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Influence of Ambient Temperature on the Reliability of Overhead LV Power Lines with Bare Conductors

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Abstract: The article presents a study on the influence of weather factors (ambient temperature) on the operational reliability of overhead low-voltage power lines with bare conductors. A method for determining the average failure intensity, average failure duration, average renewal intensity, and failure rate of overhead low-voltage power lines with bare conductors as a function of ambient temperature is presented. Based on many years of observations of power lines operated in electric power distribution networks in Poland, the empirical values of the above-mentioned reliability indicators were determined. An analysis of empirical distribution compliance with the assumed theoretical model was also carried out. The reliability studies conducted showed that the highest failure intensity of the considered power lines occurred at temperatures commonly found in Poland.

Keywords: distribution network; overhead power lines; power system stability; reliability; failure; weather factors

1. Introduction

The electric power industry is a fundamental pillar of both civilization and economic infrastructure. The rising demand for power and electricity serves as a barometer for a country's economic development. Electrical engineering plays a pivotal role in the industrialization process of a nation. Most electrical equipment forms an integral part of expansive scientific, technical, and industrial facilities. Electrical equipment's vulnerability to damage significantly impacts the functionality of numerous machines, technical equipment, plants, and industrial sectors [1–4].

Modern electricity consumers have exceedingly high expectations regarding electricity supply continuity and quality. Electricity serves as the primary energy carrier in households. Power outages disrupt consumers' lives, leading to temporary inactivity, frustration, economic and social losses, hindering professional work, and potentially endangering health or life. The repercussions of power outages extend to electricity suppliers as well. Due to power failures, suppliers not only suffer profit losses but also expenses for repairing the resulting failures and refunding customers due to failure to meet guaranteed delivery standards. Therefore, ensuring the reliability of the power system is paramount given the requirements of the modern economy and the expectations of individual customers. This situation underscores the necessity for continuous development and modernization of LV distribution power grids [5–10].

Sustaining electricity supply continuity hinges on the high reliability of power system components. A deep understanding of equipment operational principles is required as well as equipment failure analyses and research into power equipment reliability. A crucial aspect involves the reliability of transmission and distribution system components and auxiliary equipment [11–14].

Efforts to enhance product reliability encompass the entire spectrum from design development assumptions to production. A crucial aspect of product reliability is acknowledging the potential impact of environmental exposure on equipment at the outset of its development. Identifying the negative effects of specific environmental factors on equipment during product design enables a wider array of methods to mitigate disturbances at a

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lower implementation cost. Conversely, if issues arise during product reliability testing, the available methods to address them are limited, and implementation costs are higher. Environmental impact was considered at least twice during the product reliability process, namely during the design and reliability testing phases.

Random factors are primarily responsible for damage to power systems. Disruptions in electric power systems stem from various sources related to system component operation conditions and external factors. Key among these are design flaws, material deficiencies in components, aging, component overload, human error or sabotage, and weather conditions [15–18].

Environmental influence on facilities' operational behavior has long been recognized, leading to the development of relevant standardization measures. These measures determine whether a product can fulfill its purpose when subjected to specific environmental conditions for a defined duration and intensity. Given its widespread deployment, power equipment must adapt to diverse environmental conditions (climate) [19–22].

The main purpose of this paper is to quantify the actual influence of ambient temperature on the performance and reliability of power equipment operated in distribution grids. Quantitative analyses showed the influence of certain factors on technical equipment but not the degree of influence. By knowing the quantitative impact of weather factors on power equipment, it is possible to determine the ranges at which most failures occur. Having this knowledge and knowing the forecasted weather conditions, managers of the distribution grid can prepare themselves (for example, by mobilizing additional standby crews) for an increased grid failure rate. These measures can improve failure duration.

2. Materials and Methods

2.1. Influence of Ambient Temperature on Overhead Power Lines Operation

The Polish power system primarily relies on overhead grids, with buried cables reserved for use in major urban areas for LV and MV power transmission. Overhead lines are susceptible to weather and climate conditions, posing a significant disadvantage [23–25].

Factors such as high and low air temperatures, strong winds, or soot accumulation can markedly increase the likelihood of power system failures [26,27].

Temperature influences power equipment operation and can be categorized into high temperature, low temperature, and temperature fluctuations [28].

High temperatures can extensively damage products by deteriorating material properties, leading to softening, melting, sublimation, evaporation, reduced viscosity, dimensional changes, and thermal aging [29–31].

Elevated outdoor temperatures primarily affect the thermal expansion of overhead line conductors, resulting in increased conductor sagging. Thermal expansion poses a serious risk of reducing the insulation clearance between the line and objects directly beneath it, potentially leading to voltage surges. Moreover, rising outdoor temperatures are correlated with cables' maximum operating temperature. Excessive temperature increases conductor operating temperatures, causing overhead line degradation due to increased resistance and, thus, reducing capacity, especially in calm weather conditions [2,26].

Conversely, freezing temperatures increase material brittleness, viscosity, and liquid solidification while reducing mechanical strength, leading to material contraction. Changes in linear dimensions can cause mechanical damage such as jamming and galling of mating moving parts. Material contraction can weaken joints and cause fractures or breaks in parts. Additionally, frost and ice accumulation increase product weight, potentially causing damage. Electrical parameters of materials also change under the influence of freezing temperatures, affecting electrical conductivity, dielectric loss, dielectric constant, and magnetic permeability, thereby altering component and product parameters. As temperatures decrease, the dielectric loss factor decreases, whereas electrical strength and insulation resistance increase. Extremely low temperatures lead to ice buildup on overhead lines and mechanical stress [4,26,29,32,33].

In the available literature [1,5,11,12,29,34–36], the influence of weather conditions on technical equipment operation is typically discussed theoretically, with analyses presented qualitatively rather than quantitatively. Despite acknowledging this influence, these studies often fail to quantify its strength. Consequently, publications examining the actual influence of environmental conditions on equipment failure rates are scarce [37–41].

2.2. Method of Analysis

For the case study presented in this paper, statistical methods were chosen due to their high accuracy, requiring the collection of extensive statistical data. The econometric models presented in the paper were constructed using data from the Electricity Distribution Company of Poland and the Institute of Meteorology and Water Management.

Firstly the average intensity of damage to overhead lines was analyzed. The theoretical dependence used to determine the average damage intensity is formulated as follows [32,41]:

$$\overline{\lambda} = \frac{2 \cdot m}{(n_p + n_k) \cdot \Delta t} \tag{1}$$

where,

m—observed number of failures in the time interval Δt;

n_p—sample size at the beginning of the observation period;

n_k—sample size at the end of the observation period;

Δt—total observation time.

The aim of the study was to correlate environmental conditions with damage intensity λ. To achieve this, Formula (1) was adjusted by introducing τ, the relative time of occurrence of a given climatic exposure over the considered time period Δt.

To determine the temperature dependence of the intensity $\overline{\lambda} = f(T)$, it is necessary to determine the values of $\overline{\lambda}(T_i)$ for successive ranges of ambient temperature T_i [°C]. For this purpose, expression (1) considers the number of failures $m(T_i)$ that occurred in a specific i-th ambient temperature interval and the duration of this ambient temperature interval $\Delta t(T_i)$:

$$\overline{\lambda}(T_i) = \frac{2 \cdot m(T_i)}{(n_p + n_k) \cdot \Delta t(T_i)} = \frac{2 \cdot m(T_i)}{(n_p + n_k) \cdot \tau(T_i) \cdot \Delta t} \tag{2}$$

where,

$m(T_i)$—number of failures that occurred during the time interval $\Delta t(T_i)$;

$\Delta t(T_i)$—the time of occurrence of the ambient temperature T_i during the considered time period Δt;

$\tau(T_i)$—the relative time of occurrence of the ambient temperature T_i during the considered time period Δt.

$$\tau(T_i) = \frac{\Delta t(T_i)}{\Delta t} \tag{3}$$

By determining $\overline{\lambda}(T_i)$ values for successive i ranges, an empirical dependence between failure intensity and ambient temperature is derived.

However, determining empirical values $\overline{\lambda} = f(T)$ does not fully encompass the scope of the study, making an approximation function (mathematical model) necessary for this dependency.

The approximation function can be any mathematical function. Various types of functions were considered as mathematical models, including exponential, power, logarithmic, and their superpositions. For each of them, the model's degree of fit to the empirical data was determined using the Pearson correlation coefficient r. For the sake of clarity and simplicity of notation, a polynomial was adopted as the approximation function. Since the coefficients of the approximation function obtained for orders higher than fourth-order are close to zero, it was decided to approximate the function with a polynomial of at most fourth-order. The form of such a polynomial is as follows:

$$f(i) = a \cdot T^4 + b \cdot T^3 + c \cdot T^2 + d \cdot T + e \quad (4)$$

where,

i—ambient temperature value;

a, b, c, d, e—coefficients of the approximation function.

Further research determined the influence of ambient temperature on failure removal time (restoration time). The failures were assigned to the ambient temperature intervals where they occurred. In each interval, the average failure removal times $\overline{t_a}$ were determined.

Failure removal time, also called failure duration or restoration time, refers to the period during which equipment transitions from an unfit state back to a state of operable fitness. It is a crucial parameter for reliability analysis and evaluating the economic impact of failures, providing insight into the extent of failure [6].

However, determining empirical dependence $\overline{t_a} = f(T)$ does not fully encompass the scope of the study, necessitating the development of an approximation function (mathematical model) for this dependency based on the previously described Formula (4).

Assuming stationarity and ergodicity of the occurring processes, the dependence of the failure coefficient q on the ambient temperature $q = f(T)$ was determined.

The formula to determine the failure coefficient q is as follows [32]:

$$q = \frac{\overline{\lambda} \cdot \overline{t_a}}{1 + \overline{\lambda} \cdot \overline{t_a}} \quad (5)$$

By substituting the previously developed theoretical and empirical models of average damage intensity $\overline{\lambda}$ and average failure duration $\overline{t_a}$ into Equation (5), the dependence of the failure rate on the ambient temperature T $q = f(T)$ was determined.

Another reliability indicator analyzed was renewal intensity. The equation for determining the average renewal intensity $\overline{\mu}$ takes the following form [1,32]:

$$\overline{\mu} = \frac{\overline{\lambda} \cdot (1 - q)}{q} \quad (6)$$

By substituting the previously developed theoretical and empirical models of the average damage intensity $\overline{\lambda}$ and the failure rate q into Equation (6), the dependence of the average renewal intensity of equipment on ambient temperature T $\overline{\mu} = f(T)$ was determined.

To expedite the calculations in this paper, Statistica (version 13.3) and Matlab (R2021a) packages were utilized.

2.3. Statistical Data

The observation period spans ten years, during which 87,673 ambient temperature measurement points were recorded at the Kielce-Suków weather station. In addition, 10,374 faults were documented on overhead LV lines in Kielce and its immediate vicinity. According to EN 50160:2023-10 [42], a low voltage corresponds to an rms value of $U_n \leq 1$ kV. Ambient temperature statistics were obtained from the Institute of Meteorology and Water Management. Equipment failure data were sourced from the National Electricity distribution company. At the beginning of the observation period, the total length of overhead LV lines with bare conductors in this company was 1494.90 km, decreasing to 1383 km at the end of the observation. The replacement of overhead power lines with power cable lines led to a decrease in the analyzed length of power lines. The line lengths for each year of observation are shown in Table 1.

Table 1. Total lengths of analyzed LV lines in successive years of observation.

Year of Observation	1	2	3	4	5	6	7	8	9	10
Overhead LV lines with bare conductors [km]	1494.9	1495	1447	1447	1444	1432	1421	1408	1401	1383

3. Results

Analysis of the Influence of Ambient Temperature on the Reliability of Overhead LV Lines with Bare Conductors

Figure 1 shows empirical data and the approximation functions of the average damage intensity, average failure duration, average renewal intensity, and failure rate of overhead LV lines with bare conductors as a function of ambient temperature.

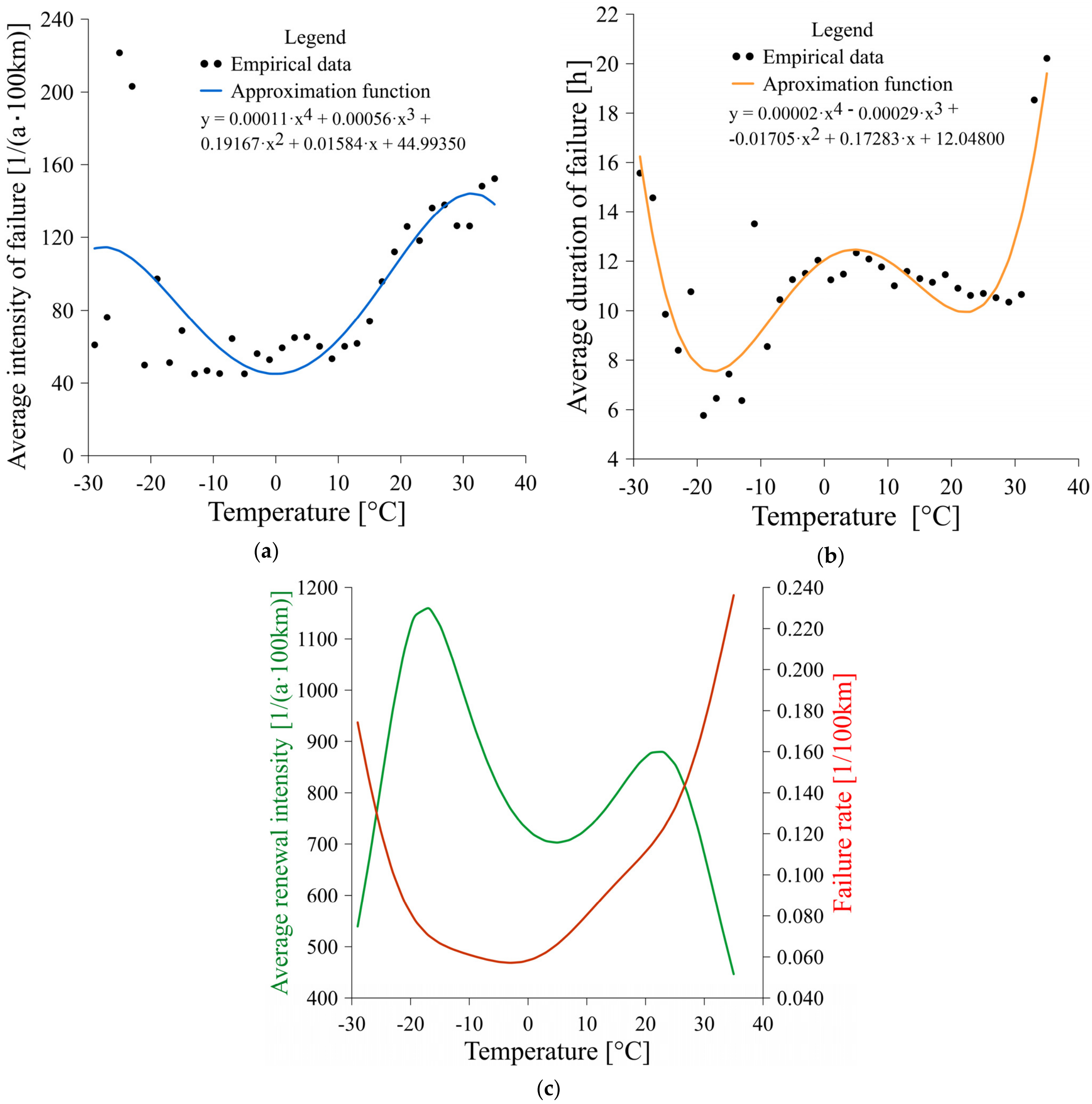

Figure 1. Dependence of average failure intensity on ambient temperature (**a**); average failure duration on ambient temperature (**b**); failure rate and renewal intensity on ambient temperature (**c**) for low-voltage overhead lines with bare conductors.

The constructed models were evaluated for goodness of fit to empirical data using the following measures: multiple correlation coefficient, coefficient of determination, coefficient of convergence, and coefficient of random variation. A sign test and a series test were also conducted. The results of this verification are shown in Table 2.

Table 2. Verification of failure intensity model for overhead LV lines with bare conductors and the duration of failure model for overhead LV lines with bare conductors.

An average failure intensity on ambient temperature $\overline{\lambda}(T_i)$ [1/(a·100 km)]					
Multiple correlation coefficient R	Coefficient of determination R^2	Coefficient of convergence φ^2	Coefficient of random variation W_e	Sign test	Series test
0.72	0.52	0.48	0.37	$l_0 = min(l^+, l^-) = min(14, 14) = 14$; $l_0 = 14 > 8 = l_\alpha$; $l_0 \notin R_\alpha = (-\infty, 8)$	$l^+ = 14,\ l^- = 14$ $k = 11,\ k_1 = 10,\ k_2 = 19$ $k_1 < k < k_2$ $10 < 11 < 19$
Average failure duration on ambient temperature $\bar{t}_a(T_i)$ [h]					
Multiple correlation coefficient R	Coefficient of determination R^2	Coefficient of convergence φ^2	Coefficient of random variation W_e	Sign test	Series test
0.87	0.76	0.24	0.13	$l_0 = min(l^+, l^-) = min(16, 17) = 16$; $l_0 = 16 > 10 = l_\alpha$; $l_0 \notin R_\alpha = (-\infty, 10)$	$l^+ = 16,\ l^- = 17$ $k = 11,\ k_1 = 12,\ k_2 = 22$ $k_1 < k < k_2$ $12 > 11 < 22$

Empirical and theoretical values derived from established models of damage intensity, failure duration, failure rate, and renewal intensity are shown in Table 3. Each row represents the average values for the right-hand-closed ambient temperature interval.

Table 3. Empirical and theoretical reliability indicators for overhead LV lines with bare conductors as a function of ambient temperature.

Temperature Range [°C]	$m(T_i)$	$\overline{\lambda}(T_i)$ **[1/(a·100 km)]**		$\bar{t}_a(T_i)$ **[h]**		$q(T_i)$ **[1/100 km]**		$\overline{\mu}(T_i)$ **[1/(a·100 km)]**	
	Number of Failures	**Empiric**	**Theoretic**	**Empiric**	**Theoretic**	**Empiric**	**Theoretic**	**Empiric**	**Theoretic**
(−30,−28>	1	60.93	113.87	15.57	16.24	0.097693	0.174314	562.74	539.38
(−28,−26>	1	76.16	114.52	14.57	13.04	0.112407	0.145616	601.37	671.91
(−26,−24>	4	221.56	112.46	9.86	10.70	0.199641	0.120781	888.21	818.64
(−24,−22>	15	203.09	108.28	8.39	9.10	0.162894	0.101113	1043.69	962.57
(−22,−20>	5	49.94	102.51	10.76	8.12	0.057814	0.086734	813.87	1079.34
(−20,−18>	15	97.23	95.64	5.76	7.63	0.060131	0.076944	1519.66	1147.38
(−18,−16>	11	51.16	88.14	6.46	7.55	0.036368	0.070631	1355.59	1159.72
(−16,−14>	26	68.87	80.40	7.44	7.78	0.055244	0.066630	1177.87	1126.26
(−14,−12>	28	45.01	72.80	6.37	8.22	0.031673	0.063960	1376.17	1065.35
(−12,−10>	55	46.80	65.65	13.50	8.81	0.067297	0.061943	648.66	994.20
(−10,−8>	63	45.16	59.24	8.55	9.48	0.042202	0.060226	1024.88	924.46
(−8,−6>	159	64.37	53.82	10.45	10.16	0.071300	0.058742	838.42	862.36
(−6,−4>	185	45.14	49.57	11.26	10.81	0.054826	0.057633	778.20	810.48
(−4,−2>	411	56.18	46.65	11.51	11.39	0.068755	0.057163	760.99	769.38
(−2,0>	574	52.79	45.17	12.03	11.86	0.067608	0.057622	728.01	738.71
(0,2>	724	59.31	45.20	11.24	12.20	0.070745	0.059240	779.10	717.83
(2,4>	659	64.91	46.77	11.47	12.41	0.078355	0.062129	763.46	706.05
(4,6>	653	65.36	49.87	12.34	12.46	0.084315	0.066249	709.85	702.83
(6,8>	601	60.21	54.42	12.09	12.38	0.076710	0.071408	724.65	707.71
(8,10>	548	53.35	60.34	11.76	12.16	0.066858	0.077301	744.66	720.27
(10,12>	607	60.09	67.48	11.00	11.84	0.070183	0.083572	796.06	739.98
(12,14>	648	61.74	75.66	11.59	11.44	0.075508	0.089892	755.89	765.97
(14,16>	750	74.09	84.64	11.30	11.00	0.087215	0.096044	775.37	796.58
(16,18>	881	95.82	94.15	11.14	10.57	0.108657	0.101998	786.02	828.92
(18,20>	791	112.03	103.89	11.46	10.21	0.127784	0.107979	764.66	858.23
(20,22>	689	125.91	113.49	10.91	9.98	0.135566	0.114500	802.88	877.71
(22,24>	487	118.12	122.56	10.62	9.96	0.125233	0.122350	825.09	879.19
(24,26>	392	136.24	130.66	10.70	10.24	0.142662	0.132511	818.77	855.39
(26,28>	243	137.85	137.31	10.53	10.91	0.142108	0.145979	832.21	803.28
(28,30>	97	126.28	141.97	10.35	12.06	0.129845	0.163480	846.28	726.44
(30,32>	41	126.16	144.08	10.65	13.81	0.133017	0.185125	822.32	634.20
(32,34>	9	148.2	143.03	18.54	16.29	0.238794	0.210064	472.43	537.86
(34,36>	1	152.32	138.17	20.22	19.61	0.260097	0.236234	433.31	446.72

The highest number of failures in overhead LV lines with bare conductors occurred within the temperature range of about −7–27 °C. These temperatures' relative time of occurrence during the observation period was also the longest. These temperatures fall within the typical range experienced in Poland throughout the calendar year. Notably, extreme temperatures, with a low frequency of occurrence during the observation period, were associated with the highest average failure intensity $\overline{\lambda}$, the highest average failure duration $\bar{t}_a$, the highest value of failure rate q, and the lowest value of average renewal intensity $\overline{\mu}$.

The highest average failure intensity $\overline{\lambda} = 221.56\ [1/(\mathrm{a} \cdot 100\ \mathrm{km})]$ was observed at an extremely low temperature of −25 °C. Conversely, the highest average failure duration ($\bar{t}_a = 20.22\ [h]$), the highest theoretical failure rate ($q = 0.236234\ [1/100\ \mathrm{km}]$), and the lowest theoretical average renewal intensity ($\overline{\mu} = 446.72[1/(\mathrm{a} \cdot 100\ \mathrm{km})]$)) were observed for a temperature of 35 °C, which marked the highest temperature recorded during the observation period.

These indicators' dependence on ambient temperature is linked to several factors. High temperatures correlate with increased lightning activity, while low temperatures coincide with ice and soot. Moreover, during periods of high temperatures, cooling conditions for equipment become challenging, potentially leading to temperatures exceeding permissible limits under heavy load conditions. Conversely, at low temperatures, the ductility of insulating materials and conductors decreases, making them more susceptible to damage from even minor external forces. Furthermore, the lubricating materials in moving joints may lose some of their properties. As a result of temperature expansion, the dimensions of the components forming the moving connections decrease, causing increased friction and potential damage during movement. Sudden temperature changes, such as those induced by precipitation during high temperatures, pose additional risks, leading to rapid cooling of heated porcelain elements (insulators, lightning arrestors). The same applies to lightning arresters operating at very low temperatures. Cyclical changes in ambient temperature adversely affect the technical condition of equipment. During hot summer weather, equipment components are heated up during the day and cooled down at night due to lower temperatures. Given the non-uniform temperature expansion of different materials, such cyclical changes in ambient temperature can lead to power equipment components leaking or loosening. A drop in temperature can adversely affect layered insulation systems, as moisture freezing within the insulation can cause damage. Moreover, at low ambient temperatures, overhead line cables contract, increasing tension forces, which, in combination with potential damage to support structures or insulators, can fail. Low ambient temperatures adversely affect the moving parts of power equipment, causing them to freeze together and fail upon movement.

4. Discussion

The influence of ambient temperature on the failure rate of electrical power equipment has long been recognized. However, there is a general lack of studies that quantify the nature of this dependency.

Analyses conducted in this study confirm that ambient temperature influences the operation of overhead LV lines with bare conductors.

Developing models for the dependence of reliability indicators on ambient temperature will enable distribution grid managers to better prepare (for example, by mobilizing additional standby crews) for increased grid failures due to forecasted meteorological phenomena. Understanding the failure rate of specific power equipment under given environmental conditions will facilitate quicker removal of anticipated failures and inform future efforts to improve the design of specific equipment. Additionally, knowledge of the models can also be used to determine optimal operational conditions for electric distribution grids.

However, the research presented in the paper does not exhaust the issue of how ambient conditions influence electric power facilities' reliability. Future research by the authors will aim to isolate other weather factors and examine their qualitative and quantitative impact on the operation of power equipment. Furthermore, the author intends to develop multidimensional reliability models that incorporate additional weather factors alongside ambient temperature.

Additionally, the weather's impact on the reliability of low-voltage overhead lines with bare conductors discussed in this article (ambient temperature) will be further investigated based on location (urban areas, rural areas).

5. Conclusions

This article presents the impact of ambient temperature on the technical conditions of overhead power lines. In the study, it was found that low-voltage overhead power lines with bare conductors are susceptible to ambient temperature changes. It is possible to quantify the effects of ambient temperature on the reliability of overhead power lines.

The effect of ambient temperature on the operation of low-voltage overhead power lines with bare conductors was defined by determining reliability indices such as failure intensity, failure duration, renewal intensity, and failure rate.

The reliability studies presented in the article were carried out using mathematical models. These models proved to be a suitable tool for assessing the failure risk of power lines under consideration. Reliability studies conducted based on data from more than ten thousand failures show that the power lines' highest failure intensity occurred at temperatures commonly found in Poland.

The results obtained allow us to conclude that ambient temperature impacts overhead power lines and requires further analysis. Further research should be carried out to apply new materials to the construction of power lines. Technological changes are also needed to reduce the negative impact of ambient temperature on this type of equipment.

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