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Problems of increasing the reliability of electrical energy transmission via high-voltage power lines in conditions of increased climate risk

Abstract: In this article, the subject of investigation is high-voltage overhead transmission lines. As known, such lines exhibit the phenomenon of "conductor galloping." Conductor galloping involves low-frequency oscillations with a significant amplitude, typically occurring during windy and icy conditions. These oscillations can be considered a factor that reduces the reliability of the power supply. This article aims to enhance the efficiency of using high-voltage overhead transmission lines under ice and wind conditions through the systematization of scattered information and knowledge, as well as the potential for discovering new directions in the study of conductor galloping. The analysis includes examining the results of multi-year statistical data observations on conductor galloping in power systems. Theoretical models of galloping are considered based on

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equations of dynamics and energy balance. Experimental data is obtained by observing a conductor galloping at a test site with the registration of vibration parameters. General reliability issues of overhead transmission lines are addressed. Results of statistical studies are analyzed, covering the complex conditions favoring the occurrence of conductor galloping, typical damages to elements of power lines, and an assessment of the expected intensity of galloping. The article presents the results from theoretical and experimental research, including physical and mathematical models of conductor galloping, conditions for instability of icy conductors in a wind flow, and some findings from experiments conducted at the test site. Methods to combat the phenomenon of "conductor galloping" are identified, providing a brief overview and analysis of existing measures to suppress conductor galloping. Suggestions are made for using the most effective and economical damper for conductor galloping in the split phase of the power line. The data presented in the article reveal key issues related to conductor galloping, existing methods for their resolution, and new avenues for researching this phenomenon and promising ideas.

KEYWORDS: conductor galloping, ice and wind impacts, energy balance, vibrations of conductors, self-oscillations

Introduction

Currently, electrical power systems are complex and expensive complexes, and the reliability of their operation is of great socio-economic importance. Significant funds are allocated to the construction of electrical networks, contributing to the overall development of the energy sector. Therefore, the rational choice of the reliability level for the operation of power transmission lines requires serious justification. An integral part of the general reliability issue in power supply is the objective consideration of the impact of various meteorological factors, with wind and freezing rain being the main contributors. The reliability of power transmission lines is of paramount importance for the maintenance of a consistent power supply and the reduction of economic losses resulting from outages. The growing energy demand and the expansion of electrical networks further emphasize the importance of addressing conductor galloping. The enhancement of these systems' resilience against meteorological stressors, such as wind and freezing rain, will assist in reducing operational risks and optimizing costs, which is of strategic importance for both energy companies and governments.

The relevance of this task is determined by the fact that the accepted level of design loads defines the reliability and cost of electrical networks. This article presents the results of statistical, theoretical, and experimental research on the phenomenon of conductor galloping and the selection of the most effective measures to combat it. Despite numerous studies on conductor galloping, reliable and effective means to address it have not been found.

Conductor galloping remains a significant challenge for the power industry, resulting in frequent disruptions and substantial maintenance costs. The current preventive and mitigation strategies are frequently either economically infeasible or insufficiently effective (Kaplun et al.

2023; Knapik 2019). There is a clear need for a more comprehensive and innovative approach to reducing the impact of these oscillations on power transmission infrastructure, particularly as electrical networks expand and become more interconnected.

According to Juraeva (2021), the occurrence of oscillations in power transmission lines, known as conductor galloping, poses a significant threat to the stability and reliability of the power supply. These low-frequency, high-amplitude oscillations are triggered by various factors such as wind, icing, mechanical impacts, and others, potentially causing damage or breakage of conductors, leading to power interruptions. More substantial and more reliable materials for conductors are used to address this issue, capable of withstanding greater mechanical loads. Imamov et al. (2019) emphasize that ensuring the stability of power systems is strategically important for society and the economy, requiring constant attention, funding, and scientific research from government authorities, energy companies, and research institutions to reduce risks and ensure uninterrupted power supply. The complexity and costly investments in electrical power systems stem from the inclusion of hundreds of thousands of kilometers of power transmission lines, numerous generating stations, and substations, requiring substantial investments in infrastructure and equipment.

Jamali-Abnavi et al. (2021) assert that the development of electrical power infrastructure, including the construction of electrical networks, demands significant financial investments crucial for the overall development of the energy sector. Therefore, considering various factors, selecting the appropriate reliability level for power transmission lines is essential. Decisions on reliability levels should also consider economic aspects such as construction and maintenance expenses and losses from potential disruptions. They must be justified in terms of economic efficiency, according to Zolriasatein et al. (2022), strong winds can induce conductor galloping, leading to oscillations and damage. Windstorms and hurricanes can topple power transmission supports or damage conductors, causing outages. Winds can also contribute to the spread of wildfires, threatening electrical infrastructure and causing power outages to prevent additional risks. Yazdani-Asrami et al. (2022) note that the design load level determines the power system’s ability to supply electricity to consumers. If design loads are underestimated, it may lead to overloads and outages, negatively impacting power supply reliability. Underestimating loads can result in excess capacity and, consequently, unnecessary infrastructure construction and maintenance expenditures. On the other hand, insufficient capacity may lead to additional costs for emergency recovery and system upgrades.

The objective of this research is to provide a comprehensive analysis of conductor galloping and its impact on the efficiency and reliability of power transmission lines. This will be achieved by systematizing existing research and data on the phenomenon. Furthermore, the study aims to identify the most effective preventive and mitigation strategies for minimizing the impact of wind and ice conditions while proposing innovative solutions for improving the reliability of high-voltage overhead transmission lines under adverse weather conditions. The attainment of these objectives will facilitate the development of more reliable and cost-effective strategies for managing power transmission infrastructure.

1. Theoretical overview

Numerous studies are dedicated to investigating the aerodynamic instability of ice-covered conductors in a wind flow and determining the critical velocity leading to conductor galloping. American researcher Den Hartog (1985) published an aerodynamic theory on the emergence of conductor galloping. According to this theory, the possibility of conductor galloping is associated with the aerodynamic instability of profiles with non-circular cross-sections. By examining a conductor segment with a non-circular cross-section (icing), suspended on springs (with a single degree of freedom) and placed in a wind flow, he established a stability criterion, represented by the Formulas (1):

$$\begin{aligned} &\frac{dL}{d\phi} \geq 0, \ \text{the system is stable} \\ &\frac{dL}{d\phi} < 0, \ \text{the system is unstable} \end{aligned} \tag{1}$$

Thus, to excite oscillations, the lift coefficient curve must have a segment with a negative slope on a sufficient range, and the icing profile should be oriented relative to the wind flow in the angle of attack zone associated with this segment.

A known drawback of this theory is that it does not account for torsional vibrations on the lines during galloping. The results of detailed aerodynamic tests in a wind tunnel within the practical range of natural ice shapes and wind speeds suggest that Den Hartog's mechanism is not the cause of the conductor galloping on overhead transmission lines (Nigol and Buchan 1981). These results also demonstrate the inadequacy of static aerodynamic data and the importance of damping for predicting dynamic instability. Nigol and Clarke (1974) proposed alternative models incorporating the effect of torsional motion. It is noted that aerodynamic interactions between torsional and linear oscillations can explain such synchronicity. In the article by Vanko and Marchevski (2014), a stability analysis procedure based on Lyapunov is systematically carried out, resulting in a Lyapunov-based galloping condition that generalizes Den Hartog's condition (2):

$$W(\alpha) = C_x\left(C_y' + C_x\right) + C_y\left(C_y - C_x'\right) < 0 \tag{2}$$

or in terms of aerodynamic quality can be represented as follows (3):

$$W(\alpha) = K' + K^2 + 1 < 0 \tag{3}$$

where: $K = C_y/C_x$.

To satisfy condition (3), it is necessary that the derivative of the aerodynamic coefficient regarding the angle of attack be negative, which can be written as condition (4):

$$K' < 0 \tag{4}$$

Generalization of the stability criterion is also found in the works of Nikitas and Macdonald (2014) and Jones (1992). In the works of Luongo and Piccardo (2005), Mingzhe and Macdonald (2016), McComber and Paradis (1998), an oscillatory system is considered, representing a profile with aerodynamic characteristics suspended on vertical and horizontal springs with three and two degrees of freedom. The conditions of aerodynamic stability for the proposed model are thoroughly examined. It should be noted that the described mechanism of the oscillatory process and the provided criteria reveal the qualitative aspect of aerodynamic stability. However, when analyzing the nature of conductor galloping over entire spans, it is necessary to consider several additional factors (span length, coefficients of bending, and torsional stiffness of fundamental conductors). In the article by Riaz et al. (1986), a stochastic model was presented for modeling the galloping of a power line, considering the randomness of aerodynamic forces. Stochastic calculus was used to obtain sufficient stability and instability conditions.

Works by Zhamanbaev et al. (2020), Polevoy (1987), Gorin et al. (2009), Shklyarchuk and Danilin (2013) are dedicated to determining the critical wind speed. According to these works, the critical wind speed at which conductor galloping occurs is directly proportional to the frequency, damping ratio, and weight of the ice and inversely proportional to the characteristic size of the ice profile and stationary coefficients of aerodynamic characteristics. Polevoy (1987) notes that the critical speed is directly proportional to the span length and inversely proportional to the number of half-waves. It should be noted that works specifically dedicated to the study of the upper critical speed at which conductor galloping ceases are not encountered. In the works of Landa (2009), Nakamura (1980), and Danilin et al. (2007), it is shown that two types of instability can occur for split-phase conductors – torsional flutter and classical flutter. The results of a comprehensive study on the ice profile blow-off in a wind tunnel are presented in the works of Xinmin (2012), Chabart and Lilien (1998), providing additional material for investigating the phenomena of conductor galloping.

The main goal of researching theoretical aspects of conductor vibrations is to develop a general mathematical model that allows for the determination of the main parameters of the oscillatory process under given conditions. These parameters include amplitude, intensity (swing range), and frequency. There are many scientific publications in Kazakhstan and other countries dedicated to the problem of conductor vibrations, which pose the greatest danger to the strength and reliability of power transmission lines. Studies on conductor galloping are conducted in various problem formulations, and the ways and methods to solve these problems are also diverse. They cover both low and high-voltage classes, as well as single and split-phase conductors. As known, split-phase conductors of power transmission lines are more susceptible to galloping than single conductors. This is explained by the presence of cross-arms in the split phase, the installation of which reduces the length of the spans, thereby increasing the torsional stiffness of the conductors and ensuring uniformity of the ice deposition shape along the entire span.

The characteristics of vibrations of a specific section of the line depend significantly on how the conductors are attached to the supports. In the simplest case, the conductors can be fixed immovably (this option is called an “anchored span”). If the line consists of several spans, intermediate supports are installed between them, to which the conductors are attached through a string of insulators. In this case, the attachment points of the conductors can move, and the lower natural frequencies of the conductors, which mainly determine their dynamics, can vary significantly compared to conductors fixed immovably. However, when developing a numerical algorithm for modeling conductor vibrations, considering multiple spans can be challenging, so sometimes an approach is used where, instead of the entire multi-span line, only one specific span is studied, the ends of which are fixed with linear springs with specific stiffness. This method significantly simplifies the research task but may lead to inaccurate results. Some full-fledged models consider the movement of the string of insulators during vibrations.

In some cases, simplified mathematical models of conductor galloping based on the analysis of energy relations of the driving system (Bekmetiev et al. 1979), using linear and linearized equations (Danilin et al. 2007; Vanko 1991), are used for the analysis of conductor galloping. As it is known, in most cases, the motion of the conductor during galloping consists of torsional motions synchronized with vertical oscillations. In some cases, when analyzing the effect of torsional motion on the magnitude of lift force, the physical model consisting of a specimen suspended on springs having torsional resistance is assumed, which does not fully describe the actual process (McComber and Paradis 1998).

2. Materials and methods

To conduct field observations of conductor vibrations (sub-vibrations and conductor galloping), as well as to test the effectiveness of dampers and study the characteristics of individual conductors and split phases, full-scale experimental sections of power transmission lines were constructed at the testing ground of the Kazakh Scientific Research Institute of Energy named after Academician Sh.Ch. Chokin (KazSRIE). Below are some activities carried out at this experimental site. One of the periodic activities for observing artificial conductor galloping was conducted in the spring of 1989. Conductor galloping was induced within a small range of wind speeds (3–10 m/s). The wind attack angle on the lines ranged from 400 to 900. The ice simulator had a D-shaped form. During 2 and 3 semi-wave conductor gallops, the wind speed V, wind attack angle α, gallop frequency ν, gallop intensity (amplitude) A_a, amplitude of torsional movements of the split phase φ_a, and conductor tension before galloping T_0 were recorded. Changes in conductor tension during galloping $T_{\min}$ and $T_{\max}$ were also noted. Tables 1 and 2 provide some observational data on the processes of conductor galloping of the split phase on anchor spans. Gallop intensity was measured using an amplitude meter developed at KazSRIE. Deviation of the angle of rotation of the split phase was recorded using a disk with an indicator attached inside the split phase. Initial tension and its changes were recorded based on the indication of a mechanical dynamometer. The gallop period was determined by recording the time, using a stopwatch, required for the split phase to complete several cycles of oscillations.

Table 1. Galloping on an anchor span with a split phase of 5 conductors

Tabela 1. Drganie galopujące na przęśle kotwicznym z rozdzieloną fazą 5 przewodów

No.	V [m/sec]	ν [Hz]	A_a [m]	φ_a [degree]	T_0 [daN]	$T_{\min}$ [daN]	$T_{\max}$ [daN]
Two-half-wave gallop							
1	3–4		0.25–0.3		2,100	1,900	2,350
2	6–7	0.45	2.5	≈600	2,100	1,600	2,500
3	6–7	0.44	3.5–4	600–800	2,000	1,600	2,400
4	5–6	0.43	3.6		2,000	1,350	2,400
5	9–10	0.45	4		2,000	1,500	2,800
6	8–10	0.45	4.5–5.5		1,950	1,250	2,900
7	8–10	0.45	4.4	≈300	1,900	1,300	2,750
8	5–7	0.41	1.9	≈150	1,850	1,700	2,100
9	5–6	0.42	3	≈200	1,900	1,650	2,300
Three-half-wave gallop							
1	4–5	0.67	0.8–0.9	≈100_	1,900		
2	8–10	0.67	0.5–0.6	≈100_	2,200	2,100	2,350
3	6–7	0.67	3–3.5	≈600	2,000	1,750	2,600

Notes: span length l = 288 m; AC conductor – 300/39; The direction of the wind to the lines in all experiments is approximately 900.

Table 2. Gallops on an anchor span with a split phase of 8 conductors

Tabela 2. Drganie galopujące na przęśle kotwicznym z rozdzieloną fazą 8 przewodów

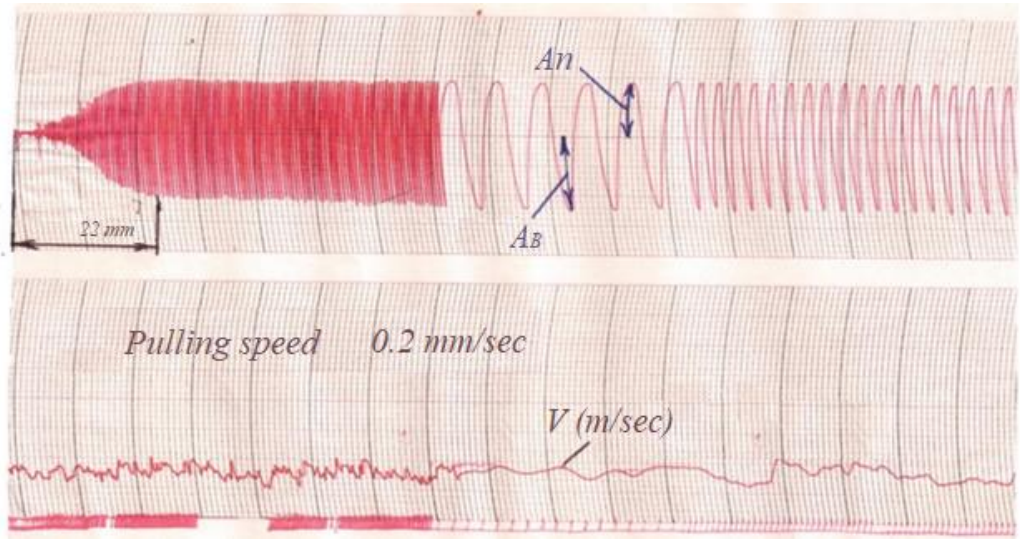
No.	V [m/sec]	α [degree]	ν [Hz]	A_a [m]	φ_a [degree]	T_0 [daN]	$T_{\min}$ [daN]	$T_{\max}$ [daN]
Two-half-wave gallop								
1	4–5	500	0.4	0.12		2,500		
2	5–6	500	0.4	0.39	50	2,500		
3	5–6	500	0.4	1.06	100	2,500	2,300	2,700
4	7–9	450	0.41	0.5		2,500	2,480	2,520
5	7–9	450	0.42	1.87	500	2,600	2,550	2,800
6	7–9	800	0.4	0.8	150	2,600	2,550	2,675
7	6–8	800	0.4	1.12	300	2,600	2,500	2,650
8	5–7	900	0.4	1.18	150	2,500	2,400	2,550
9	7–9	900	0.4	2.35	450	2,500	2,350	2,750
Three-half-wave gallop								
1	5–7	900	0.62	0.1		2,500		
2	7–8	400	0.62	0.2		2,500	2,490	2,510

Notes: span length l = 354 m; AC conductor – 300/39.

During observations of conductor galloping, in some cases, registrations of the galloping process were conducted using self-recording instruments. It is worth noting that the oscillograms below depicting the galloping of the split phase of two conductors were obtained within the framework of scientific research under Grant INTAS No. 03-51-3736, Managing the occurrence of galloping in high-voltage overhead transmission lines (Project Coordinator: Prof. Dr. Jean-Louis Lilien). The experiments were conducted in a three-span system with different spans lengths: the length of the end spans was 78 and 84 m, respectively, and the length of the intermediate span was 292 m. The following parameters were recorded during the recording of the galloping process:

1. Marks from the generator of second pulses (for determining the tape pulling speed).
2. Wind speed (according to calibration, one cell on the oscillograms corresponds to 1 m/s).
3. Lateral displacement of the conductor RF (on the oscillograms, one cell corresponds to 0.124 m).
4. Torsional movement of the RF (on the oscillograms, one cell corresponds to 1.50).
5. Changes in conductor tension (on the oscillograms, one cell corresponds to 100 daN).

As seen from the oscillogram, the wind is pulsating, with a range of variation from 6 to 10 m/s (Fig. 1). The oscillation period is about 3 seconds. This period corresponds to a frequency of 0.33 Hz, which is close to the natural frequency of oscillations of the split-phase conductors.

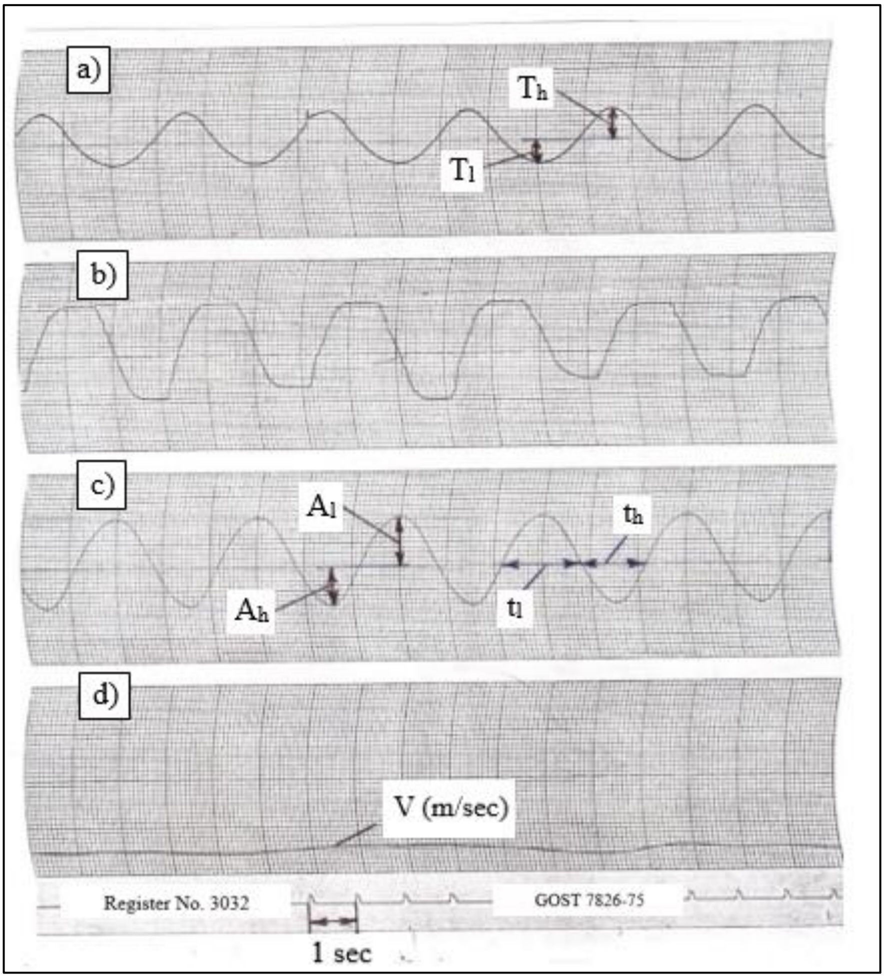


Notes: the recording was made in the middle of an intermediate span of length $l = 292$ m; conductor AC-400/51; The angle of attack of the wind to the lines is about 90°.

Fig. 1. Oscillogram of half-wave gallop

Rys. 1. Oscylogram półfalowego drgania

It also follows from the oscillogram that the amplitudes of the oscillations during galloping are not the same. The movement of the conductor from the neutral position to the uppermost Ah is slightly more significant compared to the lowermost Al. The ratio of the gallop amplitudes of the split phase Ah/Al, according to the oscillogram, is approximately 1.4 (at wind speeds of 7–9 m/sec). The amplitude ratio, according to the oscillogram, is Ah/Al = 1.3 at wind speeds of 4–6 m/sec (Fig. 2). Consequently, with a decrease in wind speed, the ratio of oscillation amplitudes also decreases.



Notes: conductor AC-400/51; intermediate span length *l* = 292 m; The angle of attack of the wind to the lines is about 90°.

Fig. 2. Oscillogram of half-wave gallop:
a) changes in conductor tension; b) torsional vibrations of the split phase; c) linear oscillations of the split phase;
d) change in wind speed

Rys. 2. Oscylogram drgania półfalowego:
a) zmiany napięcia przewodnika; b) drgania skrętne fazy rozdzielonej; c) drgania liniowe fazy rozdzielonej;
d) zmiana prędkości wiatru

It also follows from Figure 2 that when the split-phase conductors pass through the neutral position, the amplitude of linear motion is zero, and the amplitude of torsional vibration reaches its maximum. In the extreme lower and upper positions of the split phase, the amplitude of the torsional vibration is zero, and the amplitude of the transverse vibration reaches its maximum. Consequently, in the steady-state galloping process, the phase shift between the transverse and torsional vibrations is 90°. The frequency of transverse and torsional vibrations of the split-phase conductors coincides.

Another feature of oscillatory processes is that the time of half-cycles is not equal. The time required to move the split phase from the neutral position to the uppermost position and back slightly longer compared to the time if the split phase moves from neutral to extreme lower and back that is, there is inequality $t_h > t_l$. In this case, the period and frequency of the galloping conductors are determined as follows (5):

$$T = t_h + t_l = \frac{17\,mm}{10\,mm/\mathrm{sec}} + \frac{14\,mm}{10\,mm/\mathrm{sec}} = 3.1\ \mathrm{sec} \tag{5}$$

from where (6):

$$\nu = \frac{1}{T} = 0.323\,Hz \tag{6}$$

The tension of the conductor during the galloping process changes from a minimum T_h (when the split phase is in the extreme upper position) to a maximum T_l (when the split phase is in the extreme lower position). The additional load on the split-phase conductors can reach several hundred decanewtons. The additional load is 500–600 daN. It should be noted that this load increases in the case of an anchor span. In November 1984, at the KazSRIE experimental site, a natural gallop with one half-wave was observed on anchor spans 354 m and 288 m long. The phase is split, and the number of conductors in the phase for both spans is 4. The conductor grade is AC-300/39. The wind speed during natural galloping was 4–5 m/sec. The angle of attack of the wind to the lines is about 900. The sediment is drop-shaped in both spans, and the ice is transparent, about 5 mm thick. The measured weight of ice per 1 m of conductor is 0.1 daN/m. The tension of the conductor before galloping in a span of 354 m was 3218 daN and 288 m – 2300 daN.

The measured vibration amplitudes for a span of 354 m are smaller amplitude (movement of the split phase from static equilibrium to the lower position) Al – 1.2 m, large amplitude (movement of the split phase from static equilibrium to the upper position) Ah – 1.65 m. The intensity (the amplitude) of the gallop is equal to Al + Ah = 2.85 m. The gallop frequency is 0.33 Hz, which coincides with the conductors' natural frequency of free vibration. For a span of 288 m long, only the amplitude of vibrations was measured, which is Al + Ah = 2.27 m. The galloping frequency is 0.42 Hz, which also coincides with the conductors' natural frequency of free vibration. Torsional vibrations of the split phase during galloping were not visually observed in both spans.

The research carried out at the experimental site also allows us to recommend certain types of dampers for protecting power lines from conductor galloping. For example, this includes a damper (vibration-reducing device) to control the vibration of split conductors such as TDD, which combines the principles of the pendulum system and rotational vibration suppression. The damper was developed in Belgium by a team of scientists led by Professor Lilien. The TDD-type damper was successfully tested at the experimental site of the Kazakh Scientific Research Institute of Energy (KazSRIE) named after. Academician Sh.Ch. Chokin and recommended for use.

3. Results

3.1. Associated conditions leading to galloping and typical damage to lines due to conductor galloping

In developing measures to prevent the oscillation of conductors and in the design of power transmission, it is necessary to consider the conditions that cause conductor oscillations. This includes information on the maximum intensity of vibrations, as well as data on how overhead transmission lines are susceptible to oscillations depending on physical-geographical and climatic conditions, as well as typical damages to elements of overhead transmission lines (Shkaptsov 1991; Serikuly et al. 2020). This information can be extracted from long-term statistical data collected by power systems while observing conductor oscillations (Glebov 1965; Lieberman 1974; Rzhevsky and Khvoles 1977). The results of such statistical analysis are a necessary basis for taking measures to increase the reliability of overhead transmission lines in areas prone to oscillations (Lovetskaya et al. 1987; Djamanbayev et al. 2020).

Statistical analysis of data accumulated during observations of conductor oscillations indicates that the causes of these oscillations depend on several external factors, including wind speed and direction, the shape and size of ice and frost deposits, and the terrain along which the power transmission line passes. Here are the main results of such a statistical study (Lovetskaya et al. 1987; Djamanbayev et al. 2020):

1. Conductor oscillations can occur over a wide range of temperatures, from +3 to –16°C. The highest number of oscillation cases (approximately 50%) occurs at an air temperature from 0 to –5°C.

2. In most cases (about 80%), galloping occurs with an ice thickness of up to 15 mm.

3. The range of wind flow speeds favorable for conductor galloping is within 5 to 13 m/s. The average statistical value of wind speed is about 10 m/s.

These indicators were obtained in the article by Dzamanbaev et al. (2017), where probability distribution laws were determined for the parameter. The distribution density, considering the numerical values of the distribution parameters, is given by equation (7):

$$f\left(V_{\perp}\right)=0.12e^{-\frac{\left(V_{\perp}-9.81\right)^{2}}{21.9}} \tag{7}$$

where:

$V_{\perp}$ – perpendicular component of the wind flow velocity vector.

The range of wind flow attack angles to the lines is 300 to 900. In most cases (about 70%), conductor galloping was observed in the angle range from 300 to 600. There is no information on cases of galloping at an attack angle to the line less than 300. The number of cases of galloping with a duration of up to 6 hours is observed with a probability of more than 50%. The average statistical duration of galloping is about 10 hours. As is known, conductor galloping is often accompanied by the shutdown of power transmission lines. Since during intense galloping, various elements of the lines experience cyclic loads; there is a risk of fatigue damage to line elements. Existing damages to overhead transmission lines can be grouped as follows (Lovetskaya et al. 1987; Djamanbayev et al. 2020):

1. Phase-to-phase interferences with the vertical arrangement of conductors. Interferences between conductor and cable, both in vertical and horizontal conductor arrangements.
2. Breaks in conductors and cables due to arc burns or loss of mechanical strength (sharp, dynamic shocks and emerging fatigue phenomena).
3. Weakening of the mechanical strength of supports, up to damage to individual elements or complete support failure.

In the power systems of Kazakhstan, over 26 years of operating overhead transmission lines (OPL) of various voltage classes, 115 emergency shutdowns of lines of various voltage classes were recorded (Djamanbayev et al. 2020). Among them, 44 were emergency shutdowns without damage, and 71 involved damage to high-voltage line (HVL) elements. According to Table 3, the highest number of shutdown cases (without damage) occurred on 110 kV lines (case 24).

Table 3. Number of cases of damage during galloping on power lines of power systems of Kazakhstan

Tabela 3. Liczba przypadków uszkodzeń podczas drgań na liniach energetycznych systemów energetycznych Kazachstanu

No.	Nature of damage	Overhead transmission line voltage [kV]				Total
		500	220	110	35	
1	Shutdowns without damage	7	9	24	4	44
2	Damage to conductors, cables, and fittings	10	12	17	24	63
3	Damage to support elements	–	2	2	4	8
4	Total	17	23	43	32	115

Infrequently, disruptions are observed on 35 kV power lines. Most of the damage occurrences are to conductors, cables, and fittings, with 63 reported cases. Among these, medium voltage lines are the most frequently affected. The occurrence of damage or destruction to supports is relatively infrequent (only 8 cases); however, they are the most severe in their consequences regarding the duration of line downtime and the time required for repair and restoration work. Similar work on the analysis of disconnection and damage to line elements is presented in the article (Lovetskaya et al. 1987). According to this source, most outages occurred on 110 kV lines. Outages are very rarely observed on 750 kV lines. Most often, damage to conductors, cables, and fittings occurs; these statistics mainly apply to medium voltage lines of 35 and 110 kV. The least damage to support elements occurs.

3.2. Physical models of the gallop of conductors

As is known, the galloping of conductors is caused by aerodynamic forces (lift force and drag force) and aerodynamic moment generated when conductors covered with ice deposits are exposed to the airflow. The external forces acting on the conductor are primarily generated and controlled by complex movements of the conductor, consisting of vertical, horizontal, and torsional oscillations. The energy of the wind flow sustains the oscillatory process.

It is important to note that rotational movements result from external forces following translational movements. This coherence is explained by the interaction of the environment with the object through feedback between movements along the axis and rotational oscillations (Yakovlev 1971; Bekmetiev et al. 1979; Nigol and Clarke 1974). Thus, the process of conductor galloping exhibits all the characteristic features of a self-oscillating system, and it can be considered a manifestation of the phenomenon known as self-oscillations. Physically, the self-oscillatory process is quite complex. In self-oscillating systems, motion is accompanied by energy expenditure. However, this energy expenditure is compensated by inputs from a non-oscillating source (in this case, wind flow energy). The dosing of energy, both in time and magnitude, is regulated by the oscillating system. Because of this, stable periodic oscillations, known as self-oscillations, can occur in a self-oscillating system without damping.

From an energetic perspective, the mechanism of conductor galloping can be explained as follows. When analyzing the energy balance, two main types of energy should be distinguished: the active energy of the wind flow directed to sustain the galloping motion (active energy) and the energy expended to overcome aerodynamic resistance and internal friction forces in the conductors (dissipated energy). Figure 3 illustrates how the energy of the oscillating conductor and the dissipated energy change with increasing amplitude of galloping (A).

The steady amplitude of the gallop, denoted as A_0, is achieved at the moment when the energy received by the conductor from the wind is equal to the energy that is spent on overcoming the resistance and forces acting on the vibrations. That is, this happens when the condition $E_a = E_p$ is met. In this context, under conditions where the condition $E_a = E_p$ is met, the process of conductor galloping will be stationary, which means that it will be constant and will not change over time (in this example, with amplitude) $A_0 = 2.8$ m. Suppose the amplitude of a floating conductor uses an external force that acts synchronously with its movement. In that case, the energy balance will become negative (energy is added faster than it is consumed). When the

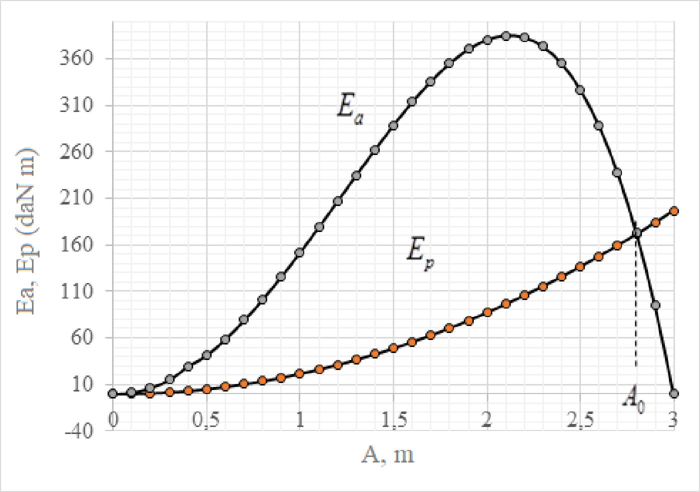


Fig. 3. Energy balance of the oscillatory process

Rys. 3. Bilans energetyczny procesu oscylacyjnego

external force ceases to act, the amplitude will begin to decrease due to energy losses that exceed the energy supplied to the system. However, over time, excess energy in the system will lead to the restoration of the amplitude to its original value. A similar situation can be observed if the amplitude decreases for some external reasons.

In the course of studying the self-oscillating process using the Van Der Pol method, a formula was developed that allows one to determine the stationary amplitude of motion of a floating object with a split phase when the wind speed V and the presence of one half-wave, the natural frequency of oscillations of the split phase ω_a, and the aerodynamic characteristics of ice-covered conductors are known (C_{D0}, C_{L0}, C_{L1} – stationary coefficients of the frontal pressure and lift force) and the lower critical wind speed V_{kp}^{l}, at which the gallop is excited (8):

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$$A_0 = \sqrt{\frac{2V^2}{\omega_a^2}\left(\frac{C_{D0}+C_{L0}}{C_{L1}}\right)\left(1-\frac{V_{kp}^{l}}{V}\right)} \tag{8}$$

The lower critical wind speed is determined by the Formula (9) (Zhamanbaev et al. 2020):

$$V_{kp}^{l} = \frac{\delta\omega_a P_{ver}}{2g\rho d_p\left(C_{D0}+C_{L0}\right)} \tag{9}$$

where:

δ – attenuation decrement,
P_{ver} – weight per unit length of the conductor, considering ice,
g – gravity acceleration,

p – air density,
d_p – characteristic size of sediment profile.

The development of theoretical models for the occurrence of self-oscillations in ice-covered conductors of overhead transmission lines has been the subject of studies by Novak and Tanaka (1974), Yu et al. (1992), and Landa (2009). In the work of Landa (2009), the phenomenon of conductor self-oscillation in a stationary airflow is explained by the generation of vortices, leading to the periodic variation of Karman forces. Issues related to the improper laying or displacement of electrical conductors pose an important challenge in prevention and mitigation. Proposed measures to combat conductor galloping can be conditionally divided into three classes (Bekmetiev et al. 1979):

1. Measures aimed at preventing ice accumulation on the conductor (ice melting, applying various water-repellent coatings to conductors).
2. Recommendations for altering the construction parameters of lines to eliminate dangerous proximity between conductors and cables (e.g., alternating spans of different lengths, widening of conductors, phase dividers).
3. Dampers actively affect the processes of ice formation and conductor galloping (conductors with increased internal friction, friction dampers, aerodynamic dampers, aerodynamic stabilizers, and pendulum dampers).

When choosing specific means to control conductor damping, it is necessary to consider their potential effectiveness in influencing the vibrational process and factors such as cost, structural complexity, and increased wind and weight loads during damper installation. These circumstances have led to various proposals primarily aimed at reducing the intensity of conductor galloping. Below, proposed measures to combat conductor galloping are briefly discussed with some comments. These measures have been more comprehensively researched and analyzed by Bekmetiev et al. (1979). It should be noted that the list of such measures will continue to expand as ongoing efforts explore other methods, which are more straightforward, more cost-effective, and, importantly, more universal, not dependent on specific line characteristics.

3.3. Observations of galloping on existing lines and experimental studies of conductor galloping at the experimental site

When designing overhead transmission lines for regions where frequent and severe conductor galloping occurs, it is necessary to take measures to prevent flashovers between phases (conductor whipping) and between phases and cables by increasing the distance between conductors (or between conductors and cables). This increase in distance should be calculated considering the possible trajectories of the conductors during the gallop. According to the rules of electrical installations, to select the distance between conductors (between conductors and cables) according to the galloping conditions, it is necessary to know some parameters of the lines and the intensity of the galloping of the conductors (oscillation range). The intensity of the galloping can be assessed based on accumulated data on the galloping of conductors on existing lines.

Numerous works are devoted to assessing the possible intensity of galloping. The results of these studies make it possible to estimate the intensity of conductor galloping under certain weather conditions and given parameters of power lines. For example, in the source by Richardson (1982), it was found that the galloping frequency is close to the natural frequency of the conductor (the difference is within 10%), while the trajectory of the conductors is an almost straight line with an angle of inclination to the vertical ±14^0. For such conditions, the maximum amplitude of the gallop is determined by Formula (10):

$$Y_{\max}\frac{0.2V_{\perp}}{f} \tag{10}$$

where:

$Y_{\max}$ – maximum amplitude of the gallop,
$V_{\perp}$ – vertical component of the wind speed;
f – frequency of the galloping.

Similar estimates were made in the works of Hunt and Richards (1969), Blevins and Iwan (1974) and Egbert (1986). According to Hunt and Richards (1969), the maximum gallop amplitude is estimated using Formula (11):

$$Y_{\max}\frac{0.26\cdot V_{w}}{f} \tag{11}$$

where:

V_w – wind speed,
f – frequency of transverse vibration of the conductor (Hz).

The experimental amplitudes are somewhat smaller than the maxima predicted by the Hunt and Richards formula. This occurs if the wind speed exceeds a certain speed (reference speed), which is given by Formula (12):

$$V_{w} > 126df \tag{12}$$

where:

V_w – reference speed,
d – conductor diameter.

Subsequently, Formula (11) is modified and reduced to the following form (13):

$$\begin{gathered} Y_{\max} = \frac{0.26\cdot V_{w}}{f}, \quad \text{if} \quad 0 \le \frac{V_{w}}{f} \le 125d \\ Y_{\max} = 33d, \quad \text{if} \quad \frac{V_{w}}{f} > 125d \end{gathered} \tag{13}$$

Relation (13) allows determining the intensity of the gallop in the case of wind speed exceeding the reference speed. The key parameters for most likely determining the line's predisposition to movement and possible gallop amplitudes are:

1. M' – parameter indicating the tendency of various types of diaphragms to cause multiple half-wave gallops (14):

$$M' = 10.67 \frac{f^3}{\lambda_g \ell^2} \tag{14}$$

where:

f – sag of the conductor,
λ_g – length of the supporting garland of insulators,
ℓ – span length.

2. T/w – span parameter that affects the value of the expected amplitude of the gallop, here T – tension of the conductor, w is the mass per unit length of the conductor (Rawlins 1981, 1986).

Based on the data (f, λ_g, ℓ, T, w) of a particular span, the parameters M' and T/w are calculated. Then, a special graphic scale or nomogram is used, which allows determining how the ratio of the expected double amplitude (intensity) of movement in gallop changes depending on the given values of M' and T/w, related to the duration of flight $2A_w / \ell$. The methodology uses the results of an analysis of observational data collected by the All-Union Energy Research Institute on 110 cases of overhead transmission lines installed in the national power system. The technique is used for the central span (single line) of 110 and 220 kV overhead transmission lines (Shkaptsov 1991).

The study by Lilien and Havard (2000) is devoted to assessing the maximum displacement (swing) of single conductor oscillations and phase separation during the galloping process. Based on the processing of 166 observational data and additional experiments, the dependence of the maximum span of the gallop on the diameter and sag of the conductor with some restrictions on the span length $(30 \le \ell \le 500)$ and wind speed (for single conductors $V \le 15$ and for split phases) $V \le 10$ was obtained:

1. For single conductors (15):

$$\frac{A_{pk-pk}}{d} = 80 \ln \frac{8f}{50d} \tag{15}$$

2. For split phases (16):

$$\frac{A_{pk-pk}}{d} = 170 \ln \frac{8f}{500d} \tag{16}$$

where:

A_{pk-pk} – span of the gallop,
d – diameter of the conductor,
f – sag of the conductor at 0°C.

Confidence intervals for the free term and the slope are also given there. Considering the interval estimate, the lower and upper limits of the expected intensity of the two-half-wave conductor gallop are presented as follows:

1. Expected minimum intensity of conductor galloping (17):

$$A_w = 0.74 + 0.28 \cdot 10^{-3}\,\ell V \sin\alpha \tag{17}$$

2. Expected maximum intensity of conductor galloping (18):

$$A_w = 1.76 + 0.68 \cdot 10^{-3}\,\ell V \sin\alpha \tag{18}$$

In this case, the following restrictions are imposed on the parameters of the regression model (19):

$$\begin{cases} 120\text{m} \le \ell \le 400\grave{\imath} \\ V \sin\alpha \le 15.6 - 0.01\ell \\ 35° \le \alpha \le 90° \end{cases} \tag{19}$$

For a more profound study of the phenomenon of conductor vibrations and to predict the quantitative characteristics of these vibrations, field tests were carried out from the moment the power lines began operating. To cause vibrations on the conductors of the experimental lines, various attachments made of wood, wax, clay, or plastic were used, which simulated icing. For example, artificial ice simulators induced oscillations (Bekmetiev et al. 1979).

3.4. Methods of dealing with the phenomena of conductor galloping

Currently, the widely recognized measure for combating the formation of ice and frost deposits is the melting of glaze ice, which is associated with some difficulties. This method of dealing with conductor galloping is applied in Norway, the USA, Japan, Canada, Sweden, Russia, and other countries. The drawbacks of this method include:

- taking the line out of operation;
- the risk of damaging weak current-carrying connectors;
- the excessively high cost of required special devices;
- at low temperatures (–10°C and below) and wind speeds exceeding 10 m/s, melting becomes impossible for conductors with large cross-sections due to insufficient power.

Preventing the formation of glaze ice by using anti-icing agents is quite tempting. The continuation of work in this direction seems promising. Changing the conductor’s cross-section at specific sections, i.e., its stepwise alteration along the span, can be achieved by attaching segments of a second conductor with a length ranging from 20 to 50% of the span (Bekmetiev et al. 1979). However, this complicates the construction of overhead transmission lines, and the overall reliability of operation may be slightly reduced. The effectiveness of such a design on sections with systematically recurring conductor galloping or on a test site should be verified in practice.

Increasing the stiffness of the system enhances restoring forces, and the frequency of its natural vibrations may also increase. This leads to an increase in the critical speed threshold at which the conductor galloping is excited. However, power transmission lines are ideally flexible threads without bending stiffness. The influence of changes in the torsional stiffness of conductors on the development and nature of conductor galloping has not been studied (Grebchenko and Kozhukhar 2018). As research shows, increasing the calculated installation tension of conductors in sections prone to systematic galloping in power transmission lines contributes to reducing the amplitude of oscillations. However, transitioning to high calculated tensions may be dangerous for the conductor's strength under high wind and ice loads, making this measure effective only in specific cases.

In most cases, conductor galloping serves as a factor for development and self-regulation due to the artificial twisting of the conductor, leading to changes in the values and even signs of aerodynamic forces, torque, and torsional frequency. For instance, the installation of additional masses on the conductor changes its natural torsional frequency, and this circumstance can be used to determine the resonance of torsional and vertical oscillations. These dampers are applied in countries such as Canada, the United States, Germany, Norway, Japan, Belgium, Slovakia, Iceland, and Latvia (Strebkov et al. 2018).

The drawback of the damper is the weak protection of the conductor from vibration and a relatively large mass of the dampers themselves. Friction dampers reduce the amplitude of conductor galloping by absorbing the energy of the oscillatory process. Increasing the energy losses during conductor oscillations can be achieved by installing special devices on the lines that use the energy dissipation effect during friction (mainly using friction disc brakes or elements of plastic bending) (Szafraniec et al. 2021; Kharlamov et al. 2014). The movement of such devices is driven by the displacement of the conductor or insulator garland. Currently, there are several patents for their designs. Reducing the length of spans while maintaining the exact structure of supports and distances between conductors is an effective measure to reduce the absolute magnitude of conductor galloping. In the case of detecting systematic intensive galloping on a specific section of constructed power lines, the installation of additional supports in the middle of the spans may be an effective measure (Bekmetiev et al. 1979; Sikorska et al. 2024). However, this measure represents a costly solution. It may have practical significance in the overall task of improving the strength of lines to increase reliability under the influence of wind and ice conditions.

For power lines with garlands of insulators, a reduction in the absolute magnitude of the gallops can be achieved by replacing the intermediate suspension with an anchor one. Of course, such an event requires appropriate testing of the supports for mechanical strength. Due to the change, like the combined vibrations of conductors and insulators, as the practice has shown when switching from an intermediate to an anchor suspension, one should expect a decrease in the calculated maximum swing ranges. However, it is necessary to consider that significant dynamic loads on the conductors arise in the anchor span. The existing rules recommend this event for the construction of electrical installations (REI) for the area where the galloping of conductors is observed. It provides for greater distances between phase conductors compared to conventional lines. The use of phase conductor spacing reduces the possibility of conductors getting tangled when galloping. To accomplish the task of phase separation supports with extended crossbars are necessary. To prevent collision of conductors during galloping, it is recommended that the distance between the phases in the vertical plane is equal to their distance in the horizontal plane (sag).

Interphase rods are used to maintain the distance between the phase conductors and the lightning protection cables by placing a string of insulators between them. This prevents them from getting too close to each other while the conductors are galloping. It is important to note that such connections do not exclude galloping but can cause coordinated vibrations of all conductors, forming a single oscillatory system. To date, they meet the requirements for lightness and flexibility and have found application on overhead transmission lines with voltages up to 500 kV in Germany, Japan, Austria, Norway, Switzerland, Canada, and America. The presence of additional winding on the conductor leads to a change in the shape of the ice deposit, as a result of which the total active energy supplied to the conductor decreases (Bekmetiev et al. 1979; Gulyaev et al. 2015). A similar effect of changing the shape of ice formation can be obtained by using a damper with a random profile. Due to the existing random profile, the resulting ice also has a non-constant (random) profile, which is why aerodynamic forces and moments arise, different in value and direction. Such absorbers are used in the USA, Sweden, South Korea, Iceland, and Canada. Many innovative methods have been created to reduce conductor vibrations, but until now, the effectiveness of these solutions has not been confirmed experimentally or by installing them on existing transmission lines.

4. Discussion

Understanding the aerodynamic aspects of the instability of ice-covered conductors is of great importance for preventing accidents and enhancing the safety of power lines, especially in regions with cold climates and frequent icing. These studies help determine how ice formation can impact the functioning of power systems and contribute to developing measures to improve reliability and prevent potential failures. The results of these studies are used in the design of transmission lines and towers to account for aerodynamic factors and ensure their stability in various climatic conditions. Realizing how icing affects the operation of transmission lines also contributes to optimizing the energy system's performance and increasing its energy efficiency. Research in this field stimulates the development of new technologies and methods to combat aerodynamic instability and conductor icing. It is important to note that these studies have significant practical value for ensuring continuous power supply in challenging meteorological conditions and play a crucial role in improving the reliability and safety of power transmission systems.

An aerodynamic theory explaining the origin of conductor galloping is based on the aerodynamic instability of profiles with non-circular cross-sections. This theory reveals how airflows can induce oscillations and vibrations in conductors, which can have negative consequences, including damage or breakage. Conductor profiles with non-standard cross-sections, such as flat or oval shapes, contribute to aerodynamic instability due to the unevenness of airflow, leading to differences in pressure and velocity around these conductors. Irregularities in the airflow generate aerodynamic forces capable of initiating conductor oscillations and vibrations (Serikuly et al. 2022; Qawaqzeh et al. 2020). These vibrations can be amplified by wind and other meteorological factors. If the amplitude of the oscillations reaches a specific value, it can cause resonance, where the vibrations become more intense. This poses a potential risk to the reliability of conductors and the power system. The range of oscillations can be significant enough to cause damage to the conductors, including their breakage or rupture. This, in turn, can lead to power outages and require expensive restoration work. Understanding this aerodynamic instability allows engineers and designers to consider this factor in designing power transmission line systems. Safety measures and methods to prevent conductor galloping, such as unique aerodynamic fairings and control systems, are also being developed. As a result, the aerodynamic instability of non-circular conductor profiles plays a critical role in ensuring the reliability and safety of power systems (Korobskyy and Siroshtan 2018; Hruban et al. 2023).

According to the findings of recent research by Rácz et al. (2023), to induce oscillations in conductors under aerodynamic instability conditions, it is most important for the lift coefficient curve to have a section with a negative slope. This means that as the angle of attack (the angle between the direction of airflow and the direction of conductor movement) increases, the lift coefficient should decrease. Additionally, the orientation of the conductor profile pitch should create conditions for aerodynamic instability in the angle of attack zone corresponding to this negative branch on the curve. It can be noted that these factors include aspects such as conductor shape, cross-section, and orientation relative to the wind direction. Engineers and designers also consider all these parameters in developing power transmission lines to minimize the risks of conductor oscillations and ensure their stability and reliability in diverse aerodynamic conditions.

Referring to the definition by Meradi et al. (2023), studies conducted in an aerodynamic tube under realistic conditions of ice shapes and wind speed indicate that the Den Hartog mechanism may not play a predominant role in inducing conductor galloping on overhead transmission lines. The Den Hartog mechanism is a theoretical model developed to explain the aerodynamic instability of conductors in windy conditions, especially in the presence of ice on the conductors. According to this theory, the presence of ice formations on the conductors alters the aerodynamic characteristics, contributing to the occurrence of conductor oscillations. This confirms that the author's work aligns with modern trends; however, data obtained during aerodynamic tests in a wind tunnel, accounting for accurate ice shapes and wind speeds, suggests that the Den Hartog mechanism may not have as significant an impact on the situation as previously assumed. Nevertheless, this work did not consider that such a situation may be influenced by additional aspects present in overhead transmission lines, which affect the aerodynamic stability of the conductors.

Tang et al. (2023) determined that when a conductor undergoes oscillations in various directions, including both torsional and linear movements, additional aerodynamic forces and interactions occur. These interactions can lead to coordinated or synchronous oscillations, meaning that the conductor's movements in different directions will be synchronized. These aerodynamic interactions and synchronicity can be crucial for aerodynamic stability and conductor vibration control on overhead transmission lines. For a more accurate understanding of the complex dynamic processes occurring with conductors under the influence of wind and other aerodynamic factors, it is necessary to develop more effective methods for preventing and controlling conductor vibrations. This will significantly enhance the reliability of power transmission systems. There are differences with this work in that the authors did not emphasize the importance of specific aerodynamic factors, such as wind speed, conductor shape, and cross-sectional dimensions.

Zhang et al. (2023) note that the oscillatory system is an abstract model used to analyze aerodynamic vibrations and the dynamic behavior of objects exposed to wind and other aerodynamic factors. Within this model is an object with specific geometric parameters and aerodynamic properties influenced by the airflow. This object can have various shapes, sizes, and characteristics, such as aerodynamic lift and drag coefficients. This study's oscillatory system characteristics were analyzed and examined more precisely. It can be added that the vertical and horizontal springs in this system support and control the profile's movement. The vertical spring allows the object to move vertically, up and down, while the horizontal spring enables horizontal movement, left and right. These springs add degrees of freedom that allow the object to undergo oscillatory movements in both directions.

Shu et al. (2023) demonstrated through their work that the span length, i.e., the distance between supports, is crucial when analyzing conductor vibrations. Larger spans can cause more prolonged and complex conductor vibrations, significantly impacting the structure and reliability of the transmission line. The conductor stiffness coefficients in bending and torsion, dependent on the material and construction of the conductors, are also vital. They determine how resistant the conductors are to bending and twisting moments acting on them. These coefficients can vary depending on the conductor type and current condition, such as tension levels. Considering these parameters is necessary for a more accurate understanding and modeling of aerodynamic conductor vibrations and their impact on the transmission line. However, it was not pointed out and considered in this work that the mass of the conductors also influences their vibrations. Larger masses can create inertial effects that are crucial to consider in the analysis. Additionally, it is worth noting that wind force and direction along the span can vary significantly, which is an essential factor as wind is a primary cause of aerodynamic conductor vibrations, highlighting the difference between this work and the author's.

Bendík et al. (2023) noted that random aerodynamic forces can vary depending on factors such as temporal changes in wind conditions and meteorological parameters. A stochastic model accounts for this randomness, allowing an assessment of the types of vibrations that may occur on the transmission line in different scenarios. Such a model's primary goal is to determine the probability and characteristics of aerodynamic conductor vibrations accurately. This, in turn, helps engineers and designers create more reliable and safe power transmission systems and make more informed decisions in variable aerodynamic conditions. It is also necessary to incorporate into the research findings that the stochastic model allows for considering diverse factors and their random variations, a crucial aspect of power engineering. It is important to develop risk management systems that may include monitoring and forecasting climate changes and strategies for responding to extreme situations. This allows for the timely prevention of potential power supply failures.

Conclusions

This article presents a comprehensive analysis of conductor galloping and its implications for the reliability and efficiency of high-voltage overhead transmission lines, with a particular focus on regions characterized by harsh weather conditions. The study identifies the principal factors that contribute to the phenomenon of conductor galloping, including wind speed, the angle of attack, and the formation of ice deposits. These findings highlight the intricate nature of the phenomenon, underscoring the necessity for an integrated strategy to mitigate its impact.

One of the most significant findings of this research is identifying wind speed and span length as the most influential variables affecting the intensity of galloping. Furthermore, creating innovative dampers that can inhibit galloping at its nascent stages presents a promising avenue for enhancing the dependability of power lines. These dampers offer a cost-effective and efficient alternative to existing solutions, with the potential to reduce operational risks and costs.

It would be beneficial for future research to focus on expanding the experimental data on conductor galloping under different environmental conditions, including varying ice deposit shapes and wind speeds. Furthermore, an investigation into developing new materials for conductors more resistant to aerodynamic forces would be advantageous. Another avenue for further investigation could be integrating innovative monitoring systems for the real-time detection and mitigation of conductor galloping. These developments will create a more reliable and efficient power supply infrastructure, thereby ensuring operational stability in adverse conditions.

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Problemy zwiększania niezawodności przesyłu energii elektrycznej liniami wysokiego napięcia w warunkach zwiększonego ryzyka klimatycznego

Streszczenie

W niniejszym artykule przedmiotem badania są napowietrzne linie przesyłowe wysokiego napięcia. Jak wiadomo, takie linie wykazują zjawisko „galopowania przewodów”. Polega ono na niskoczęstotliwościowych oscylacjach o znaczącej amplitudzie, które zazwyczaj występują podczas wietrznych i oblodzonych warunków. Te oscylacje mogą być uznane za czynnik zmniejszający niezawodność dostaw energii. Celem tego artykułu jest zwiększenie efektywności wykorzystania napowietrznych linii przesyłowych wysokiego napięcia w warunkach lodu i wiatru poprzez systematyzację rozproszonej informacji i wiedzy, jak również potencjalne odkrycie nowych kierunków badań nad tym zjawiskiem. Analiza obejmuje badanie wyników wieloletnich obserwacji danych statystycznych dotyczących galopowania przewodów w systemach energetycznych. Modele teoretyczne tego zjawiska są rozważane na podstawie równań dynamiki i bilansu energetycznego. Dane eksperymentalne są uzyskiwane poprzez obserwację galopowania przewodów na poligonie testowym z rejestracją parametrów wibracji. Poruszono ogólne kwestie niezawodności napowietrznych linii przesyłowych. Analizowane są wyniki badań statystycznych, obejmujących złożone warunki sprzyjające występowaniu galopowania przewodów, typowe uszkodzenia elementów linii energetycznych oraz ocena spodziewanej intensywności galopowania. Artykuł przedstawia wyniki badań teoretycznych i eksperymentalnych, w tym fizyczne i matematyczne modele galopowania przewodów, warunki niestabilności oblodzonych przewodów w strumieniu wiatru oraz niektóre wyniki eksperymentów przeprowadzonych na poligonie testowym. Zidentyfikowane są metody przeciwdziałania zjawisku „galopowania przewodów”, przedstawiając krótki przegląd i analizę istniejących środków tłumienia tego zjawiska. Zaproponowano zastosowanie najskuteczniejszego i ekonomicznego tłumika dla galopowania przewodów w podziale faz linii energetycznej. Dane przedstawione w artykule ujawniają kluczowe problemy związane z galopowaniem przewodów, istniejące metody ich rozwiązania, a także nowe kierunki badań nad tym zjawiskiem i obiecujące pomysły.

Słowa kluczowe: galopowanie przewodów, wpływy lodu i wiatru, bilans energetyczny, drgania przewodów, samooscylacje