Climate Impacts on Quality of 6 kV Overhead Lines Operating at Mining Companies

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Abstract. Technological innovation in the mining industry involves the extensive use of new high-power, energy-intensive, and high-performance mining machinery that should be reliable in its operation. The key mining company equipment includes mining excavators, drilling rigs, crushing and screening units, and mine drainage facilities. Providing the fault-free power supply and the efficient operation of the electrical infrastructure of a mining company is a priority, and it depends on the quality of the power supply system and its elements. Power supply system failures reduce the operational efficiency of mining machinery, processing sections, and the mining company as a whole, which results in reduced power consumption, uneven loading schedule, failures to meet the output plans, and increased prime costs for the products. The analysis of the electrical infrastructure power supply system at a mining company shall help us assess the quality of operations and their efficiency and develop actions to reduce the idle times of electrical equipment, provide uninterrupted power supply and plan the activities of the mining company in the wholesale electrical power market more accurately.

1. Introduction
The reliability of power supply systems (PSS) at mining companies is a key factor for the improvement of mining equipment efficiency. Mining equipment idle times due to dead voltage caused by damaged power lines result in failures to fulfill mining, overburden, and drilling-and-blasting operations schedules.

The power supply systems of mining companies are operated under specific conditions and comprise overhead electric power lines (OL) and cable lines (CL), mobile packaged transformer
substations (MPTS) of 35/6 kV, EPTS of 6/0.4 kV, SDS of 6/0.4 kV. Mobile machines are connected to power supply feeders (PSF) via mobile switching stations (SS), such as HVDS or SDS [13, 32].

The features of open cut mining PSF operation include the following:
- harsh operating conditions due to the regular movement of mining and conveyor machinery;
- outdoor installation, large land areas of mines, and decentralized workplaces, which complicates grid layouts;
- working at various mining horizons and elevation differences induce problems for overhead cable PSF construction and operation;
- blasting works may damage PSF, thus PSF are disassembled before the blasts and installed back again;
- there are always some personnel and a large number of mobile machines and mechanisms near the PSF.

Ambient weather conditions, comprising a multitude of factors, have a significant impact on the operation of a mining company's power supply system. Thus, it is necessary to study the reliability of power supply systems to account for the changes in the operation of electromechanical equipment of coal mines that occurred in recent years.

2. Review of literature, current state analysis

A power supply system whose reliability is attributed to a number of factors [27, 15, 14] may facilitate the productive operation of power consumers and help maintain high mining operation safety.

It is only possible to identify the true causes of failures and find ways to improve the robustness of the power supply system through the analysis of the statistics on the damage rates for its elements. Failures are the only validation criterion for practical decisions and theoretical concepts. Over the last years, open coal mines that increased their outputs, mining machinery fleet, and installed capacities have also seen some increase in the mining electrical equipment downtime due to the damaging of 6 kV PSF. [16, 22, 21]

Power supply system failures at open mines reduce the efficiency of mining machinery, processing sections, and the coal mines as a whole due to the reduced output, increased prime costs, and reduced industrial safety. The analysis of failure distribution across the power supply system components allows one to describe the most typical damages and failures occurring at mining companies.

The reliability of coal mine power supply systems and their components is one of the key factors providing the efficiency of mining machinery in the context of high intensity and comprehensive mechanization automation of open mine operations. The uninterrupted power supply to consumers in mines facilitates not only their productive operation but also maintains a high level of mining operation safety [24].

Research works like [19] present the results of statistical data analysis obtained from the monitoring of mining company power lines, as well as the correlation coefficients between the number of line failures and the factors impacting line reliability (line length, the number of consumers, sealing-offs, angle towers, the impact angle for prevailing winds, operating life, and power line loads). The calculation of new line reliability can be based on the quantitative reliability assessments of the existing power lines to select the best grid layout and determine the number of repairs personnel.

The model presented in [8, 3] is based on the statistics. It helps assess the reliability of simple substation electric circuits using probabilistic methods and the classical reliability theory for real branched networks, as well as assess the significance and the further development prospects for these methods.

The authors of [12] rationalize the comprehensive use of structural and informational (temporal) backup in mining company power supply systems. They determined the degree of impacts of disturbing factors on the power supply system with or without backup facilities [1]. The authors suggest indicators to determine the operating parameters of electrical systems with various backup types using the theory of stochastic processes and backup efficiency coefficients (failure and fault-free operation probabilities for the system, the expected pause value, the average failure frequency, and
intensity) [11]. Some research works [12, 9] suggest improving the reliability via the analysis of company power supply systems affected by a set of negative factors such as higher harmonics, short circuits, and reduced voltages.

The authors of [6] analyzed the reliability of the distribution grid and viewed the information entropy as a measure of uncertainty. They suggested a simple mathematical model that helps determine the entropy of a network based on the Shannon approach to the definition of information.

Paper [2] identifies the root causes of voltage drops and deviation occurrences in mining company power supply systems. The authors determined the degree of impacts of voltage swings and deviations caused by various factors on the dynamic and static robustness of mining company power supply systems. Paper [4] suggests a new method using an improved model of logistical regression that reflects the probability of failures for overhead lines located in the same area. This model can be used to forecast the reliability of the electric device in real-time.

The methodology suggested in [5] uses the probabilistic wind model to produce the rate of overhead line failures due to winds, as well as the modeling method to reproduce the random behavior of components against the time series of wind speed. This method can be useful in the assessment of overhead line reliability taking into account wind loads, which makes it fit for reliability studies. Thus, overhead lines and the overall system reliability are tested using historical wind speed time series instead of traditional weather models.

Article [10] suggests increasing the reliability of external power supply for mining companies based on the alternative approach to assessment using the structural order indicator and minimum data inputs to calculate the changes in reliability dynamics due to their increasing decisions.

Paper [7] justifies the possibility of accounting for air temperature and statistical analysis of weather station observations obtained for various confidence probable limited calculated values of air temperature for the selection of wire sections of power lines to improve the efficiency and reliability of power grids.

It is only possible to identify the true causes of failures and find ways to improve the quality of operations of a mining company's power supply system through the analysis of the statistics on the damage rates for its elements. The shutdown analysis is the only validation criterion for practical decisions and theoretical concepts.

In this article, we aim to construct regression models based on the statistics obtained from the reports of Neryungrinsky open mine over 2011-2020. Since the statistics on the coal mine operations were obtained over a long period, there is enough data on the parameters determining the reliability of the power supply system to construct mathematical models.

Based on the survey of power engineers, the factors determining the failure rates of open mine power supply systems include the following: the number of high-voltage consumers connected to the same feeder, the length of the power lines, weather and climate conditions (wind speed, precipitation, etc.), and blasting operations.

3. Analyzing and modeling emergency shutouts of overhead lines at a mining company

The Neryungrinsky coal mine is located in the southern part of the Republic of Sakha (Yakutia) at an elevation of 800 meters above sea level. Its power supply system and mining equipment are operated under harsh weather conditions of the Far North.

Electric power is supplied to the mine via two circular-layout 35 kV overhead power lines with an overall length of 27.6 km. Under normal operating conditions, the circle is open, and if one of the power lines is down or when it is necessary to perform maintenance works, the power is supplied via the other line until the problem is fixed. The mine power supply system is based on the deep high-voltage commissioning principle. Mobile 35/6 kV 6.3 MVA substations are located as close to the key consumers (excavators, drilling machines, and water pumps) as possible. The 6 kV distribution grids supplying power to excavators and drilling machines are mobile and have mixed overhead cable structures. The length and composition of power lines change constantly along with the development of mining operations. The overall length of the mobile power lines is over 40 km. [13]
During operation, mining company power supply systems experience significant impacts from various factors linked to mining, geological, and weather conditions, as well as development plants [23, 20, 13]. The identification and accounting for the factors impacting the failure rate of the power supply system components is a prioritized goal of this research and open mine power supply system reliability analysis. Some of these factors have crucial impacts, while others are insignificant and usually random. Considering the practical use of mathematical models, it is necessary to review the factors that reflect the operating conditions of power supply system components and are accounted for during production. The latter is important because the data on the correlations between the failure rates of open mine distribution grids and the factors registered during production are required for their control, analysis, and forecasting.

We used dispatchers’ operating logs, repair logs, as well order and duty fulfillment logs for 2011-2020 as the source of information on failures. To study the quality of operation, we identified the causes of power supply system component shutdowns. We processed 45,000 entries retrieved from operating logs of the mining company’s power dispatcher service. These exist both in paper and on electronic media. Figure 1 shows the percentages of all high-voltage 6 kV power line shutdowns within the mining company power supply system [28].

To analyze the quality of operations, we used the company (Neryungrinsky open mine) data for 10 years between 2011 and 2020.

The failure recording system is based on the classification of shutdown causes. This classification is based on assigning each power line shutdown cause with a unique 3-digit code [28].

![Pie chart showing causes of 6 kV overhead power line shutdowns]

Figure 1. Causes of emergency shutdowns of 6 kV overhead power lines.

The analysis of overhead power line failures (Figure 1) showed that the majority of failures were caused due to cable overlapping (18%, 342 hours 14 minutes), insulator punctures (21%, 412 hours 27 minutes), cable burn-offs at joints (20%, 391 hours 39 minutes), and cable breaks (24%, 475 hours 41 minutes).

To reduce the failure rate of 6 kV overhead power lines, electric fitter crews that repair and maintain the power supply system inspect the lines every month according to the set schedule. The results of the inspections are recorded in the Power Line Inspection Log.
The operation of mining company distribution grids is heavily influenced by weather conditions, such as air temperature fluctuations, ambient humidity, and wind speed (gusts) [26, 17, 31, 18, 29, 30].

Figure 2 shows the graphic dependencies between the failure rates of high-voltage 6 kV power lines and the factors in question. The figure shows that if any of the factors increases, the failure rate increases as well, which makes further action justifiable.

![Graphs a), b), c) showing the dependencies between failure rates and factors.](image)

**Figure 2.** The graphic dependencies between the failure rates of high-voltage 6 kV power lines and the factors in question: a) total precipitation per month; b) wind speed; c) temperatures.

To calculate the impacts of the said factors on the quality of operation of the mining company's power supply system, we processed the statistics on failure shutdowns of 6 kV overhead lines for 2011-2020. Table 1 presents the distribution of average failure count and impact factors across the months of the year. The data on weather factors for the period in question were retrieved from [http://www.pogoda.ru.net](http://www.pogoda.ru.net). We used the overhead power line failure data to construct the distribution (Figure 3) that shows that there were more accidents during summer months due to thunderstorms, and in spring and autumn due to high humidity, temperatures nearing 0°C, and significant wind loads. To exclude negative values from the calculations, we increased all of the temperature values by 50°C.

We used mathematical methods for data processing, such as formulating regression equations via the least-squares method [25].
Table 1. The distribution of the average failure count of 6 kV overhead power lines and the factors in question across the months of the year.

| Month   | Precipitation, mm | Minimum air temperature $t_{min}^{'} = t_{min} + 50^\circ C$ | Average air temperature $t_{av}^{'} = t_{cp}$ | Maximum air temperature $t_{max}^{'} = t_{max} + 50^\circ C$ | Wind speed, m/s | Number of failures |
|---------|-------------------|-------------------------------------------------------------|-----------------------------------------------|-------------------------------------------------------------|-----------------|-------------------|
| January | 12.5              | 17.68                                                       | 20.98                                         | 24.59                                                       | 1.90435         | 4                 |
| February| 7.3               | 23.76                                                       | 28.68                                         | 34.03                                                       | 2.375           | 7                 |
| March   | 18                | 33.9                                                        | 39.85                                         | 46.05                                                       | 3.3175          | 5                 |
| April   | 27                | 38.82                                                       | 44.36                                         | 49.46                                                       | 3.652           | 14                |
| May     | 37.7              | 51.19                                                       | 56.68                                         | 62.12                                                       | 3.999           | 10                |
| June    | 13                | 61.52                                                       | 69.18                                         | 76.97                                                       | 3.679           | 13                |
| July    | 192.7             | 62.23                                                       | 66.19                                         | 72.86                                                       | 3.365           | 16                |
| August  | 145.9             | 59.48                                                       | 63.6                                          | 68.58                                                       | 3.544           | 21                |
| September| 61.8             | 49.17                                                       | 53.3                                          | 57.98                                                       | 3.232           | 15                |
| October | 59.3              | 43.15                                                       | 46.23                                         | 50.39                                                       | 3.494           | 6                 |
| November| 32.5              | 23.5                                                        | 27.55                                         | 31.67                                                       | 2.888           | 3                 |
| December| 12.6              | 12.83                                                       | 16.48                                         | 19.93                                                       | 2.2825          | 3                 |

Figure 3. The distribution of 6 kV overhead power line failures across the months of the year (%).
Table 2 presents regression equations reflecting paired correlations between the failure rates of 6 kV overhead lines within the mining company distribution grid and the total precipitation per month, wind speed, maximum, minimum, and average temperatures.

The closest correlation was observed between the number of failures and the minimum temperature (a correlation rate of 0.69).

Figure 4 shows regression lines characterizing the correlation between the number of overhead line failures and the amount of precipitation per month, as well as maximum, minimum, and average temperatures.

The analysis of regression lines for the correlation between the failure count and temperature showed that the highest failure rates are observed between –20 °C and +5 °C in spring and autumn, and up to +27 °C during summer months. This can be attributed to significant differences between daytime and nighttime temperatures during spring and autumn, which can result in damages if combined with high humidity. During the summer months (June, July, and August), most of the power cutoffs are caused by thunderstorms combined with strong gusts.

Table 2. The correlations between the failure shutdowns of 6 kV overhead lines and weather factors.

| Impact                      | Average value | Average value | Root square deviation | Coefficient of determination, $R^2$ | Regression equations |
|-----------------------------|---------------|---------------|-----------------------|-------------------------------------|----------------------|
| Total precipitation, mm.    | 51.691        | 9.75          | 58.59                 | 5.95                                | 0.47                 | $y = 0.0697l +6.1463$ |
| Minimum air temperature     | 39.769        | 9.75          | 17.49                 | 5.95                                | 0.699                | $y = 0.2848t_{min} -1.5781$ |
| Average air temperature     | 44.423        | 9.75          | 18.02                 | 5.95                                | 0.685                | $y = 0.2737t_{av} -2.4076$ |
| Maximum air temperature     | 49.553        | 9.75          | 18.97                 | 5.95                                | 0.668                | $y = 0.2566t_{max} -2.9651$ |
| Wind speed, m/s             | 3.144         | 9.75          | 0.645                 | 5.95                                | 0.352                | $y = 5.4808v -7.4838$  |
Figure 4. The changing of mobile 6 kV power line failure rate depending on weather factors: a) total precipitations per month; b) minimum air temperature, \( t_{\text{min}} = t_{\text{min}} + 50^\circ\text{C} \); c) average temperature \( t_{\text{av}} = t_{\text{av}} + 50^\circ\text{C} \); d) maximum temperature \( t_{\text{max}} = t_{\text{max}} + 50^\circ\text{C} \); e) windspeed.

The regression equations [25] obtained as a result of approximation can only approximately describe the correlation between the overhead line failure count and a specific factor. The calculated
number of failures obtained by inserting the factors in the regression equation varies significantly from the actual distribution, which is shown in Figure 5. The graph also shows that temperature is the most significant factor.

![Figure 5. The comparison of calculated and actual distributions.](image)

To analyze the correlations between the failure rate of 6 kV overhead power lines and the wind direction, we analyzed the power supply system of the Neryungrinsky coal mine and the wind directions. During the period in question, 23 failures due to wind gusts were recorded. The downtime for them equaled 20 hours. The analysis of power line locations showed that the majority of the faulty lines were perpendicular to the wind direction. Thus, to reduce the impacts of the wind on the failure rates of overhead power lines, it is necessary to locate the mobile lines so that the prevailing (north-western) winds had the smallest impact possible on them.

We also analyzed the impact of weather factors on all of the coal mine overhead cable lines. The distribution of open-mine distribution lines is shown in Figure 6.

![Figure 6. The distribution of combined (overhead-cable) power line failures across the months of the year.](image)
To assess the impact of weather factors, we drew up a table illustrating the distribution of their values across the months of the year (Table 3) and found regression equations (Table 4). Figure 7 shows the graphic correlations between the number of failures and the impacting factors. As we can see, the minimum temperature is the most significant of the factors because its correlation rate is 0.855.

We used the regression equations to construct distributions of the calculated failure count across the months of the year but this distribution differs from the actual one, as we can see in Figure 8.

**Table 3.** The distribution of 6 kV overhead-cable power line failures and impacting factors across the months of the year.

| Month   | Total precipitation, mm. | Minimum air temperature $t_{min}' = t_{min} + 50$ | Average air temperature $t_{av}' = t_{av} + 50^\circ C$ | Maximum air temperature $t_{max}' = t_{max} + 50^\circ$ | Number of failures |
|---------|--------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------------------------|--------------------|
| January | 12.5                     | 17.68                                        | 20.98                                        | 24.59                                       | 256                |
| February| 7.3                      | 23.76                                        | 28.68                                        | 34.03                                       | 241                |
| March   | 18                       | 33.9                                        | 39.85                                        | 46.05                                       | 301                |
| April   | 27                       | 38.82                                        | 44.36                                        | 49.46                                       | 336                |
| May     | 37.7                     | 51.19                                        | 56.68                                        | 62.12                                       | 346                |
| June    | 13                       | 61.52                                        | 69.18                                        | 76.97                                       | 324                |
| July    | 192.7                    | 62.23                                        | 66.19                                        | 72.86                                       | 387                |
| August  | 145.9                    | 59.48                                        | 63.6                                         | 68.58                                       | 448                |
| September| 61.8                     | 49.17                                        | 53.3                                         | 57.98                                       | 333                |
| October | 59.3                     | 43.15                                        | 46.23                                        | 50.39                                       | 292                |
| November| 32.5                     | 23.5                                         | 27.55                                        | 31.67                                       | 233                |
| December| 12.6                     | 12.83                                        | 16.48                                        | 19.93                                       | 247                |

**Table 4.** The correlations between the 6 kV overhead-cable line failure rates and weather factors.

| Impact                                      | Average value $\bar{X}$ | Average value $\bar{Y}$ | Root-mean-square deviation $S_x$ | Root-mean-square deviation $S_y$ | Coefficient of determination, $R^2$ | Regression equations |
|---------------------------------------------|--------------------------|--------------------------|----------------------------------|----------------------------------|-------------------------------------|----------------------|
| Total precipitation, $l$, mm.              | 51.691                   | 312                      | 58.59                            | 64.39                            | 0.583                               | $y = 0.839l + 268.6$ |
| Minimum air temperature, $t_{min}' = t_{min} + 50^\circ C$ | 39.76                    | 312                      | 17.49                            | 64.39                            | 0.731                               | $y = 3.147t_{min} + 186.8$ |
| Average air temperature, $t_{av}' = t_{av} + 50^\circ C$ | 44.423                   | 312                      | 18.02                            | 64.39                            | 0.707                               | $y = 3.006t_{av} + 178.4$ |
| Maximum air temperature, $t_{max}' = t_{max} + 50^\circ C$ | 49.553                   | 312                      | 18.97                            | 64.39                            | 0.685                               | $y = 2.809t_{max} + 172.7$ |
Figure 7. The changing of combined (overhead-cable) 6 kV power line failure rate depending on weather factors: a) total precipitations per month; b) minimum air temperature, $t_{\text{min}} = t_{\text{min}} + 50{\degree}C$; c) average temperature $t_{\text{av}} = t_{\text{av}} + 50{\degree}C$; d) maximum temperature $t_{\text{max}} = t_{\text{max}} + 50{\degree}C$
4. Conclusion

The analysis of overhead power line failures showed that the majority of failures were caused due to cable overlapping (18%), insulator punctures (21%), cable burn-offs at joints (20%), and cable breaks (24%).

The obtained mathematical models for overhead line damages can help assess the efficiency of the administrative, engineering, and production activities performed at the coal mine to improve the quality of power supply system operation at the mining site. Based on predictor assessments, we can manage the costs of purchasing cabling and wiring products, power line recovery materials, and specialized equipment. We can use the deviations of the actual failure counts for 2011-2020 from the mathematical model to assess the economic effect of the activities implemented and materials purchased.

The practical value of this research work is that its results can be used to develop forecasting models for power supply system failures, design mining company power supply systems, select power line layout and routing, perform the structural optimization and operational mode improvements of power supply systems, calculate the economic losses due to the quality of the power supply systems and their components, and organize maintenance and repair activities for mining company stationary substations and distribution grids in a rational way.

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