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Influence of atmospheric conditions represented by wind, precipitation and air temperature on the intensity of failures of medium-voltage power lines

Abstract *The article presents the impact of atmospheric conditions represented by wind, precipitation, and air temperature on the intensity of damage to medium-voltage power lines. It discusses the mechanism of damaging these devices due to the influence of wind, atmospheric precipitation, and high and low temperatures. The method of modelling the relationship between the intensity of failures of power objects and the values of various environmental factors is discussed. The results obtained during many years of research for medium-voltage power lines operated in national electric power distribution networks are presented. The econometric modelling method was used for this purpose.*

Streszczenie. *W artykule przedstawiono wpływ warunków atmosferycznych reprezentowanych przez wiatr, opady oraz temperaturę powietrza na intensywność uszkodzeń linii elektroenergetycznych SN. Zaprezentowano w nim mechanizm uszkadzania tych urządzeń na skutek oddziaływania wiatru, opadów atmosferycznych oraz wysokich i niskich temperatur. Omówiono metodę modelowania zależności intensywności awarii obiektów energetycznych od wartości różnych czynników środowiskowych. Zaprezentowano wyniki uzyskane podczas wieloletnich badań dla linii elektroenergetycznych SN eksploatowanych w krajowych sieciach dystrybucyjnych energii elektrycznej. Wykorzystana została w tym celu metoda modelowania ekonometrycznego.* ***(Wpływ warunków atmosferycznych reprezentowanych przez wiatr, opady oraz temperaturę powietrza na intensywność awarii linii elektroenergetycznych średniego napięcia)***

Keywords: electrical distribution networks, overhead power lines, cable lines, failures, failure intensity, wind, atmospheric precipitation, air temperature
Słowa kluczowe: elektroenergetyczne sieci dystrybucyjne, napowietrzne linie elektroenergetyczne, linie kablowe, awarie, intensywność awarii, wiatr, opady atmosferyczne, temperatura powietrza

Introduction

Electricity is the cornerstone of modern society. Access to electric power grids determines the development of industry and local communities, thus enabling and shaping settlements. In many cases, electricity is the sole systemic energy carrier. Therefore, maintaining high standards of energy quality and ensuring its continuous supply to consumers is currently a crucial aspect. This is achievable through proper design, construction, and operation of electric power grids. During the network design phase, the most important issue is the optimal selection of construction materials and equipment parameters to ensure their reliable operation. Proper operation, in turn, is not possible without a thorough understanding of the laws and principles governing the reliability of electric power equipment. Establishing appropriate operating methods is possible based on many years of observations of individual electric power equipment, including their failure rates. Such research allows for determining the causes of failures, as well as identifying the weakest elements of equipment and the weakest devices in the power grid. Despite numerous research efforts and scientific developments, the issue of reliability of electric power equipment and systems has not yet been fully understood. Further analyses and research to enhance our knowledge of the mechanisms of damage formation are necessary in this regard. This, in turn, will be the basis for developing methods to reduce the failure rate in electric power systems. The significance of the problem is evidenced by the considerable number of publications on this topic [2, 4, 5, 8, 11, 17, 22, 44, 46].

The definition introduced in 1974 in document [21] and reiterated in many standardization documents worldwide states that reliability should be understood as the ability of objects to perform specified functions under specified conditions and within a specified period of time, while simultaneously not exceeding permissible parameters. In most studies, “specified conditions” are treated as constant, assuming that reliability is only a function of time. This is obviously a mistaken assumption because time does not directly affect the reliability of objects. The ability or inability of an object to perform specified tasks (functions) is the result of the interaction of various internal and external (environmental) exposures. These exposures change over time, and these changes are probabilistic in nature. Another simplification leading to improper research conclusions is assuming a constant resistance of the tested objects to exposures. However, due to the cumulative effects of exposures and the continuous change in operating conditions, the endurance of the object also changes and has a random nature. It becomes important to establish the mutual relationships between the momentary resistance (endurance) of the object and the exposure occurring at the same moment. Due to the difficulty of gathering reliable empirical data and the laborious nature of such research, this issue is usually overlooked in studies on the reliability of electric power systems and equipment.

The main factors significantly influencing the reliability of electric power systems are environmental exposures. Their impact on the operational properties of objects has long been known. Already in the 1950s and 1960s, many countries developed standardization acts regarding environmental testing, allowing to determine whether an object will be able to perform its tasks undisturbed if certain environmental exposures act on it with a specified intensity and for a specified time [28–32, 34–42]. Environmental conditions and requirements are also specified in general provisions, common provisions, or other detailed subject standards concerning devices, apparatus, and relays used in electric power installations. They are also defined in specifications, functional requirements, guidelines, and standards developed by transmission system operators and distribution systems [15, 16].

Currently, there are few studies in the scientific-technical literature on the impact of environmental conditions (e.g., climatic) on the operation of electric power systems [9, 24]. Much more often, the focus is on analysing the impact of weather on the variability of electrical loads or energy production in renewable sources (photovoltaic power plants, wind farms), e.g., [7, 14, 23, 43]. If studies on the impact of environmental factors on the reliability of electric power systems are conducted, usually two aspects are considered: the impact of temperature and the combined impact of other environmental exposures [11, 12, 19, 21]. However, as statistics on the failure rates of electric power equipment show, the consequences of factors such as lightning strikes, wind, air humidity, icing, and rime are very significant. Therefore, there is a need for detailed analysis and independent examination of the individual factors' impact on the occurrence of damage to electric power objects. A serious problem that may arise in this case is, as mentioned earlier, the lack of reliable data on the basis of which such an analysis could be conducted. In the official reliability statistics conducted by distribution companies, environmental factors are rarely indicated as the cause of damage (with lightning strikes, icing, and rime being exceptions). Electricians repairing faults in power grids usually do not have sufficient knowledge to recognize the mechanism of equipment damage. Therefore, very often, the cause of the damage is recorded as the enigmatic statement “Aging processes” or “Unknown cause” on the fault report.

In this article, the authors present the results of analyses regarding the impact of atmospheric conditions, represented by air temperature, wind speed, and precipitation, on the failure rate of medium-voltage power lines. The mechanisms of how these factors affect electric power equipment are discussed. The method of modelling the relationship between the intensity of failures of power objects and the values of various environmental factors is discussed. The results obtained during many years of research for medium-voltage power lines operated in national electric power distribution networks are presented.

All the analyses were carried out at the level of significance $\alpha = 0.05$.

Influence of air temperature, wind speed, and precipitation on electric power equipment

The range of temperatures occurring on Earth is very large. The maximum air temperature in the shade in open spaces is about 60°C (the highest observed being 56.7°C). Conversely, the lowest temperatures reach almost -90°C (the lowest observed being -89.2°C). The range of temperatures observed is obviously dependent on geographic latitude. The record temperatures recorded in Poland are -41.0°C (Siedlce) and 40.2°C (Prószków near Opole).

High temperature can cause numerous damages to equipment and electric power objects because it deteriorates the properties of their construction materials, causing softening, melting, sublimation, evaporation, viscosity reduction, size change, and thermal aging.

Mechanical deformations resulting from the expansion of materials are particularly significant in the case of connecting materials with different coefficients of expansion or in the case of uneven heating of a structural element made of one material but of significant dimensions. Mechanical deformations are the cause of numerous mechanical damages and lead to changes in the electrical parameters of equipment. Softening and melting of plastic materials lead to weakening or damage of equipment structures and to leaks of casting compounds. On the other hand, thermal aging of materials leads to a reduction in their durability. For electrical devices, the influence of high temperatures is crucial. According to [19], it results in: decreased electrical resistance across and on the surface of dielectrics, reduced dielectric breakdown strength, changes in the dielectric constant of all dielectrics, increased dielectric losses, and increased electrical resistance of metals.

It should be noted that the surface temperature of electrical devices located in open air without protection can significantly exceed the air temperature in the shade and reach over 100°C.

Conversely, negative temperatures cause materials to become more brittle, increase viscosity and solidification of liquids, reduce mechanical strength, and cause material shrinkage. As a result of size changes, mechanical damage occurs, including rubbing and jamming of moving parts. Material shrinkage, and thus the structural elements of devices, can weaken joints and cause fractures and cracks. Most materials harden and become more brittle at negative temperatures. Changes in the hardness and dimensions of seals can lead to device leaks. The viscosity of greases and oils increases, making it difficult for moving parts to operate, potentially leading to damage if the greases freeze. Under the influence of negative temperatures, the electrical parameters of materials change, such as electrical conductivity, dielectric loss, dielectric constant, and magnetic permeability. It should also be noted that the surface temperature of devices placed in open air can be significantly lower than the ambient temperature due to heat radiation [19].

Rapid temperature changes can also cause damage to electric power objects. These changes result from daily air temperature variations, fluctuating sunlight, sudden wetting of equipment, and so on. The largest daily temperature amplitude observed on Earth is 55.5°C.

Devices exposed to direct sunlight (surface temperatures above 100°C) and then suddenly soaked by rain (with hail temperatures around 0°C) are particularly vulnerable to sudden temperature changes.

These changes can cause mechanical stresses in construction materials. Rapid expansion and contraction of materials lead to weakened connections, cracks, and fractures. Sealed devices may become unsealed due to these temperature fluctuations [19].

The range of wind speeds observed on Earth is very large. The maximum measured wind speed in a gust was over 110 m/s (113.33 m/s – Barrow Island, Australia). The highest officially recorded wind speed in a gust in Poland was 95.83 m/s (Meteorological station on Śnieżka). However, these are not record values. Much higher wind speeds are reached in tornadoes. The highest value on Earth, recorded by Doppler radar, was over 133.33 m/s (Oklahoma, USA), while in Poland, it was 102.50 m/s (near Lublin). The average annual wind speed in Poland is around 3-4 m/s. The highest wind speeds occur in late autumn, winter, and early spring. During these times, they are often accompanied by sub-zero air temperatures and heavy precipitation. Such environmental conditions are unfavourable and contribute to the occurrence of failures in electric power equipment, particularly overhead lines.

All overhead electric power objects and their components are subject to stresses resulting from wind action, with the type and degree of stress varying depending on the specific element and its location (environmental conditions). The effects of wind exposure can vary. Generally, they can be divided into reversible and irreversible effects. Reversible effects refer to events where the object returns to its initial serviceable state once the exposure ceases (e.g., transient faults in lines). Irreversible damages can be further divided into sudden damages, caused by very strong exposures, and cumulative damages, resulting from a large number of exposure cycles with small or medium values.

Wind speed directly affects the statics of power lines, generating forces acting on structures and conductors. Therefore, wind is a factor influencing the selection of construction solutions for overhead line elements, such as support structures, conductors, and insulators. In cases of incorrect estimation of wind pressure forces, serious mechanical damage to these elements can occur. Strong wind gusts primarily contribute to mechanical damage to lines by breaking conductors, damaging insulators, toppling or breaking support structures (poles), or even causing branches (or entire trees) to fall onto power lines [1].

Under the influence of wind, conductors deviate from their proper positions (present during calm weather) and can come dangerously close to neighbouring phase conductors or structures, causing short circuits [3].

Rapid changes in wind speed can induce mechanical stresses in construction materials. This can lead to weakened connections, cracks, and fractures [19].

Discussing the impact of wind on the performance of electrical power equipment, one cannot overlook the issue of air mass temperature. Particularly adverse conditions for electrical equipment occur with high-speed wind and very low air temperatures (winter period). Such wind causes a much faster reduction in the temperature of structural elements than would occur in calm weather. This situation, in turn, leads to an increase in the brittleness of materials, increased viscosity and solidification of liquids, reduced mechanical strength, and contraction of materials. As a result of size changes, mechanical damage occurs, including rubbing and jamming of moving parts. Material shrinkage, and thus the structural elements of devices, can weaken joints and cause fractures and cracks. The above phenomena primarily depend on the occurrence of negative ambient temperatures; however, they are significantly accelerated under conditions where high-speed wind occurs at negative temperatures.

The most common damages to lines, at low wind speeds, include conductor breakage, insulator damage, connector and clamp fractures, and loosening, resulting in conductor slipping. It can be assumed that these damages are mainly due to aeolian vibrations (with frequencies ranging from approximately 3 Hz to 150 Hz), which are caused by the release of so-called Karman vortices (vortex shedding) on the leeward side of the conductor. Conductor galloping (with vibration frequencies typically from 0.1 Hz to 3 Hz) has a somewhat lesser impact. Galloping of conductors is caused by wind speeds ranging from 6 m/s to 25 m/s. Vibrations induced by galloping can cause conductors to come closer together, or even damage conductors, insulators, and support structures. In the case of bundled conductors, torsional oscillations may occur. The galloping phenomenon intensifies with uneven icing of the conductors.

The destructive effect of vibrations is a superposition of three fundamental mechanisms. The first mechanism involves the cyclic bending of a vibrating conductor. This results in cyclically varying bending stress, which adds to the static tensile stress. The second mechanism is fretting corrosion. During cyclic bending between individual wires, micro-slips occur. These wires are subjected to significant compressive forces, leading to mutual abrasion of their surfaces. As a result of this abrasive wear, the local cross-sectional areas of the wires decrease. When the first wires in the bundle are damaged, the third mechanism emerges, which involves a reduction in the active cross-section of the conductor. This leads to an increase in the stress on the remaining wires in the bundle, as well as a local rise in temperature and overheating of the conductor.

Rain mainly affects power distribution devices and transmission communication equipment. During rainfall, the electrical properties of insulators also change significantly, depending on the intensity of the rain [6].

The conductivity of rainwater and its amount are crucial for the electrical properties of insulators. Rainwater with high conductivity significantly lowers the discharge voltage of insulators. Away from cities, rainwater in the atmosphere has lower conductivity than in industrial atmospheres. It is believed that the conductivity of rainwater can be a more dangerous threat to insulators than a layer of dust. Tracking discharges on insulators usually occur during rain and strong winds, especially when the rain falls on the insulators at a steep angle relative to their axis. A significant decrease in tracking discharge voltage and an increase in dielectric losses are observed, especially during sleet. Snow itself usually does not pose a serious risk to electrical equipment [6].

Methodology for studying the impact of atmospheric factors on the reliability of power equipment

Due to the influence of weather factors on the occurrence of damage to power equipment and the duration (removal) of their failures, the impact of atmospheric factors on the intensity of damage and the duration of failures (restoration) of power equipment is analysed.

The average intensity of damage to power equipment can be determined from the relationship [10, 11, 18, 20, 45]:

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

where: m – the 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.

To determine the failure intensity as a function of air temperature, wind speed, and precipitation $\bar{\lambda} = f\left(T, W, O\right)$, point values $\bar{\lambda}_i\left(T_i, W_i, O_i\right)$ for successive combinations of temperature ranges T_i, wind speed W_i, and daily precipitation sum O_i must be determined. For this purpose, equation (1) takes into account the number of failures $m_i\left(T_i, W_i, O_i\right)$ that occurred in a specific combination of climate factors (exposures) (air temperature, wind speed, daily precipitation sum), as well as the duration of this combination of intervals $\Delta t_i\left(T_i, W_i, O_i\right)$ during the observation period under consideration:

$$\bar{\lambda}_i\left(T_i, W_i, O_i\right) = \frac{2 \cdot m_i\left(T_i, W_i, O_i\right)}{\left(n_p + n_k\right) \cdot \Delta t_i\left(T_i, W_i, O_i\right)} \tag{2}$$

where: $m_i\left(T_i, W_i, O_i\right)$ – number of failures that occurred in a given combination of air temperature, wind speed, and daily precipitation sum intervals, n_p – sample size at the beginning of the observation period, n_k – sample size at the end of the observation period, $\Delta t_i\left(T_i, W_i, O_i\right)$ – number of hours during the observation period in which specific combinations of intervals occurred: air temperature, wind speed, and daily precipitation sum.

By determining the values of $\bar{\lambda}_i\left(T_i, W_i, O_i\right)$ for successive intervals, an empirical relationship of failure intensity as a function of air temperature, wind speed, and daily precipitation sum is obtained.

Determining the empirical function $\bar{\lambda} = f\left(T, W, O\right)$ does not exhaust the problem of studying the dependence of failure intensity on the considered atmospheric factors. It is also important to determine the functional form of these dependencies, i.e., to implement mathematical models.

Modelling the impact of air temperature, wind speed, and daily precipitation sum on the failure intensity of medium voltage power lines

To determine the impact of wind speed, air temperature, and daily precipitation sum on the occurrence of failures in medium voltage (MV) power lines, extensive reliability studies were conducted. Econometric models of failure intensity and restoration time were developed, using the values of the considered weather factors as independent variables. In the considered models, the intervals of climatic factors were analysed on the principle that each interval of a given factor was combined with each interval of every other factor. In total, 393,984 intervals were created. The number of combinations of intervals in which failures occurred, and thus non-zero values of average failure intensity, for individual lines is as follows: bare overhead MV lines – 890 observations (over 15 years), semi-insulated overhead MV lines – 21 observations (over 13 years), and MV cable lines – 465 observations (over 15 years).

Knowledge of discrete values of failure intensity and the values of environmental factors, during the interaction of which power line failures occurred, enables the creation of a general multiple regression equation in the form:

$$\begin{aligned} \bar{\lambda}\left(T,W,O\right) &= a\cdot T^4 + b\cdot T^3 + c\cdot T^2 + d\cdot T + \\ &+ e\cdot W^4 + f\cdot W^3 + g\cdot W^2 + h\cdot W + i\cdot O^4 + \\ &+ j\cdot O^3 + k\cdot O^2 + l\cdot O + m \end{aligned} \tag{3}$$

where: *T* – air temperature value [°C], *W* – wind speed value [m/s], *O* – daily precipitation sum value [mm], *a*, *b*, *c*, *d*, *e*, *f*, *g*, *h*, *i*, *j*, *k*, *l*, *m* – coefficients of the approximating function.

To implement the above mathematical model, the econometric modelling method was used. The functional form of the intensity was determined for individual medium voltage lines, and the obtained theoretical models were verified by determining their compliance with empirical data.

The failure intensity of medium voltage overhead lines with bare conductors is described by an econometric model in the form:

$$\lambda = \underset{(2{,}19\cdot 10^{-6})}{20{,}4\cdot 10^{-6}}\cdot W^3 + \underset{(4{,}2\cdot 10^{-4})}{49{,}93\cdot 10^{-4}} \tag{4}$$

To determine the quality of the model fit to empirical data, the following measures were used: multiple correlation coefficient, coefficient of determination, convergence coefficient, standard error of estimation, and the coefficient of random variability. Additionally, the F Fisher-Snedecor test was conducted. The results of the model verification are presented in Table 1.

As follows from relation (4), the factor most strongly affecting the failure rate of MV lines with bare conductors is the wind. The influence of other atmospheric factors is so weak that they were rejected in the procedure of creating the econometric model. The theoretical variability of the failure intensity of overhead lines with bare conductors is presented in Figure 1.

The failure intensity of medium voltage overhead lines with partially insulated conductors is described by an econometric model in the form:

$$\lambda = \underset{(2{,}01\cdot 10^{-4})}{9{,}71\cdot 10^{-4}}\cdot W^2 + \underset{(1{,}59\cdot 10^{-4})}{13{,}83\cdot 10^{-4}}\cdot O + \underset{(7{,}07\cdot 10^{-6})}{48{,}86\cdot 10^{-6}} \tag{5}$$

The results of the model verification are presented in Table 2.

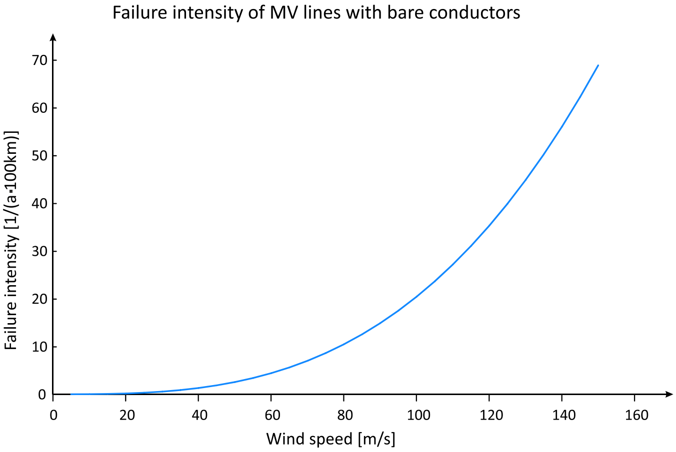

Fig. 1. Theoretical failure intensity of overhead lines with bare conductors depending on wind speed

As follows from relation (5), the factors most strongly affecting the failure rate of MV lines with partially insulated conductors are wind and atmospheric precipitation. The influence of other atmospheric factors (including ambient temperature) is so weak that they were rejected in the procedure of creating the econometric model. The theoretical variability of the failure intensity of overhead lines with partially insulated conductors is presented in Figure 2.

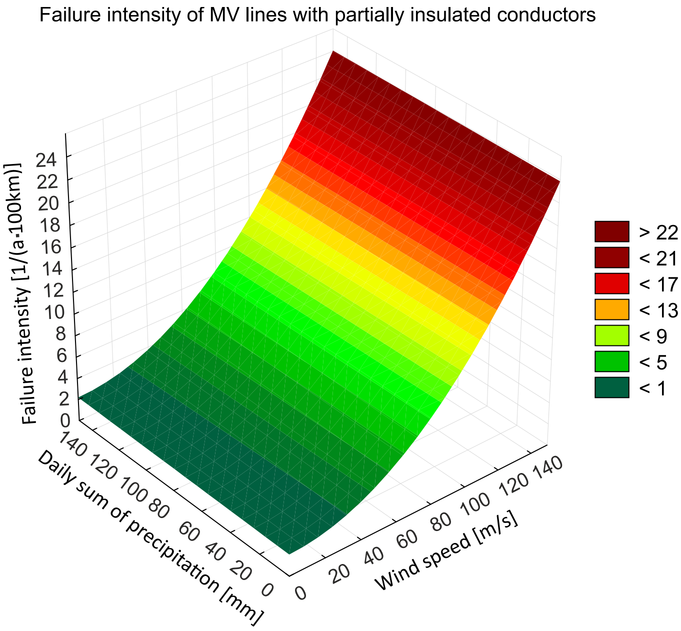

Fig. 2. Theoretical failure intensity of overhead lines with partially insulated conductors depending on wind speed and daily sum of precipitation

The failure intensity of medium voltage cable lines is described by an econometric model in the form:

$$\lambda = \underset{(4{,}67\cdot 10^{-6})}{1{,}88\cdot 10^{-5}}\cdot T^2 + \underset{(1{,}59\cdot 10^{-4})}{17{,}71\cdot 10^{-4}}\cdot O + \underset{(1{,}9\cdot 10^{-6})}{14{,}24\cdot 10^{-6}} \tag{6}$$

The results of the model verification are presented in Table 3.

As follows from relation (6), the factors most strongly affecting the failure rate of MV cable lines are air temperature and atmospheric precipitation. The influence of other atmospheric factors (including wind speed) is so weak that they were rejected in the procedure of creating the econometric model. The theoretical variability of the failure intensity of MV cable lines is presented in Figure 3.

Conclusions

The developed mathematical models allow for the determination of failure intensity and recovery time of MV power lines in the case of simultaneous influence of multiple atmospheric factors. As the analyses have shown, these models are quite simple to apply, and the results obtained using them largely correspond with the statistical data from electricity distribution companies. These models can be used in further reliability studies of power lines. The authors have already made initial attempts to use them in simulation algorithms based on Petri nets.

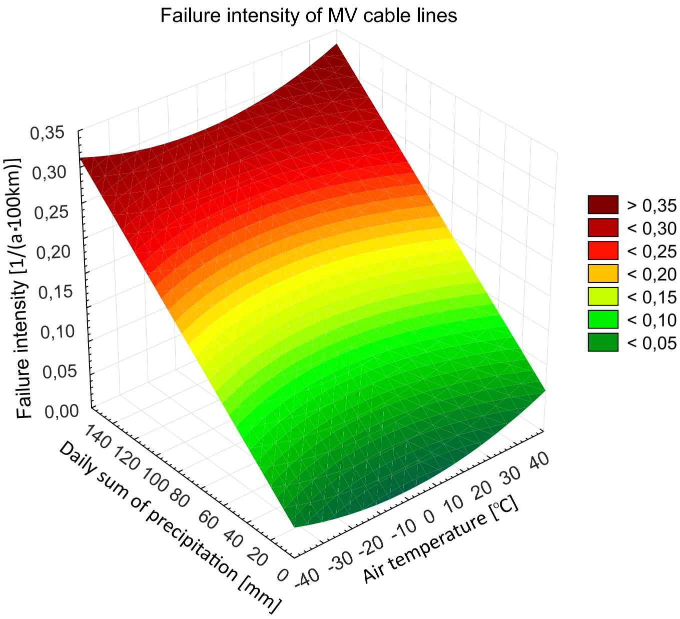

Fig. 3. Theoretical failure intensity of MV cable lines depending on air temperature and daily sum of precipitation

They can also be utilized by distribution companies to optimize network operation, such as by deploying a larger number of repair teams during periods of increased equipment failure rates due to forecasted weather conditions.

The results of the presented studies have been compared with the results obtained for several selected populations of MV lines operated in the country. The obtained results are consistent. For different regions, characterized by different terrain configurations, and thus different wind speeds, temperature distributions, and atmospheric precipitation, slightly different econometric models are obtained. However, these variations do not significantly impact the final result of assessing the failure intensity of MV lines. It is worth noting that all studied line populations were located in wind zone W1 [27, 33]. In Poland, wind zones W2 and W3 occur only in the mountainous areas and a narrow coastal strip.

The developed econometric models of failure intensity indicate that wind is the most influential factor in causing failures of overhead MV lines. As wind speed increases, the failure intensity significantly rises. For overhead lines with bare conductors, this relationship follows a cubic function, while for overhead lines with semi-insulated conductors, it follows a quadratic function. For cable lines, the most influential factor affecting the failure intensity is air temperature.

Considering the requirements of standards [25 – 27, 33], it should be stated that wind speeds up to 20 m/s (and even slightly higher) should not cause failures of MV overhead lines. The fairly common occurrence of failures within this wind speed range suggests that the predominant nature of the damages is cumulative—fatigue-related. The most common damages to lines, at low wind speeds, include conductor breakage, insulator damage, connector and clamp fractures, and loosening, resulting in conductor slipping. It can be assumed that these failures are primarily caused by

Table 1. Verification of the model of failure intensity of overhead lines with bare conductors

Correlation coefficient R	Determination coefficient R^2	Convergence coefficient φ^2	Standard error of estimate S_e	Random variability coefficient W_e	Fisher-Snedecor Test (*F*-test)
0,72	0,52	0,48	0,0001	1,50	889,42 > 4 $F > F^*$ *The degree of fit of the model to the data is sufficiently high*

Table 2. Verification of the model of failure intensity of overhead lines with partially insulated conductors

Correlation coefficient R	Determination coefficient R^2	Convergence coefficient φ^2	Standard error of estimate S_e	Random variability coefficient W_e	Fisher-Snedecor Test (*F*-test)
0,78	0,61	0,39	0,0002	1,19	11,73 > 3,68 $F > F^*$ *The degree of fit of the model to the data is sufficiently high*

Table 3. Verification of the model of failure intensity of cable lines

Correlation coefficient R	Determination coefficient R^2	Convergence coefficient φ^2	Standard error of estimate S_e	Random variability coefficient W_e	Fisher-Snedecor Test (*F*-test)
0,75	0,57	0,43	0,0002	1,89	276,38 > 3,15 $F > F^*$ *The degree of fit of the model to the data is sufficiently high*

aeolian vibrations. On the other hand, galloping-induced vibrations can lead to the convergence of conductors and even damage to conductors, insulators, and supporting structures. In the case of bundled conductors, torsional oscillations may occur. The galloping phenomenon intensifies with uneven icing of the conductors.

This allows for the conclusion that anti-vibration protection in overhead medium-voltage (MV) lines is not fully effective, or that vibration dampers are underutilized. The cumulative nature of many observed damages also indicates insufficient oversight by energy companies over MV overhead lines. In such situations, even minor mechanical damage, if not detected in time, can lead to line failures at sufficiently high wind speeds.

Based on long-term studies, the authors have found that despite significant advances in materials engineering and numerous structural changes in MV overhead lines, they are still insufficiently resistant to wind loads. Their reliability studies, which included over a thousand failures, demonstrated that the failure rate of these lines significantly increases for wind speeds above 12 m/s [13].

The most influential factor affecting the occurrence of cable line failures is the daily rainfall amount combined with air temperature. Significant daily rainfall can lead to moisture ingress in layered insulation, especially in cable terminations and joints, promoting the occurrence of short circuits. In extreme cases of prolonged rainfall (even lasting several days), ground subsidence or landslides can occur, resulting in cable rupture. The impact of air temperature on cable lines is primarily observed at cable exits to overhead structures and in the overhead sections of cable lines. In the case of high temperatures, natural cooling of the cable becomes quite difficult, leading to an increase in its temperature and, over time, to insulation failure. The lack of protection for cables against direct sunlight can also lead to exceeding the insulation's temperature limits and cause its destruction.

Numerous cable line failures result from the combination of moisture due to atmospheric precipitation and low temperatures. In these cases, the damage usually occurs in sections that are conducted overhead or at the approaches of cable lines to support structures and stations. In such situations, the failure results from moisture that has entered cable terminations and joints, which then freezes into ice crystals due to significant temperature drops, causing a non-uniform electric field distribution. Repeated cycles of this process eventually lead to insulation damage. It is also important to note the numerous instances of improper protection of protective ducts, allowing rainwater or groundwater to enter. When this water freezes, it leads to significant mechanical stresses that result in insulation damage.

The obtained results indicate that the problem of the impact of wind, ambient temperature, and atmospheric precipitation on power line failures, including MV lines, is not yet fully understood. Further research is necessary to apply new materials or introduce technological changes in line constructions to reduce the negative impact of environmental (climatic) factors on these devices.

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