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Article

Assessment of the Risk of Damage to 110 kV Overhead Lines Due to Wind

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Abstract: The article presents an assessment of the risk of damage to 110 kV overhead power lines as a result of the impact of wind of variable speeds on that equipment. A statistical method for the assessment of the reliability of power structures in conditions of variable strength of the structure and at variable exposure values is presented. This method is based on the analysis of the shape and mutual location of the distributions of the probability density of the momentary resistance (strength) of the tested structure and the exposures of variable values occurring in its surroundings. The risk of wind damage to 110 kV lines has been determined on the basis of many years of observations of wind speed and failure rate of the lines. Wind has been shown to be the fault factor or co-factor responsible for damage in one in five failures of such equipment. The final part of the article includes an analysis of the obtained results and their interpretation.

Keywords: reliability; 110 kV overhead lines; wind; damage; distribution grids

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1. Introduction

Electricity is the basis for the functioning of modern society. Access to power grids determines the development of industry and local communities, and thus also enables and shapes settling. In many cases, electricity is the only systemic energy carrier. Therefore, it is very important nowadays to maintain high standards of energy quality and continuity of energy supply to consumers. This is possible in the case of proper design, construction and operation of power grids. At the stage of grid design, the most important issue is the optimal selection of construction materials and equipment parameters, ensuring their failure-free operation. Correct operation, in turn, is not possible without in-depth knowledge of the laws and rules governing the reliability of power equipment. Determination of appropriate methods of operation is possible on the basis of many years' observations of individual power equipment units, including their failure rate. Such research allows the determination of the causes of failures, but also identifies the weakest equipment components and the weakest units in the power grid. Despite many research works and studies, the issue of the reliability of power equipment and systems is still not fully recognised. Further analysis and research are needed to increase our knowledge of damage mechanisms. This, in turn, will form the basis for developing methods to reduce failure rates in power systems. The importance of the problem is evidenced by the significant number of publications on this subject [1–7].

The definition introduced in 1974 in document [8] and reiterated in many standardization documents all over the world states that reliability should be understood as the ability of structures to perform a given function under certain conditions and for a specified period of time, while not exceeding permissible parameters. In most tests, "specific conditions" are treated as constant, assuming that reliability is only a function of time. This is obviously an incorrect assumption since time does not directly affect the reliability of structures. The ability or inability of a structure to perform specific tasks (functions) is a result of the impact of various internal and external (environmental) exposures. These exposures change over time, with these changes being probabilistic. Another simplification leading to incorrect research conclusions is the assumption of the permanent resistance of tested structures to exposure. Meanwhile, due to the cumulative effect of exposures and the continuous change of working conditions of a structure, its resistance varies and is also random. It is therefore important to establish the relationship between the momentary resistance (strength) of a structure and the exposure at the same time. Due to the problem of collecting reliable empirical data and the labour intensity of this type of research, this issue is usually omitted in work on failures of power systems and equipment.

Factors that have a major impact on the failure of power systems are environmental exposures. Their impact on the operational properties of structures has been known for a long time. As early as in the 1950s and 1960s, standardisation acts on environmental testing were established in many countries to check whether a structure would be able to carry out its tasks undisturbed if certain environmental exposures were encountered at a certain intensity and for a certain period of time. Currently, there are few studies on the impact of environmental conditions (e.g., climatic conditions) on the operation of power systems in the scientific and technical literature [9,10]. Much more often, the influence of weather on the variability of electrical loads [11] or the production of energy in renewable sources (photovoltaic and wind power plants) is analysed, e.g., [12–15]. If studies on the influence of environmental factors on the failure of power systems are already carried out, two aspects are usually taken into account: the impact of temperature and the total impact of other environmental exposures [4,8,16,17]. Meanwhile, as the statistics of power equipment failure show, the effects of such factors as lightning, wind, air humidity, icing and rime are very high. It is therefore necessary to carry out detailed analyses and independently examine the impact of particular factors on the occurrence of damage to power grid structures. A serious problem that may arise in this case is, as already mentioned, the lack of reliable data on the basis of which such an analysis could be conducted. In the official statistics of failure conducted by distribution companies, the environmental factor is very rarely indicated as the cause of damage (except for lightning, icing and rime). Electrical fitters who repair faults in power grids usually do not have enough knowledge to recognize the failure mechanism of a device. Therefore, very often, they enter enigmatic statements such as "ageing processes" or "cause unknown" as the cause of damage in the failure report.

The data presented in Figure 1 illustrates the structure of the causes of damage to 110 kV overhead lines and is quite reliable. It comes from the author's research, based on more than a thousand 110 kV overhead line failures that occurred in central Poland (wind zone W1). It should be emphasized that in every doubtful case the author tried to verify the cause of the line damage. Only in a few cases, which are shown in Figure 1 as "Other and unknown", it was not possible to identify the cause unambiguously. As the statistics of electricity distribution companies show, wind is the factor responsible for almost every fifth 110 kV overhead line failure (Figure 1). Why does this happen when wind impact on cables and supporting structures is taken into account when designing power lines [18–21]? There can be many potential causes. First of all, the wind speed assumed for the design calculations may be too low, which underestimates the maximum design value of forces acting on the line structure. Moreover, during operation, lines may be too poorly monitored, which may lead to a situation where small mechanical damage (loose connectors or ties, wire stripping, etc.) not detected at the right moment, at a sufficiently high wind speed cause line failure. In such a situation, the wind is only a factor accelerating damage. There is also a possibility that official statistics of distribution companies are not very reliable. In order to determine the risk of damage to 110 kV overhead lines due to wind, extensive reliability tests have been carried out.

The aim of the research, the results of which are presented in the article, was to develop a mathematical model allowing for an accurate assessment of the risk of damage to 110 kV lines due to external (environmental) factors, in this case wind. This model is based on probability theory and mathematical statistics. In general, its idea is to determine the probability of the simultaneous occurrence of a certain momentary strength (resistance) of a structure to an existing exposure and a certain momentary value of this exposure. This issue ultimately boils down to the analysis of shape and mutual location of probability density distributions of these two random variables (structure strength and exposure values).

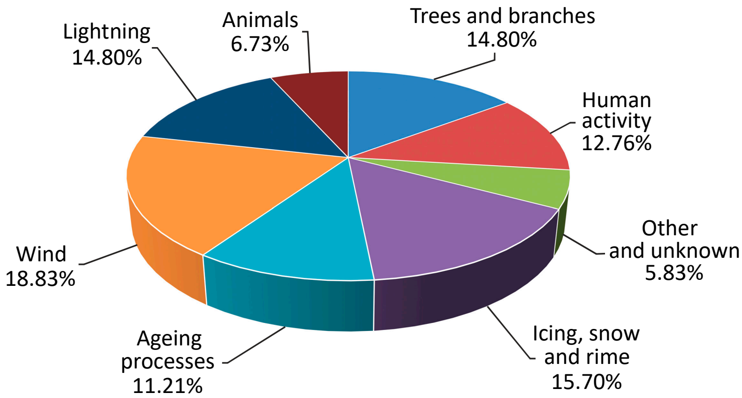

Figure 1. Percentage share of causes of 110 kV overhead line failures [4].

2. Materials and Methods

2.1. Impact of Wind on the Operation of Power Equipment

All overhead power equipment and its components are subject to wind exposure, with the type and degree of exposure varying depending on the component under consideration and the place of its operation (environmental conditions). The effects of wind exposure may vary. In general, they can be divided into reversible and irreversible. The concept of reversible effects should be understood as events that are characterised by the structure returning to its initial condition of operability once the exposure has subsided (e.g., transient short circuits in power lines). Irreversible damage, in turn, can be divided into sudden, very strong exposures, and cumulative, resulting from a large number of low or medium exposure cycles. The models and analyses presented later in the article concern irreversible effects only.

The range of wind speeds observed on Earth is very wide. The maximum measured wind speed in a gust was over 110 m/s (113.33 m/s-Barrow Island, Australia). The highest wind speed in a gust measured officially in Poland was 95.83 m/s (Meteorological Station on Śnieżka). However, these are not record values. Much higher wind speed values are reached in a whirlwind. The highest value on Earth, registered with Doppler radar, was over 133.33 m/s (Oklahoma, USA), while in Poland it was 102.50 m/s (near Lublin). Average annual wind speed in Poland is about 3–4 m/s. The highest wind speeds occur in late autumn, winter and early spring. Then they are usually accompanied by negative air temperatures or large quantities of precipitation. Such environmental conditions are unfavourable and are conducive to the occurrence of power equipment failures, especially overhead lines.

Wind speed has a direct effect on line statics, causing forces to act on structures and wires. Therefore, wind is a factor influencing the choice of structural solutions for overhead line elements such as: supporting structures, wires and insulators. If the wind pressure force is incorrectly estimated, serious mechanical damage to these components can occur. However, large gusts of wind primarily contribute to the occurrence of mechanical damage to the lines by breaking the wires, damaging insulators, overturning or breaking the supporting structures (pillars), or even dropping branches (or falling whole trees) on the power lines [22].

Under the influence of wind, the cables lean out of their proper position (occurring in windless weather) and may come too close to the adjacent phase wires or to the structure, causing short circuits [3].

Rapid changes in wind speed can cause mechanical stress in structural materials. This leads, among other things, to weakened joints, cracks and fractures [17].

When discussing the impact of wind on the operation of power equipment, the issue of air mass temperature cannot be ignored. Particularly unfavourable conditions occur for power equipment in the case of high-speed wind and very low temperature (winter period). Such wind reduces the temperature of structural elements much faster than would be the case in windless weather. Such a situation in turn causes an increase in the brittleness of materials, increased viscosity and solidification of liquids, reduced mechanical strength and shrinkage of materials. As a result of the change in size, mechanical damage occurs, consisting, among other things, in the seizing and jamming of matching moving parts. Shrinkage of materials, and thus of equipment components, can weaken joints and cause fractures and cracks. A change in the hardness and dimensions of seals may cause the equipment to unseal. The viscosity of greases and oils increases, which makes it difficult for moving parts to work, until they are damaged if the greases freeze. Under the influence of negative temperatures, the electrical parameters of materials change, including electrical conductivity, dielectric loss, dielectric constant and magnetic permeability [16]. The above phenomena depend primarily on the occurrence of negative ambient temperatures, but are nevertheless considerably accelerated in conditions where at negative temperatures there is a wind of significant speed.

Wind also influences the process of failure recovery. Its high speed can significantly hinder the work of repair teams, which in turn increases the duration of failures. Under extreme conditions it can make repair work impossible [22].

2.2. Data and Sources

Statistical data on wind speed come from meteorological stations located in Świętokrzyskie Voivodeship in Poland. These stations are observation points of the Institute of Meteorology and Water Management. The data is in the form of hourly average wind speeds and was recorded between 2007 and 2016.

Figure 2 marks the area covered by the research. According to standard [19], this area belongs to wind zone W1.

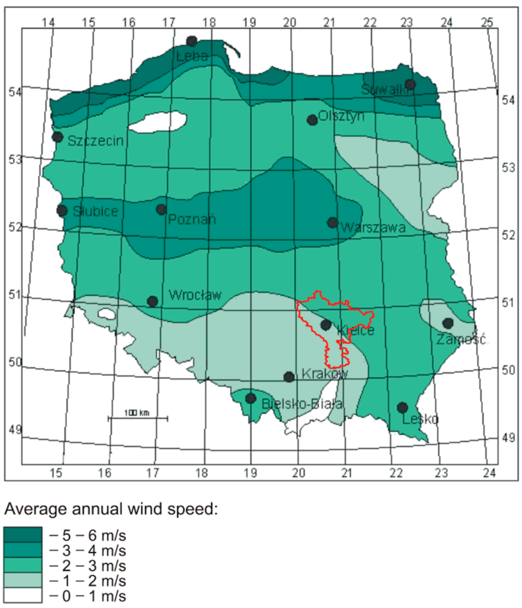

Figure 2. The wind map of Poland with a marked area of the conducted reliability tests of 110 kV lines (acc. to the Institute of Meteorology and Water Management).

The random sample of wind speed, collected over 10 years of observation, has a total of 87,648 samples.

The data on 110 kV line failure rate comes from selected regions of Świętokrzyskie Voivodeship in Poland. The Distribution System Operator here is the largest Polish distribution company. The research period covers the years 2007 to 2016. During this period, 1453 km of 110 kV lines were in operation in the observed area. The surveyed population of lines includes structures of different ages. The share of lines of different ages is presented in Table 1.

Table 1. Age structure of the analysed 110 kV lines.

<10 Lat	10–25 Lat	25–40 Lat	>40 Lat
11%	17%	30%	42%

The 110 kV overhead lines built in the 1970s and 1980s were designed according to the guidelines included in standard [23]. It was in force until 1998, when it was updated and supplemented to bring it into line with Western European standards. In subsequent years, these lines were designed according to the standards contained in standard [24]. In 2002, standard [20] was implemented in the Polish normalization. It has been amended and supplemented many times in the following years, including in 2005, 2007, 2010, 2013 and 2016. Additional provisions defining the standards for the construction of right-of-way structures in Poland are specified in standards [18,19,21]. Currently, the basic requirements for overhead lines already at the design stage are contained in standard [20], which is the equivalent of the European standards, extended by Normative National Aspects (NNA) [19]. The NNA includes, among others, deviations from the standard resulting from existing national legislation or practices.

Due to the limited volume of the article, it is not possible to present all the designs of 110 kV lines, therefore the most important aspects of the 110 kV line design will be discussed. In Poland, aluminium conductor steel-reinforced cables are used as cables in 110 kV overhead lines in Poland. The recommended designs are: AFL-6-240 mm^2, AFL-8-350 mm^2 and AFL-8-525 mm^2. In older solutions, there are few instances of using AFL-6-120 mm^2 cable. The 110 kV lines are protected against lightning with one or two AFL-1,7 ground wires with cross-sections of 50, 70 and 95 mm^2 and AFL-6 ground wires with cross-sections of 120 and 240 mm^2. In new constructions, OPGW wire with built-in telecommunication fibre optic cable is very often used.

Mainly B2, O24 or OS24 series steel lattice poles are used as supporting structures for 110 kV lines. Tubular poles, e.g., EWN series, are also increasingly used.

LP75 or LPZ75 series long-rod insulators are used as insulators in 110 kV lines. Composite insulators, such as the ŁO, ŁP or ŁPV series, are increasingly used in new construction.

The large variety of design solutions of 110 kV line forces the necessity of conducting reliability tests for a random test, which is not fully homogeneous. The obtained parameters and reliability indicators are in this case averaged values for the whole population.

Observation of 110 kV overhead line failure rate covers a period of 10 years. During this time 223 failures of the lines were observed.

2.3. Model Approach-Unreliability Testing of a Structure under Conditions of Its Variable Strength and under Exposures of Variable Values

On the basis of the analysis of the strength of power structures and their environmental exposures occurring in the place of operation, three characteristic cases of their probability density function relations can be distinguished (Figure 3):

1. Relatively low dispersion of load values:

$$\sigma_L << \sigma_S, \tag{1}$$

2. Relatively low dispersion of strength values:

$$\sigma_L >> \sigma_S, \tag{2}$$

3. Approximate dispersion of load and strength values:

$$\sigma_L \approx \sigma_S, \tag{3}$$

where: σ_L denotes load standard deviation and σ_S the structure strength standard deviation.

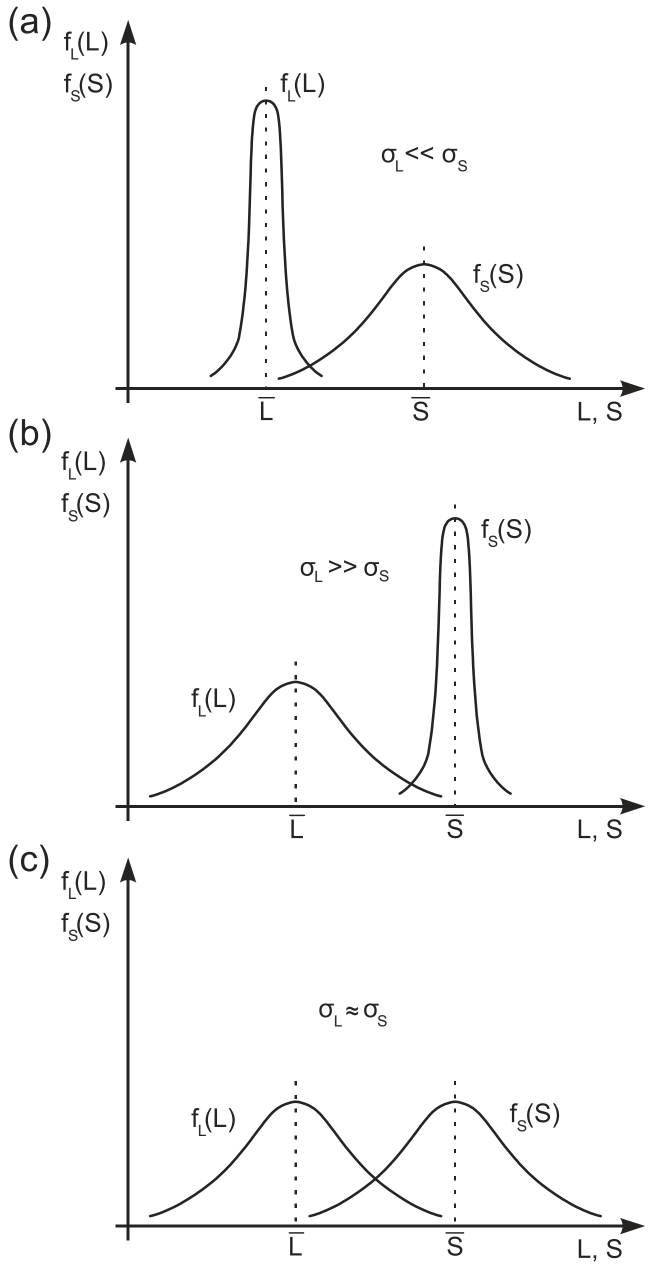

Figure 3. Functions of load (exposure) probability density $f_L(L)$ and element's strength $f_S(S)$ for the three cases of their relation under consideration (cases (**a**–**c**) are discussed in the text).

In the first presented case (Figure 3a), where the load has a small spread of values (concentrated load), while the strength of the structure is characterized by high variability of values, the reliability of the structure R can be expressed by a relation:

$$R \cong \int_{\bar{L}}^{\infty} f_S(S)dS, \tag{4}$$

where: $f_S(S)$ denotes the structure's strength probability density function and $\overline{L}$ is the expected value of the structure's load.

The situation is different in the case presented in Figure 3b. This is a small spread of the structure's strength values (concentrated strength), with a significant spread of the load values. In this situation the reliability of the structure can be described as:

$$R \cong \int_0^{\overline{S}} f_L(L)dL, \tag{5}$$

where $f_L(L)$ is the structure's load probability density function and $\overline{S}$ is the expected value of the structure's strength.

The issue is much more complex for the case presented in Figure 3c. In this situation, consideration should be given to the mutual location of the probability distribution of the individual load and strength values of a structure. The probability that the load of a structure will not exceed its momentary strength is the probability of the simultaneous occurrence of two independent events (Figure 4), i.e.:

– structure's load of L_{li}:

$$p_1 = f_L(L_{li})dL, \tag{6}$$

– structure's strength greater than or equal to $S_{li} = L_{li}$:

$$p_2 = \int_{L_{li}}^{\infty} f_S(S)dS, \tag{7}$$

where: $L_{li} = S_{li}$–structure's limit loads, equal to its maximum strength.

As these random events are independent, the probability of their simultaneous occurrence is equal to the product of the probability of their occurrence:

$$p = p_1 \cdot p_2 = f_L(L_{li})dL \cdot \int_{L_{li}}^{\infty} f_S(S)dS, \tag{8}$$

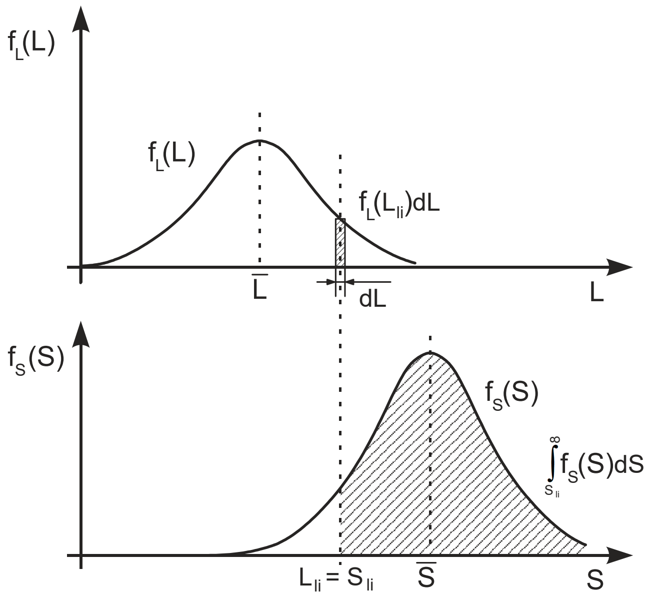

Figure 4. Graphical representation of the simultaneous occurrence of two independent events, i.e.,: a structure's load of L_{li} and a structure's strength greater than or equal to $S_{li} = L_{li}$.

The consideration of the first two options is justified if the average load values $\overline{L}$ and strength values $\overline{S}$ differ significantly, i.e., $\overline{L} << \overline{S}$. Otherwise, dependencies (4) and (5) may lead to results with significant errors.

In the case of analyses concerning power equipment, we are usually dealing with case (c). Such equipment is manufactured in an accurate and careful manner. However, it has different manufacturers who manufacture units according to different designs, different technology and using different materials. Moreover, different conditions of operation are the reason for the occurrence of various ageing mechanisms, which affect the durability of structures in different ways. Thus, electrical equipment and structures show a relatively high scatter of strength characteristics. During operation, they have to cope with loads of considerable value dispersion. We can treat current and voltage loads as the load of the device in the basic range. However, mechanical and environmental exposures (temperature, wind, humidity, etc.) of the device can also be treated as a load in a wider range.

The measure of the reliability of a structure is the probability that its strength will be greater than the applied load, over the whole range of the occurring loads. This probability can be expressed by the relation:

$$R = P(S > L) = \int_0^\infty f_L(L) \cdot \int_L^\infty f_S(S) dS dL, \tag{9}$$

or

$$R = P(S > L) = \int_0^\infty f_S(S) \cdot \int_0^S f_L(L) dL dS, \tag{10}$$

In order to eliminate two random variables, S and L, they are often replaced by one variable, Z:

$$Z = S - L, \tag{11}$$

In this case, dependencies (9) and (10) take the form:

$$R = P(Z > 0), \tag{12}$$

The probability that the instantaneous strength of a structure will be less than its load is, in this case, equivalent to the probability of failure of the structure F. The determination of this probability allows the risk of damage to be assessed. It completes the probability R to unity:

$$F = 1 - R = 1 - \int_0^\infty f_L(L) \cdot \int_L^\infty f_S(S) dS dL, \tag{13}$$

or

$$F = 1 - R = 1 - \int_0^\infty f_S(S) \cdot \int_0^S f_L(L) dL dS, \tag{14}$$

Depending on the type of equipment and structures under analysis and their loads, the distributions $f_L(L)$ and $f_S(S)$ take different functional forms. Usually, with a fairly good approximation they can be described with a model in the form of normal distribution.

3. Results and Discussion

3.1. Analysis of the Impact of Wind Speed on the Failure Rate of 110 kV Overhead Power Lines—A Case Study

In order to be able to use the presented model in practice, it is necessary to determine the theoretical function of the probability density function of the wind speeds that occur, which in this case are the exposure, and the theoretical density probability function of the wind speed at the moment of failure of 110 kV overhead lines, expressing the momentary limit resistance in the analysed model. These models were implemented using the parametric and non-parametric estimation theory, widely described in the literature on the basis of mathematical statistics and probability theory. In order to determine the reliability of both models, the statistical hypotheses of the functional form of the model were verified at the level of materiality $\alpha = 0.05$, by Kolmogorov's λ test, Pearson's χ^2, and a sign test.

On the basis of official data received from meteorological services, the distribution of the probability density of exposure, which is the wind speed at the place of operation (along the route) of 110 kV overhead lines, was determined. The empirical distribution of wind speed is shown in Figure 5.

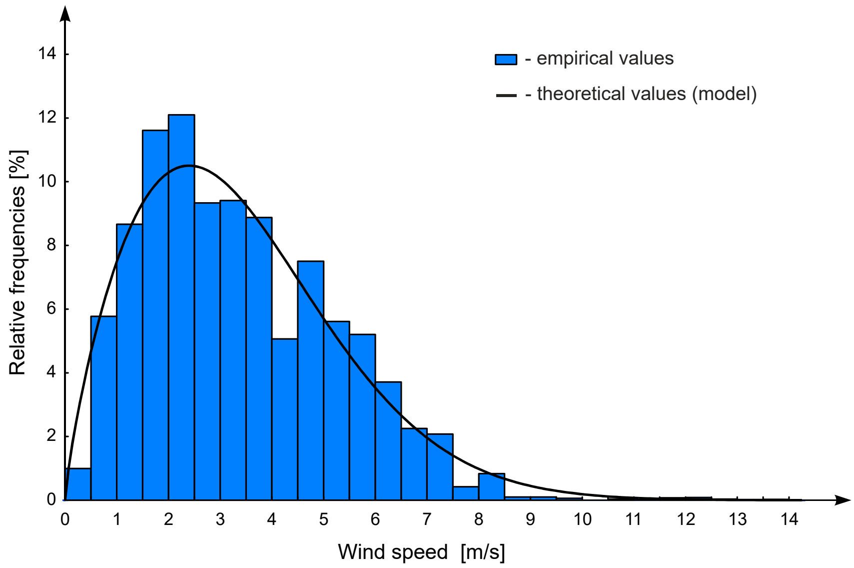

Figure 5. Empirical and theoretical wind speed probability density function at 110 kV overhead line locations.

The hypothesis has been put forward that the probability density function of winds of different speeds can be modelled by means of Weibull distribution in the form:

$$f_L(W) = \frac{c}{b} \cdot \left(\frac{W}{b}\right)^{c-1} \cdot e^{-\left(\frac{W}{b}\right)^c} \quad W \in (0; +\infty), \tag{15}$$

where b denotes scale parameter, c is shape parameter, and W is wind speed.

The determined distribution parameters are: $b = 3.7904$ and $c = 1.5518$.

After substituting the determined values into Equation (15), the theoretical function of the probability density of occurrence of winds of different speeds takes the form:

$$f_L(W) = 0.1963 \cdot W^{0.5518} \cdot e^{-0.1265 \cdot W^{1.5518}}, \tag{16}$$

The theoretical wind speed probability density function is shown in Figure 5.

The hypothesis was verified at the significance level of $\alpha = 0.05$ by Kolmogorov's λ and Pearson's χ^2 tests. The following results were obtained: $\chi^2 = 7.92 < \chi^2_\alpha = 9.39$; $\lambda = 1.184 < \lambda_\alpha = 1.358$. On the basis of the tests carried out, there are no grounds for rejecting the hypothesis of the Weibull distribution of wind speeds at 110 kV overhead lines.

On the basis of empirical data covering a ten-year period of observation of 110 kV overhead lines, failure tests of these structures were also carried out depending on wind speed at the moment of damage. On their basis, a probability density function of 110 kV overhead lines strength (resistance) to an external factor (exposure), i.e., wind, was determined. Empirical data had to be standardised for this purpose because the lengths of the time intervals for the occurrence of individual wind speeds are not the same. The standardization methodology is presented in detail in [16]. Due to the fact that the lines are of different lengths, the parameters and reliability indicators were compared to the arbitrary length of 100 km of lines. The empirical values and the theoretical probability density function of the 110 kV line resistance to load, which is wind speed, are shown in Figure 6.

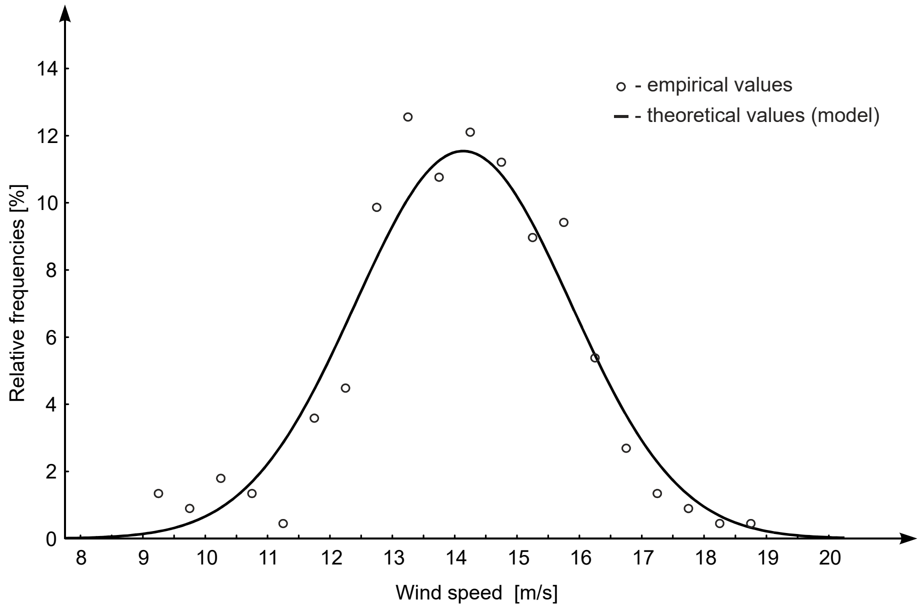

Figure 6. Empirical and theoretical probability density function of 110 kV overhead power lines resistance to load (exposure) in the form of wind occurring in their place of operation.

An attempt was made to implement a theoretical model for the obtained empirical distribution of the line failure probability density function depending on wind speed. On the basis of a detailed analysis of the results obtained, it was assumed that this function can be modelled using a normal distribution in the form:

$$f_S(W) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{(W-m)^2}{2 \cdot \sigma^2}}, \tag{17}$$

where m is expected value of random variable W and σ is the standard deviation of random variable W.

The determined normal distribution parameters are: $m = 14.1621$ and $\sigma = 1.7309$.

After substituting the determined values into Equation (17), the theoretical function of 110 kV overhead line failure probability density takes the form:

$$f_S(W) = 0.2305 \cdot e^{-\frac{(W-14.1621)^2}{5.9920}}, \tag{18}$$

The theoretical function of 110 kV overhead line failure probability density is shown in Figure 6.

Verification of the distribution hypothesis was carried out by means of a character test at a significance level of $\alpha = 0.05$. The verification results obtained are as follows $l_0 = \min(l^+, l^-) = \min(9; 11) = 9$; $l_0 = 9 > 5 = l_\alpha$; $l_0 \notin R_\alpha = (-\infty; 5)$. Based on the test carried out, for a significance level of $\alpha = 0.05$, there is no reason to reject the hypothesis that the probability density function has the form of a normal distribution described by Equation (18).

In the case under consideration, danger exists if the wind speed limit is exceeded, which can lead to damage to lines or to a considerable acceleration of the damage process. By substituting dependencies (15) and (17) into Equation (10), the reliability of the 110 kV line can be determined:

$$R = P(S > L) = \int_0^\infty f_S(S) \cdot \int_0^S f_L(L) dLdS = \int_0^\infty \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{(S-m)^2}{2 \cdot \sigma^2}} \cdot \int_0^S \frac{c}{b} \cdot \left(\frac{L}{b}\right)^{c-1} \cdot e^{-\left(\frac{L}{b}\right)^c} dLdS, \quad (19)$$

After calculating the internal integral, Equation (19) takes the form:

$$R = \int_0^\infty \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{(S-m)^2}{2 \cdot \sigma^2}} \cdot \left[-e^{-\left(\frac{L}{b}\right)^c} + K\right]_0^S dS = \int_0^\infty \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{(S-m)^2}{2 \cdot \sigma^2}} \cdot \left[1 - e^{-\left(\frac{S}{b}\right)^c}\right] dS, \quad (20)$$

where K is the integration constant.

After performing elementary transformations, the following dependency is obtained:

$$R = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot \left[\int_0^\infty e^{-\frac{(S-m)^2}{2 \cdot \sigma^2}} dS - \int_0^\infty e^{-\left[\frac{(S-m)^2}{2 \cdot \sigma^2} + \left(\frac{S}{b}\right)^c\right]} dS\right], \quad (21)$$

There are two integrals in the above notation, which can only be solved analytically in an approximate way or, as in the case of the first one, using special functions (here, Laplace's functions). However, since both integrals are marked, their value can be determined much more easily using computer methods. The Matlab function was used in the research carried out. For the previously determined parameters m, σ, b and c, the values of both integrals and then the probability of correct operation of the 110 kV line at the considered variability of wind speed were calculated:

$$R = \frac{1}{1.7309 \cdot \sqrt{2 \cdot \pi}} \cdot [4.338723 - 0.004798] = 0.998894 \; [1/100 \text{ km}]$$

The measure of damage risk in this case is the probability of power line damage F, which complements probability R to unity:

$$F = 1 - R, \quad (22)$$

After substituting the data, we obtain:

$$F = 1 - 0.998894 = 11.06 \times 10^{-4} \; [1/100 \text{ km}]$$

3.2. Analysis and Interpretation of Results

The developed mathematical model allows determination of the risk of damage to a structure when its strength is dependent on many external factors and changes over time in a random way, as well as for random variability of occurring exposures. As the analyses have shown, the model is quite simple to apply and the results obtained are consistent with the statistical data of electricity distribution companies. This model can also be implemented in analytical simulation methods. The author has already made the first attempts to use it in simulation algorithms based on Petri nets. However, this method has two disadvantages. The first one is the need to calculate quite complicated definite integrals. However, this disadvantage can be eliminated by using computer methods. For the analyses presented, the Matlab package was used. The second disadvantage is the need to have a fairly extensive statistical database. These data is in many cases are unavailable (failure data is treated as confidential commercial data of the company) or, as in the case of weather data, are quite expensive to obtain. In the absence of reliable input, the results obtained will also be unreliable.

The developed mathematical model allowed the author of the article to conduct quite complicated and interesting analyses. So far, the author has not encountered any similar research results in the scientific literature. Thematically similar scientific studies are based primarily on elementary statistical analysis of data on failure rates of specific power equipment or structures. The author's publications to date have also presented the resultant reliability indicators of equipment, determined on the basis of all failures occurring, regardless of their cause. Therefore, the approach presented in the article can be considered as original.

On the basis of the results of reliability tests of 110 kV overhead lines available in the scientific literature [4,25] it can be concluded that the total probability of damage to these lines ranges from 53.51×10^{-4} 1/100 km to 62.36×10^{-4} 1/100 km. Thus, in the most favourable case, wind is the cause of damage or a factor facilitating damage in approximately 17.74% of 110 kV power line failures (20.67% in an extreme situation). This indicates the need for further research to increase the wind load resistance of 110 kV line structures. Studies on the combination of different structural materials also seem to be important. An improper combination of different materials, for example with significantly different coefficients of thermal expansion, can lead to loosening of connections and breaking of wires or their extension and, as a result, to damage of lines in strong, low-temperature winds.

The obtained results were also compared with the results obtained for several selected populations of 110 kV overhead lines operated in Poland. The results obtained are convergent. For different regions with different terrain and therefore different wind speeds, a slightly different shape of the probability density function is obtained, but to an extent that does not significantly affect the final result of the 110 kV overhead line damage risk assessment. The maximum difference in damage risk, as compared to the value presented in this article, did not exceed 12%. This allows to conclude that the analysed population (random sample) represents, in the context of the examined statistical characteristic, the reliability properties of the general population. However, it should be stressed that all the examined line populations were located in wind zone W1 [19,20]. In Poland, wind zones W2 and W3 occur sporadically, mainly in the mountain area and in a narrow coastal strip.

Taking into account the requirements of standards [18–21], it should be stated that wind speeds up to 20 m/s (and even slightly higher) should not cause failure of 110 kV overhead lines. The quite common occurrence of line failures in this wind speed range suggests that the dominant character of failures is cumulative–fatigue. The most common line defects, at low wind speeds, are conductor breakage, insulator damage, breakage of connectors and brackets and their loosening, resulting in the conductor slipping out. It can be assumed that these damages are mainly due to aeolian vibrations (frequency from about 3 Hz to 150 Hz), resulting from the release of so-called Kármán vortex shedding on the leeward side of the conductor. Slightly less impact is exerted by conductor galloping (frequency of vibrations usually from 0.1 Hz to 3 Hz). Conductor galloping is caused by wind speeds in the range from 6 m/s to 25 m/s. Vibrations caused by galloping can cause the conductors to come closer together and even damage the conductors, insulators and supporting structures. Torsional oscillations may occur in the case of bundled conductors. The phenomenon of galloping is intensified in case of uneven icing of the conductors.

The destructive effect of vibrations is a superposition of three basic mechanisms. The first one consists in cyclic bending of the conductor subject to vibrations. It results in the occurrence of a cyclic alternating bending stress, which is added to the static tension. The second mechanism is frictional corrosion. During cyclic bending between the individual wires, microslip occurs. These wires are subject to considerable pressure, which leads to mutual friction of their surfaces. As a result of the friction wear discussed, the local cross-sections of the wires are reduced. When the first wires in the bundle are damaged, a third mechanism appears, namely the active cross-section of the wire decreases, which leads both to an increase in the tension of the remaining wires in the bundle and to a local increase in temperature and overheating of the conductor.

The above analysis shows that the vibration protection in 110 kV overhead lines is not fully effective or that the use of vibration dampers and anti-vibration conductors is too low. The cumulative nature of many of the defects occurring also indicates that the supervision of 110 kV overhead lines by power companies is too weak. In such a situation, even slight mechanical damage not detected at the right time, at a sufficiently high wind speed, causes line failure.

4. Conclusions

On the basis of many years of research, the author concluded that despite significant progress in material engineering and many structural changes of 110 kV overhead lines, they are still not resistant enough to wind load. In his reliability tests, based on more than a thousand failures, the author has shown that the intensity of damage to these lines increases significantly for wind speeds above 12 m/s [4]. This article presents an analysis of mutual relations between the load represented by wind speed and the strength of the complex reliability system, which 110 kV overhead power lines are. On its basis, the risk of damage to a line as a result of the wind affecting its structure was determined. In order to do this, it was necessary to establish the distributions of the probability density of wind speed that occurs at the place where the line is operated and the distribution of the wind speed at which the damage occurred, the cause or contributory factor of which was the wind.

The analyses and research presented in the article were carried out using the developed mathematical model. The model has proven to be a very good tool to assess the risk of damage to complex power structures such as 110 kV overhead lines.

The tests carried out have shown that wind is a failure factor or a co-responsible factor in about 18–20% of 110 kV line failures. This is a very large share. The obtained results confirm the conclusions resulting from the analysis of the documentation of electricity distribution companies (Figure 1) that wind is the cause of about 19% of all 110 kV overhead line failures.

The results obtained allow us to conclude that the problem of wind influence on overhead lines, including 110 kV lines, is not yet sufficiently recognized. Further research work should be carried out in this area in order to apply new materials to the line structures or to introduce technological changes reducing the negative impact of wind on such equipment.

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