.** Change diagrams in the supply of electricity in the network (from networks) OKE (a) and losses (b) in these networks.

Of course, these losses most are associated with commercial and technical losses caused by objective power transmission factors. But, in addition, a significant the losses part is also due to forced power supply interruptions due to the electrical networks elements state through which the electric energy transport is carried out. Let's consider the studied networks state. According to data at the 2020 beginning, the main OKE electric networks elements wear amounted to: 86.7% for power transmission lines and 82.4% for transformer substations [14]. It should be noted that the wear dynamics is determined directly by the electrical network operating mode. The worst operating conditions are low-voltage networks characteristic, which account for all overhead power lines about 65% in the OKE branches. In accordance with the order [15], the interruption average duration single indicator in the electric energy
transmission is established as a criterion for assessing damage, characterizing the power supply reliability level. At the same time, this indicator \( (\Pi_T) \) is determined in each settlement regulation period within the long-term regulation period:

\[
\Pi_T = \frac{T_{IP}}{N_{TT}}.
\]

In this expression: \( T_{IP} \) – the actual total all interruptions duration in the electric energy transmission in relation to network organization's services consumers for the estimated regulation period, hour; \( N_{TT} \) – the maximum number consumers connection the network organization's services points to the electric network for the estimated regulation period, pcs. In the OKE networks, this indicator value was, respectively: in 2014 – 0.0068; in 2015 – 0.0085; in 2016 – 0.0144; in 2017 – 0.0055; in 2018 – 0.0031.

Let's consider the failures dynamics, as well as the downtime and the corresponding electricity under-supply during these periods in the electric OKE branches networks in the studied (2016-2020) time interval.

Figure 2 shows changes graphs in the failures number in the OKE branches for the study period.

The Figure 2 analysis showed the following. The largest failures number occurs in the Angarsk branch OKE electrical networks. During the study period (from 2016 to 2020), 183 failures occurred in them, with the largest damage number occurring in 2019 (48). In the other branches, the failures number during the study interval was distributed as follows. The second most damaged is the Irkutsk branch – 129 failures, followed by the Mamsko-Chunsky branch networks (101). The Kirensky networks (13 failures) and Taishetsky (29) branches are least susceptible to damages. The forced downtime time and the under-supply amount for the failure period is distributed somewhat differently (Figure 3). Despite the fact that the largest failures number is in 2019, the breaks duration this year is the smallest – 979.4 hours. The longest break time is 2998 hours corresponds to 2016 (Fig. 3a). During this time, the electricity under-output amounted to 1102.5 thousand kWh (Fig. 3b). In 2020, the total failures duration was 656 hours, which corresponds to an 822 thousand kWh under-output. In general, during the studied time interval, the interruption in power supply in 10 branches amounted to 6749.25 hours, for which the electricity under-output amounted to 4277.86 th.kWh. At the electricity cost in 2021 for 1 kWh, equal to 1.17 rubles [16]. The damage from the electricity under-supply amounted to 5 005 096.2 rubles (340 345.8 USD).

In order to analyze the branches work by year months each, let's look at Figures 4 and 5.
Figure 3. Changing the failures duration time (a) and the electricity under-supply amount (b) in the OKE branches.

Figure 4. The total refusals number by the year month in the OKE branches.

The diagrams analysis (Fig. 4, 5) showed the following. The damages number (except for 2017) increases from year to year: 2016-107 outages, 2018 – 184, 2019 – 192, 2020 – 203 (in 2017 – 91). According to the year seasons, the situation is as follows: the largest damages number in 2016 falls on the May month (16.8% of all failures), in 2017 – August (13.2%), in 2018 – December (16.85%), in 2019 – April (19.8%) and in 2020 the most "damaged" months were June and (13.8%). At the same time, the longest time of power supply interruption corresponds to: in 2016. – June (25.5% of the total break time this year), in 2017 – May (23.4%), in 2018-January (18.25%), in 2019 – September (20.23%) and in 2020 – July (18.7%). The largest electricity under-supply amount as failures result by year months is distributed as follows: in 2016, the largest undersupply occurred in August (the total undersupply this year 19.65%), in 2017-in April (19.93%), in 2018 – in May (17.92%), in 2019 – in June (15.87%) and in 2020 – in March (15.36%).
Figure 5. The total time supply interruptions duration power (a) and the total electricity undersupply amount (b) by month in the OKE branches.

As can see, there is no significant correlation for the year certain months according to the any criteria (failures, break time, under-supply). Of course, this is due to the territorial and climatic the regions features along which power transmission lines are traced. The greatest data significance can be obtained on the probabilistic basis and statistical analysis (discussed below). The reasons for the power grid equipment damage, as shown by the literary sources analysis [17-19], may be the following: 54.0% all outages are associated with the dynamic behaviour of wires under the wind influence and icy-wind loads. They can be caused by the following damages one: wire breakage (24.9%) or breakage wire binding to the insulator (9.8%), the wires burning during their dangerous approaches and clashing (17.0%), the insulator breaking from the hook or pin (2.3%) [17]. As a rule, the following damages are recorded in the overhead power transmission line (OPTL) failures logs: violations in consumer networks, damage to insulators, damage to wires, arresters, OPTL poles; wind load, snow, ice, insulation overlap, and others. According to published data [18, 19], in Russia, disconnections in this voltage class networks are caused by the following reasons: about 11% damage in consumer networks; up to 42% wire breakage, 6% damage to fuses, damage to switching equipment - more than 7%. In the OKE branches electrical networks, the main damage causes are: wind load, damage to the disconnecter, wire breakage, falling trees, as well as damage to switching devices [20]. The most damaged the considered overhead lines elements are: wires, supports, insulators, and switching devices. The clashing and wires overlapping are associated with the wires ' sag arrows unbalancing, which leads to multi-level their oscillations amplitudes under a squally wind load. Damage to the switching equipment (mainly the disconnectors inclusion on the "short circuit" and disconnecting them "under load") in most cases is associated with the illegal operational personnel action and non-compliance with the planned measures and by regulatory documents repairs provided in full.

Let's will perform a probabilistic-statistical changes analysis in failure events in the OKE branches networks for the studied time interval. The such an analysis purpose is to determine the distribution a random variable law (in our case, this is a failure event), which allows us to predict with a sufficient reliability possible change degrees in emergency situations in the electrical networks under consideration. According to the initial data analysis on emergency outages for ten OKE branches for 2016-2020 (Fig. 6a) the largest emergency shutdowns number occurred in 2020. At the same time, the failures number increases annually, with the 2017 exception, in which the studied parameter value is half as much as in subsequent years.

Based on the failures data by month (Fig. 6b), it is impossible to draw an unambiguous conclusion about the seasonal component impact on emergency shutdowns. So, in 2016, the accidents occurred most in January, April, May, July and August, and in 2017 – almost the failures third for the year took place in November and December. In 2018, more than outages 70% were detected in the autumn-winter
period, while in 2019 and 2020, on the contrary, only them accounted 14 and 12% for the winter months, respectively. In this regard, it is possible to simulate the situation with a preventive assessment on the constructing basis a failure probability distribution function to determine a specific series value for a given probability. As noted in [19], most accidents are associated with damage to complete transformer substations, insulators and switching equipment, which most likely occurs due to equipment wear. In addition, the equipment breakdowns number and failures depends on the maintenance timeliness, compliance with the operation terms, the personnel competence, etc. For a preventive the power supply systems reliability assessment, the probability distribution laws are often used: normal, gamma, Weibull, exponential, etc. [21-24].

![Figure 6](image.png)

**Figure 6.** Change in the total failures number (a) and their change by the year month (b) in the observed period in the OKE branches networks.

The probability distribution law construction is possible only in cases when the intra-row the observations long-term series values relationship is weak or absent. When identifying the relationship between the sample values or refuting this hypothesis, an autocorrelation coefficient is used, calculated by the next formula:

$$ R_t = \frac{\sum_{i=1}^{n} (x_i - \bar{x}_i) \cdot (x_{i+t} - \bar{x}_{i+t})}{\sigma_i \sigma_{i+t} (n-t-1)}, \quad (1) $$

where \( n \) – sample size; \( \tau \) – the shift order, varying from 0 to \( m \) (\( \tau = 0, 1, 2, \ldots, m \)); \( x_i \) – the series values from \( x_1 \) to \( x_n \); \( \bar{x}_i \) and \( \sigma_i \) – the average value and standard for the sample part from 1 to \( n-\tau \); \( x_{i+t} \) – the series values from \( x_{1+\tau} \) to \( x_{n+\tau} \); \( \bar{x}_{i+t} \) and \( \sigma_{i+t} \) – the average value and standard for a sample size from \( 1+\tau \) to \( n \).

The autocorrelation function ordinates change from -1 to 1. When shifting, the autocorrelation coefficient \( R_0=1 \). Usually, a relationship is considered significant if \( R_0 \geq 0.3 \).

Note that the weak significant presence intra-row connection (0.7 \( \geq R_0 \geq 0.3 \)) increases the variation coefficient values and the asymmetry coefficient, therefore, corrections are introduced to calculate them, taking into account the autocorrelation function ordinates. Since the failures the autocorrelation coefficient number value in the OKE networks for 2016-2020 is 0.3, the intra-row communication is weak, which allows us to apply the probability distribution laws to estimate the number values. The emergency occurrence failures probability was estimated using the normal law and the Gamma distribution (Figure 7a).

According to the agreement Kolmogorov criteria (Kolmogorov-Smirnov) and Pearson [25], the normal and Gamma distributions correspondence hypothesis to experimental data is accepted. Based on the obtained distribution function, it is possible to estimate the accidents probability, which is important for risk assessment. In particular, according to the normal law, for probabilities 0.05, 0.5 and 0.95, the...
emergency shutdowns number corresponds to the indicators \( x_{0.05} = 2, x_{0.5} = 12, x_{0.95} = 24 \), and according to the Gamma distribution \( x_{0.05} = 4, x_{0.5} = 11, x_{0.95} = 24 \). In other words, under favorable conditions, 2 (4) accidents will occur, under unfavorable conditions – 24, under averaged conditions – 12 (11).

![Figure 7](image)

**Figure 7.** Empirical data, normal and Gamma probability distribution law (a) seasonality index (v), the emergency outages number by the year month in the OKE branches.

The autocorrelation studied parameter coefficients calculation for 2016-2020 by month showed that in most cases there is a weak significant intra-row relationship \((R_1 > 0.3)\). According to the February to April, October and November data, the failures number on electric networks is characterized as a random variable and can be described using the probability distribution law. At the same time, due to the limited sample values, the probabilistic models construction by month is impractical.

At the next stage, the seasonal component presence assessment in the failure series was carried out (Figure 7b). The least squares method was used to isolate the trend and the seasonal component from an emergency outages number [26]. According to the received trend, the emergency shutdowns number increases over time, although not significantly.

\[
y = 0.204t + 6.744. \tag{2}
\]

The seasonality indices in Figure 7b show that the greatest increase in emergency outages occurs in April, June and December. In February and March, the equipment failures number is the lowest. Then the indicator jumps again in the growth direction. In May, the refusals decreases number again, and in June, the refusals increases number almost to the April level. In the refusals following months, there is a decrease in the refusals, until November. In December, there is an increase in refusals, and in January there is a decrease again.

3. **Conclusions**
Based on the conducted the electric networks state studies the Irkutsk region OKE branches for the 2016-2020 period, the following conclusions can be drawn.

1. The preventive emergency shutdowns assessment for favourable, averaged and unfavourable conditions was made. The studied electrical networks have an unsatisfactory condition, with a total wear reaching 87%. The electric networks elements average annual wear was: overhead lines – 80.5%; cable lines – 8.1%; TS – 83.6%.

2. This leads to high damage to the electric networks elements, as which result the total damage from electricity amounted under-supply to more than 5 million rubles (68 124.35 USD).

3. The greatest damage is the Angarsk and Irkutsk branches networks characteristic (the average annual value all failures is 23.55 and 16.6%). The Kirensky and Taishetsky branches networks are the least damaged annually (1.67 and 3.73%, respectively).

4. The probabilistic and statistical analysis performed showed that in 2016, accidents occurred most in January, April, May, July and August, and in 2017, almost the failures third for the year took place
in November and December. In 2018, more than outages 70% were detected in the autumn-winter period, while in 2019 and 2020, on the contrary, only them accounted 14 and 12% for the winter months, respectively.

5. The preventive emergency shutdowns assessment for favourable, averaged and unfavourable conditions was made.

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