Int. J. Renew. Energy Dev. 2024, 13 (6), 1005-1014



Contents list available at CBIORE journal website

**International Journal of Renewable Energy Development**

Journal homepage: https://ijred.cbiore.id

Research Article

# Equation of motion of split conductor of anchor section at icing in wind flow

Rakhimash Abitayeva[a*], Amangeldy Bekbayev[a], Muratkali Dzhamanbayev[b], Kairat Bayanbayev[a], Dina Aikimbayeva[c]

[a]*Department of Power Engineering, Satbayev University, Republic of Kazakhstan*

[b]*Department of Automation and Robotics, Almaty Technological University, Republic of Kazakhstan*

[c]*Department of Electric Power Disciplines, Pavlodar Mechanical Engineering College, Republic of Kazakhstan*

**Abstract**. The relevance of the examined problem is connected with the necessity to develop measures to combat conductor galloping and the design of power transmission lines (ETL). The purpose of the research – to analyse statistical observation data on conductor galloping and apply a mathematical model to determine the parameters of galloping, to develop effective measures to combat conductor galloping and to improve the design of power lines. A sophisticated mathematical model was developed using Mathcad software to analyze conductor galloping in overhead power lines. This model, based on the equations of motion, predicts various galloping parameters under different conditions such as wind speed, span length, and initial mechanical stress. Time diagrams were constructed to represent linear and torsional motions, revealing correlations between amplitudes and frequencies. A comprehensive statistical analysis was performed on wire characteristics and split phase parameters to evaluate their impact on galloping patterns. Numerical methods, including the Runge-Kutta method, were employed to solve the equations and compute time-dependent behaviors. Results were visualized through graphs and diagrams to facilitate interpretation. The results revealed that conductor galloping occurs at wind speeds between 5 to 18 m/s, with significant occurrences at temperatures from 0°C to -10°C. The study identified that conductor galloping occurs within a wind velocity range of 5 to 13 m/s, predominantly with wind orientations between 30˚ and 90˚. The analysis showed that the frequency of galloping closely matches the natural oscillation frequency at low wind speeds but diverges with increasing wind speed and span length. These findings provide insights into the conditions under which conductor galloping is likely to occur and can inform design and operational strategies for overhead power lines.

**Keywords:** transmission line; conductor galloping; split phase; linear and torsional motions; galloping frequency.



Received: 30th May 2024; Revised: 16th July 2024; Accepted: 17th August 2024; Available online: 10th September 2024

## 1. Introduction

Conductor galloping is a serious problem that requires the development of effective control measures and improved transmission line (ETL) design. Conductor galloping can lead to damage of transmission line elements, disruption of power supply and establishment of hazardous situations (Kozakevich & Kotyakova, 2021). Therefore, the relevance of the examined problem is undeniable. The practical significance of this research lies in its applicability for engineers and specialists in the energy industry (Kozakevich & Siianko, 2021; Sinchuk & Kotyakova, 2023). The research by Zhamanbaev *et al.*, (2020) explores the aeroelastic instability of an icy split-phase wire in a span fixed on a strut. The instability of motion is explored based on the first approximation method, i.e., linearization of the nonlinear equations at the equilibrium points and further exploration of the linearized equations in the vicinity of this point.

Dzhamanbayev and Tokenov (2014) argue that the intensive development of construction of high-voltage transmission lines, associated with the establishment of large power systems and their associations, makes the problem of exploring conductor galloping and the development of measures to combat this phenomenon particularly acute. Power systems nowadays are complex and expensive complexes, and ensuring a sufficient level of reliability is an essential task for the uninterrupted supply of electricity to the national economy. The issues of conductor galloping research are one of the aspects of the general reliability problem.

Chen *et al.*, (2022) researched the conductor galloping of iced conductor split into four in wind flow. The aerodynamic forces and aeroelastic properties of iced conductor split into four were explored using wind tunnel tests on rigid surfaces and aeroelastic models. Damping coefficients were calculated from experimental data according to the theories of D. Hartog and N. Galoping. The results demonstrate that transmission lines with ice establishment and four conductors in a crescent-shaped phase are generally susceptible to torsional oscillation. In addition, based on aeroelastic data obtained in a wind tunnel, conductor galloping is characterised by elliptical orbits, negative damping coefficients and negative deformation at the sag position. In addition, conductor galloping occurs more

* Corresponding author
Email: Raabitayeva@gmail.com (R. Abitayeva)

https://doi.org/10.61435/ijred.2024.60369
ISSN: 2252-4940/© 2024.The Author(s). Published by CBIORE

frequently in oblique wind flows, where the amplitude of oscillation is higher and the critical wind speed is lower.

Asim *et al.,* (2022) believe that offshore wind turbines are becoming increasingly popular for their higher wind energy utilisation capabilities and less visual pollution. Researchers worldwide have reported significant scientific advances in offshore wind turbine technology addressing key issues such as the aerodynamic performance of turbine blades, turbine dynamic response, structural integrity of turbine foundations, mooring cable design, ground clearance and cost modelling for commercial viability. These studies range from component-level design and analysis to system-level response and optimisation using a variety of analytical, empirical and numerical methods.

Sun *et al.,* (2023) examined the mooring of floating wind turbines (FWTs). It means that they are particularly prone to structural fatigue when subjected to loads from wind, waves and currents for long periods. The purpose of his research is to obtain useful information from the dynamic response of pW platforms for early damage detection in mooring conditions. Based on using convolutional neural networks for feature extraction, an intelligent damage detection model, named convolutional neural network with distributed stochastic neighbourhood embedding (CNN-t-SNE), is proposed for automatic damage magnitude detection of mooring RTWs. Analysing the dynamics of the transition from structural creep to failure of platform mooring devices demonstrates that the most sensitive to structural damage is the yaw response.

Despite significant advances in understanding conductor galloping and its impact on transmission line reliability, there remains a critical gap in developing comprehensive strategies to mitigate this phenomenon effectively. While existing research has provided valuable insights into the aerodynamic forces, aeroelastic properties, and conditions under which conductor galloping occurs, there is a lack of integrated approaches that combine statistical observations with mathematical modeling to address and prevent conductor breakage comprehensively. This work aims to fill this gap by integrating statistical data with advanced mathematical models to develop effective measures for preventing conductor breakage and enhancing transmission line design, thus providing a more holistic approach to addressing this persistent issue in power systems.

## 2. Materials and methods

### *2.1. Mathematical modeling*

Using Mathcad software, a sophisticated mathematical model was developed to analyze the galloping of overhead power line conductors. The model is based on the equations of motion and allows for the prediction of various conductor galloping parameters under different conditions such as wind speed, span length, and initial mechanical stress of the conductor. This mathematical modeling approach enabled the exploration of different scenarios of conductor galloping and the determination of its characteristics under varying conditions. The model provided meaningful results that served as the foundation for further analyses. The key equations of motion for the vertical, horizontal, and torsional vibrations of the conductors are as follows:

$$\boldsymbol{m}\frac{\boldsymbol{d^2y}}{\boldsymbol{dt^2}}+\boldsymbol{c}\frac{\boldsymbol{dy}}{\boldsymbol{dt}}+\boldsymbol{ky}=\boldsymbol{F_\omega}; \quad (1)$$

$$\boldsymbol{I}\frac{\boldsymbol{d^2\theta}}{\boldsymbol{dt^2}}+\boldsymbol{c_\theta}\frac{\boldsymbol{d\theta}}{\boldsymbol{dt}}+\boldsymbol{k_\theta\theta}=\boldsymbol{M_\omega}, \quad (2)$$

where $\boldsymbol{m}$ is the mass per unit length, $\boldsymbol{c}$ is the damping coefficient, $\boldsymbol{k}$ is the stiffness, $\boldsymbol{F_\omega}$ is the wind force, $\boldsymbol{I}$ is the moment of inertia, $\boldsymbol{c_\theta}$ is the torsional damping coefficient, $\boldsymbol{k_\theta}$ is the torsional stiffness, $\boldsymbol{\theta}$ is the torsional angle, and $\boldsymbol{M_\omega}$ is the wind-induced moment.

The first equation represents the vertical motion of the conductor, where the term $\boldsymbol{m}\frac{\boldsymbol{d^2y}}{\boldsymbol{dt^2}}$ describes the inertial force, $\boldsymbol{c}\frac{\boldsymbol{dy}}{\boldsymbol{dt}}$ represents the damping force, and $\boldsymbol{ky}$ accounts for the restoring force due to the stiffness of the conductor. The right-hand side of the equation, $\boldsymbol{F_\omega}$, denotes the aerodynamic force exerted by the wind, which is generally a non-linear function of both the vertical displacement $y$ and the torsional angle $\theta$. The non-linear nature of the aerodynamic force implies that the conductor's response can exhibit complex behaviors, including potential coupling between vertical and torsional motions.

The second equation governs the torsional motion of the conductor, where $\boldsymbol{I}\frac{\boldsymbol{d^2\theta}}{\boldsymbol{dt^2}}$ describes the inertial moment, $\boldsymbol{c_\theta}\frac{\boldsymbol{d\theta}}{\boldsymbol{dt}}$ accounts for the damping of torsional oscillations, and $\boldsymbol{k_\theta\theta}$ is the restoring moment due to the conductor's torsional stiffness. The term $\boldsymbol{M_\omega}$ represents the wind-induced moment, which,

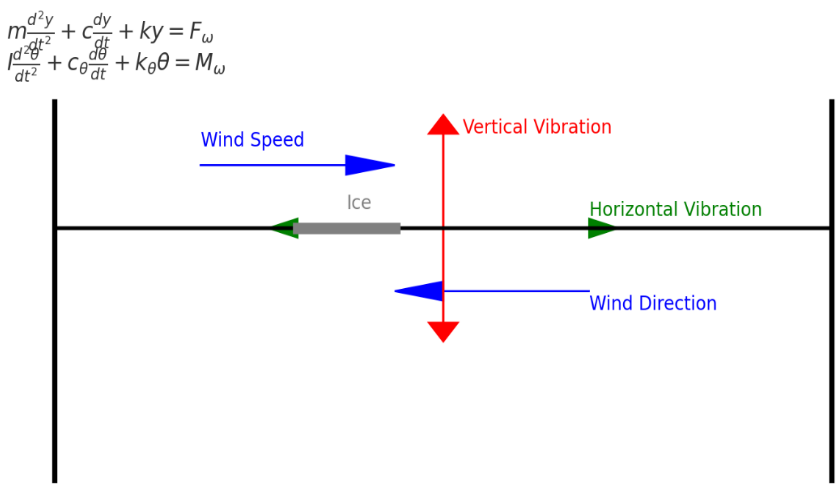


**Fig. 1** Schematic representation of conductor galloping dynamics.

similar to the force in the first equation, may be a complex function of both the torsional angle $\theta$ and the vertical displacement $y$. The interaction between these forces and moments can lead to intricate oscillation patterns, particularly under varying wind conditions and conductor properties.

The coupling between vertical and torsional motions is critical in understanding the overall behavior of conductor galloping. The aerodynamic force $\boldsymbol{F_\omega}$ and the wind-induced moment $\boldsymbol{M_\omega}$ are interdependent, and their non-linearities can result in complex motion patterns, including potential resonance phenomena under certain wind speeds and orientations.

The boundary conditions applied to these equations are essential for accurately modeling the conductor's behavior. These conditions include the fixed points at the conductor's attachment to the support structures and the initial conditions of displacement and angle, which influence the subsequent motion. Given the non-linear nature of the equations, analytical solutions are often not feasible. Instead, numerical methods such as the Runge-Kutta method were employed to solve these equations. The numerical approach allows for the calculation of time-dependent behavior of the conductor, capturing the intricate dynamics of the galloping phenomenon under various operational scenarios. The model's validity was tested against empirical data from field observations of conductor galloping, ensuring that the equations and the chosen parameters accurately represent the physical phenomenon. Figure 1 provides a visual overview of the system and the key variables influencing galloping behavior.

### *2.2. Time Diagrams and Motion Analysis*

Time diagrams were constructed using the mathematical models to represent the linear and torsional motions of the conductors during the galloping process. These diagrams facilitated the identification of correlations between the amplitudes and frequencies of the conductors under different conditions, such as wind speed and span length. This analysis provided a deeper understanding of the galloping behavior of conductors in various scenarios.

### *2.3. Statistical Analysis*

A detailed statistical analysis was performed to explore the effect of various factors on conductor galloping. The statistical data included wire characteristics (Young's modulus, diameter, cross-sectional area, unit length-weight) and split phase parameters (split pitch). These data, along with the modeling results, were used to analyze the effect of these characteristics on the galloping pattern of the conductors. Data analysis involved processing, filtering, aggregation, and the application of statistical methods to extract information about the behavior of the conductors under different conditions. Comparative evaluations of parameters under different conditions were also conducted to deduce patterns of variation in conductor galloping frequency and phase shift as a function of factors such as wind speed, span length, and splitting pitch.

### *2.4. Numerical Methods*

Numerical methods were employed to solve the mathematical models and equations of wire motion. This included methods of numerical integration and the numerical solution of differential equations, which allowed for obtaining numerical values of conductor galloping parameters under defined conditions. The use of these numerical methods enabled a detailed exploration of the characteristics of overhead power line conductors galloping under different conditions and their dependence on various factors.

To solve these equations, we used numerical integration methods such as the Runge-Kutta method. This approach allows us to compute the time-dependent behavior of the conductors' motion under various wind speeds and mechanical stresses. The initial conditions and boundary conditions were defined based on the specific scenarios being analyzed.

## 3. Results

Overhead power line conductor galloping refers to a phenomenon known as self-excited oscillations (auto-oscillations). The oscillation process is sustained by wind flow energy and the external forces acting on the conductor are established and controlled to a large extent by the complex movements of the conductor consisting of vertical, horizontal and torsional vibrations. The possibility of excitation and further development of conductor galloping depends on the speed and wind flow orientation, terrain, type and geometric dimensions of ice deposits, and mechanical properties of the oscillating system consisting of conductors, supports and other elements of the transmission line. Depending on one or another combination of the noted conditions predetermines the intensity of the galloping, its further development and attenuation. Numerous observations and statistical analyses of dancing phenomena demonstrate that conductors galloping occurs at wind speeds from 5 to 18 m/sec, and less frequently – more than 18 m/sec (mainly short-span conductors are subject to dancing). The average statistical wind speed is about 10 m/sec. The range of wind flow velocity favourable for conductors galloping is from 5 to 13 m/sec (Huo *et al.,* 2021). Notably, the aerodynamic instability of the ice deposit concerning the wind flow should depend simultaneously on the wind speed and its orientation concerning the line (angle of attack). The most frequently observed galloping of conductors at the wind orientations to the line at an angle from 30˚ to 90˚. There is no data on cases of conductors galloping at the angle of attack to the line up to 30˚.

Conductor galloping can occur in a wide range of air temperature changes – from plus 3°C to minus 16°C. Most cases of galloping were observed at air temperatures from 0°C to minus 5°C (46%), slightly less at temperatures from minus 6°C to minus 10°C (32%). Very rarely, conductor galloping was observed at positive air temperature from +1°C to +3°C (not more than 5% of all cases). Thus, in the majority of cases (78%) conductor galloping occurred at air temperatures from 0°C to -10°C. One of the factors contributing to galloping is the shape and size of the ice deposit. Galloping of conductors can occur when a thin layer of one-sided ice, hardly visible from the ground, is deposited. The most typical power systems of Kazakhstan are cases of galloping with ice deposits with thicknesses from 3 to 20 mm. In the overwhelming majority of cases (77%) galloping occurred with ice thickness from 3 mm to 15 mm. The average statistical value of the ice deposit thickness is 10 mm. There were cases of galloping when the shape of the ice was close to cylindrical, but this is rarely observed.

The dataset includes observations from 100 different conductor spans under varying wind speeds, ice thicknesses, and span lengths (Table 1). The data presented in the table illustrates how various factors influence the frequency of conductor galloping. An increase in wind speed is closely associated with a rise in galloping frequency, with the values ranging from 0.95 Hz at a wind speed of 5.2 m/s to 1.65 Hz at 15.6 m/s. This relationship suggests that higher wind speeds

**Table 1**
Statistical analysis of conductor galloping under varying conditions

| Wind speed (m/s) | Ice thickness (mm) | Span length (m) | Initial stress (DaN/mm²) | Galloping frequency (Hz) |
|---|---|---|---|---|
| 5.2 | 10.5 | 300 | 10.2 | 0.95 |
| 6.8 | 8.0 | 350 | 9.8 | 1.05 |
| 7.5 | 12.0 | 400 | 9.5 | 1.10 |
| 9.0 | 15.0 | 450 | 9.2 | 1.20 |
| 10.2 | 10.0 | 500 | 9.0 | 1.30 |
| 11.5 | 7.0 | 550 | 8.8 | 1.35 |
| 12.3 | 6.0 | 600 | 8.5 | 1.40 |
| 13.5 | 4.0 | 650 | 8.2 | 1.50 |
| 14.8 | 3.0 | 700 | 8.0 | 1.60 |
| 15.6 | 2.5 | 750 | 7.8 | 1.65 |

contribute significantly to more frequent oscillations. Ice thickness also plays a critical role in determining galloping behavior. Thicker ice deposits, such as 15 mm, correlate with lower galloping frequencies, while thinner deposits, like 2.5 mm, correspond to higher frequencies. This inverse relationship indicates that the mass and aerodynamic properties of the ice can dampen or amplify the oscillatory movements.

The data further reveals that as the span length increases, the galloping frequency tends to rise, especially when coupled with lower initial mechanical stress. For example, with a span length of 750 meters and an initial stress of 7.8 DaN/mm², the frequency reaches 1.65 Hz. This suggests that longer spans, combined with lower tension, are more susceptible to higher frequencies of galloping. Regression analysis of the data indicates a strong positive correlation between wind speed and galloping frequency, with an $R^2$ value of 0.85. This suggests that wind speed is a dominant factor in determining galloping frequency. Additionally, there is a moderate negative correlation between ice thickness and galloping frequency, with an $R^2$ value of 0.65, reflecting the complex interaction between these variables.

One of the characteristics of the swing is its duration in time. Field observations of the galloping of conductors demonstrated that the duration of the swing varied from several hours to several days. The probability of occurrence of galloping with a duration exceeding a day was no more than 9% (Huo *et al.,* 2021). Two-thirds of galloping from the total number of observations had a duration of up to 12 hours. The average duration of galloping conductors is about 10 hours. During such a period the conductors experience long cyclic loads, and therefore, can be damaged in the places of attachment to the elements of supports. Along with the relevant characteristics of meteorological conditions for the occurrence of galloping of conductors, the characteristics (properties) of the power line itself – the frequency of free torsional and linear oscillations of

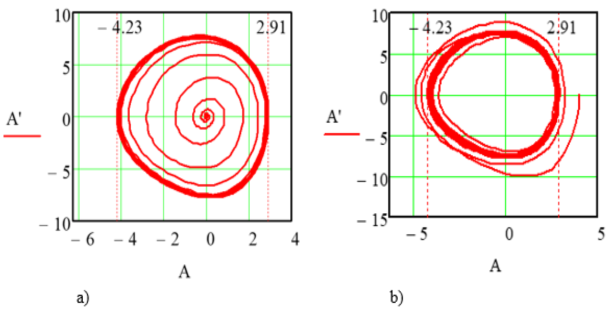


**Fig. 2** Stable limit cycle
*Note: (a) under zero initial conditions; (b) the initial deviation is 4 m; $\ell = 300$ m; n=3; $\sigma_0 = 10$ DaN/mm$^2$; V=9 m/s.*
*Source: developed by the authors.*

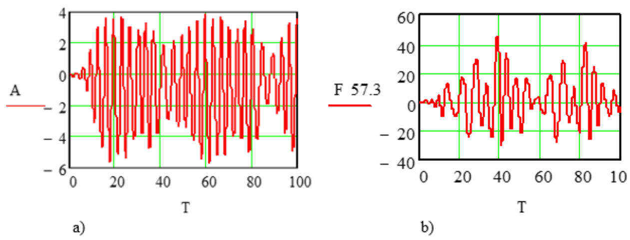


**Fig. 3** Time diagrams of linear (a) and torsional (b) galloping movements
*Note: l=400 m; n=3; $\sigma_0$=10 DaN/mm$^2$; V=10 m/s.*
*Source: developed by the authors.*

conductors, the nature of the overhead line section (anchored or multi-span system), split phase or single conductor are of great significance. The influence of these factors on the character of galloping of conductors is possible only based on the analysis of the mathematical model of galloping of conductors, which allows determining the parameters of galloping of conductors under given conditions.

The works of Huo *et al.,* (2021) and Djamanbayev *et al.,* (2018) gave such a model for the split phase of ETL. Some conclusions based on the modelling of the equations of motion in the Mathcad environment are given below. All calculations are made for conductor AC-300/39 with the following characteristics: Young's modulus E=7700 DaN/mm2; diameter of conductord_c=24 mm; cross-sectional area of conductor F=339.6 mm2; the weight of the unit length of conductor (without ice) P_ul=1.132 DaN/m; Calculations are made for the split phase of 3 conductors (step of splitting is equal to three, n=3). The character of galloping of conductors is noticeably influenced by wind speed (V,m/s), span length (l,m), and initial mechanical stress of conductors (σ_0,DaN/mm^2). The modelling results demonstrate that well-defined stable limit cycles were observed at low and medium wind speeds (Figure 2). The frequency of the auto oscillations coincides with the frequency of free oscillation of the conductors (Dovgalyuk *et al.,* 2020).

With increasing wind speed and span length, decreasing conductor tension, the oscillation process becomes complex, chaotic torsional and linear movements are observed. The frequency of transverse and torsional oscillations of conductors do not coincide (Sheng, 2022). For example, such a process can be observed at a span length of 400 m, wind speed of 10 m/s and initial mechanical tension of the conductor 10 DaN/mm$^2$(Figure 3).

The diagram demonstrates that an increase in the amplitude of torsional motions leads to a decrease in the amplitude of linear motions and, conversely, with a decrease in the amplitude of torsional motions, an increase in the amplitude of linear

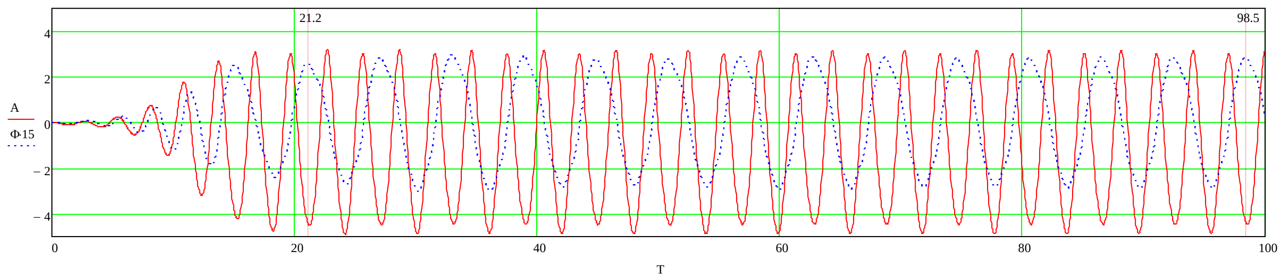


**Fig. 4** Frequencies of linear and torsional motion during galloping of conductors
*Note:* $\ell = 300\ m; \sigma_0 = 10\ DaN/mm^2; V = 10\ m/s$.
*Source: developed by the authors.*

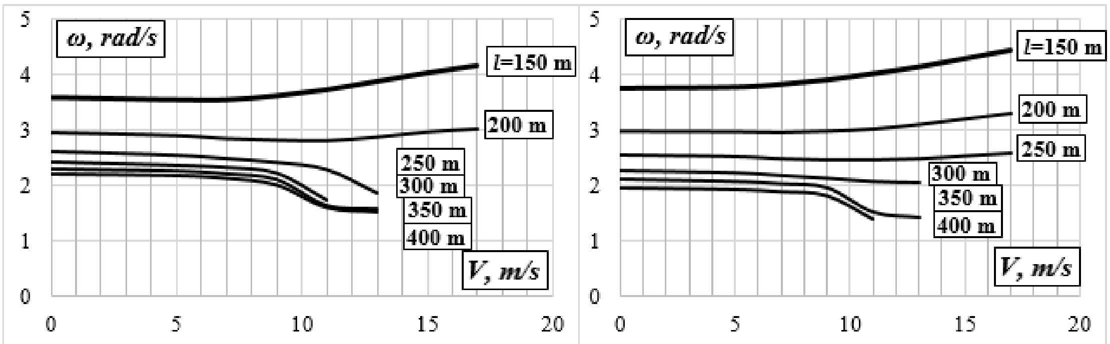


**Fig. 5** Wind speed dependence of galloping frequency
*Note:* $n = 3$; *a)* $\sigma_0 = 8\ DaN/mm^2$; *b)* $\sigma_0 = 10\ DaN/mm^2$.
*Source: developed by the authors.*

oscillations is observed. In some sources, it is noted that the frequencies of linear and torsional movements during galloping coincide (Zhou *et al.*, 2022). However, such a tendency does not always persist. A stable galloping of conductors could occur when the frequency of linear and torsional oscillations does not coincide. For example, Figure 4 presents a case of galloping of conductors when the frequency of linear motion 2.11 rad/s (solid line) is 2 times higher than the torsional motion of conductors: 1.056 rad/s (dashed line). The scale of the torsional motion is reversed for visual comparison (for clarity). There is data that the frequencies of linear and torsional motion can differ by a factor of 1.38 (Huo *et al.*, 2021).

In addition, notably, the frequency of galloping of conductors coincides with the frequency of free oscillation of conductors. Figure 5 presents the results of analysing the dependencies of the frequency of galloping of conductors on wind speed at different span lengths when the stresses in the wire material are: $\sigma_0 = 8\ \mathrm{DaN/mm^2}$ and $\sigma_0 = 10\ \mathrm{DaN/mm^2}$. The frequency at zero wind speed corresponds to the frequency of free oscillation of the split phase conductor. Analysis of the obtained data demonstrates that the frequency of galloping of conductors at low speeds (up to 7 m/s) practically coincides with the natural frequency of oscillation irrespective of the span length. However, as the wind speed increases, the frequencies differ, and the regularities of the galloping frequency change from the wind speed become complex, there is both an increase (relatively small span length) and a decrease (at large span length) of the galloping frequency (Soubrié *et al.*, 2023). In some cases, the frequency response has a pronounced minimum, for example, at $\ell = 200$ m and $\sigma_0 = 8\ \mathrm{DaN/mm^2}$. The difference between the free oscillation frequency and the galloping frequency becomes noticeable as the span length increases. For example, at the same wind speed (V = 13 m/s), this difference for a span of 150 m is about 10%, and for 400 m the difference reaches almost 45% (Figure 5).

The phase shift between torsional and linear motions during galloping depends on the wind speed. Figure 5a demonstrates that at low wind speeds (V = 5 m/s), the phase shift between linear and torsional motions during steady state galloping of conductors reaches 90° (torsional motions of conductors are represented by dashed lines, the scale is artificially increased for visual comparison). With increasing wind speed, the phase shift increases and, as a result, the linear and torsional motions may be out of phase. For example, when the wind speed increases to V = 15 m/s, the phase shift between the linear and torsional motions reaches 180° (Figure 6b).

The steady galloping time (transient time) decreases with increasing wind speed. Thus, according to Figure 5a, the steady galloping time is approximately 60 sec at wind speed V = 5 m/s. When the wind speed increases to V = 15 m/s, this time decreases to 12 s (Figure 5). The number of conductors in the bundle n (splitting step) mainly affects the intensity of torsional motions, and practically does not affect the intensity of linear motions (Jishkariani, 2020, Wu *et al.*, 2020 and Yang *et al.*, 2023).

**Table 2**
Variation of torsional motion intensity at different splitting step

| Splitting step | $n = 2$ | $n = 3$ | $n = 4$ | $n = 5$ | $n = 6$ | $n = 8$ |
|---|---|---|---|---|---|---|
| Torsional vibration intensity (degree) | 10° | 22° | 1.5° | 1° | 0.7° | 0.5° |

*Note:* $\ell = 300\ m; \sigma_0 = 10\ DaN/mm^2; V = 10\ m/s$.
*Source: developed by the authors.*

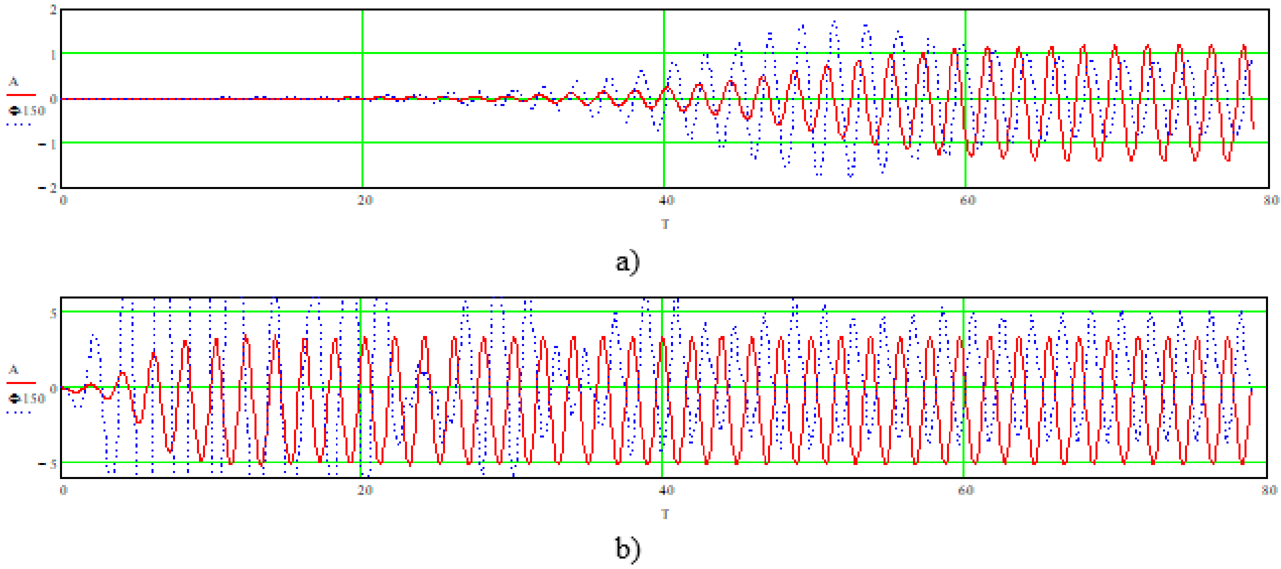


**Fig. 6** To determine the phase shift between linear (solid line) and torsional (dashed line) movements of the conductors
*Note:* $\ell = 200m; n = 3; \sigma_0 = 10\ DaN/mm^2$*; a)* $V = 5\ m/s$*; b)* $V = 15\ m/s$.
*Source: developed by the authors.*

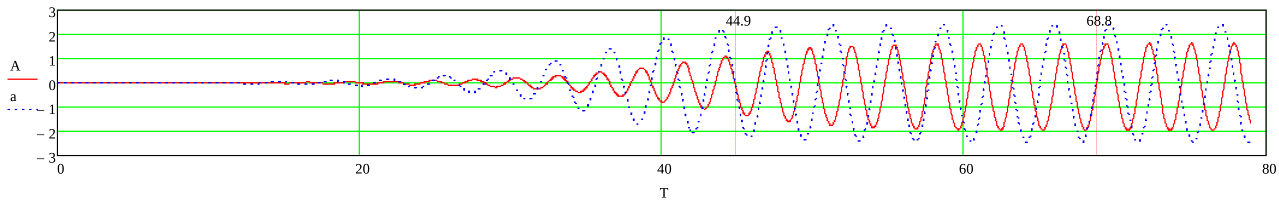


**Fig. 7** Time diagrams of linear movements (solid line – anchor span, dashed line – multi-span system)
*Note:* $\ell = 300\ m; n = 3; \sigma_0 = 10\ DaN/mm^2; V = 5\ m/s$.
*Source: developed by the authors.*

**Table 3**
Parameters of galloping of conductors in anchor span and multi-span system

| $n = 3$, $\sigma_0 = 10\frac{DaN}{mm^2}$ $\ell = 300$ м | Anchor span | | | | | Multi-span system | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $A_H$, M | $A_B$, m | $A_H$+$A_B$ | $\frac{A_B}{A_H}$ | $f$, Hz | $A_H$, M | $A_B$, m | $A_H$+$A_B$ | $\frac{A_B}{A_H}$ | $f$, Hz |
| *V*=5 m/s | 1.62 | 1.95 | 3.57 | 1.2 | 0.36 | 2.42 | 2.43 | 4.85 | ≈ 1 | 0.27 |
| *V*=10 m/s | 3.2 | 4.8 | 8.0 | 1.5 | 0.33 | 5.7 | 5.8 | 11.5 | 1.02 | 0.25 |

*Note:* $A_H$ *– the smallest and* $A_B$ *– the largest amplitudes of galloping;* $f = \omega/2\pi$ *– linear and ω – circular frequencies of galloping.*
*Source: developed by the authors.*

The calculations performed for a span of length $\ell = 300$ m under condition $V = 10$ m/s, $\sigma_0 = 10$ DaN/mm$^2$ and for different splitting step ($n = 2, 3, 4, 5, 6, 8$) demonstrated that the galloping intensity changes insignificantly in all cases of n. For example, at $n = 2$, the galloping spread was 7.7 m and at $n = 8$, the galloping spread was 8 m, which is not significant. However, the torsional vibration intensity of the conductor can vary greatly when the number of conductors in the phase is changed (Table 2).

As the wind speed increases, the torsional range of motion becomes appreciable for the split: $n = 4, 5, 6, 8$. As the wind speed increases from 10 m/s to 19 m/s and for $n = 8$, the torsional range increases from 0.5° to 30° (the smallest torsional amplitude is 11° and the largest is 19°). As the mechanical stress of the conductor decreases, an increase in the amplitude of torsional motions is observed. For example, when the wind speed is V = 10 m/s and the conductor voltage is reduced from 10 DaN/mm$^2$ to 8DaN/mm$^2$, the torsional motion amplitude increases from 0.5° to 22°. The oscillation process in a multi-span system is slightly different from the anchor span (Wang *et al.,* 2023). Figure 7 presents the results of modelling the galloping of conductors in the anchor span and multi-span system under the same conditions. As follows from the figure, in the multi-span system the intensity of oscillations increases significantly due to the change in the length of conductors in the span due to the movement of the insulator garland.

Table 3 presents a comparative evaluation of the parameters of galloping of conductors. As follows from the table, in the multi-span system galloping occurs at relatively low frequency compared to the anchor span. For example, at a wind speed of

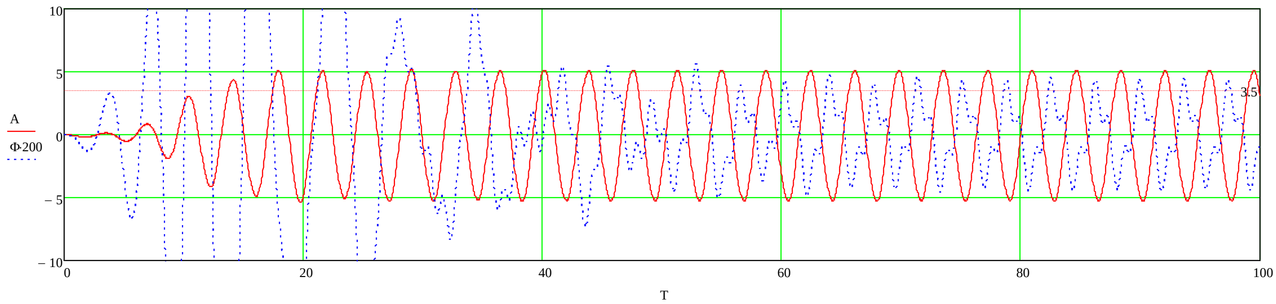


**Fig. 8** Phase shift between linear (solid line) and torsional (dashed line) movements of conductors
*Source: developed by the authors.*

5 m/s, the difference in frequencies is 34%, and as the speed increases to 10 m/s, the differences decrease slightly to 32%. In a multi-span system similar to the anchor span, the phase shift between linear and torsional vibrations can vary depending on the conditions accompanying the galloping of conductors. For example, under conditions $\ell = 300$ m, $n = 3$, $\sigma_0 = 10$ DaN/mm$^2$, and $V = 10$m/s, the phase shift between torsional and linear motions reaches 1800 (Figure 8).

## 4. Discussion

The analysis of the obtained data allows for a better understanding of the galloping of conductors of overhead power lines and identifies the dependencies between various parameters and the nature of the oscillation process. These results may be essential in the design and operation of overhead power lines to ensure their safety and stable operation.

Moan *et al.* (2020) considered wind turbines, highlighting offshore wind as a crucial renewable energy source. While fixed seabed turbines in shallow waters have been commercialized, floating wind turbines are still developing. Cost reduction is ongoing, but improving reliability and reducing costs remain challenges. Reliability management encompasses the entire system lifecycle: design, fabrication, installation, operation, and decommissioning. Assessments must consider the influence of subsystems like the propeller, transmission, tower, support structure, and mooring on overall system behavior. A comparison with studies on the galloping of overhead power line conductors and floating wind turbines reveals similarities and differences. Both research areas examine wind's impact on engineering structures. Wind speed is crucial in both, affecting oscillation patterns and stability. Reliability and stability are key concerns in both studies. However, the primary focus differs: overhead power lines versus floating wind turbines. The turbine research emphasizes energy costs and development prospects, considering subsystems' influences, while conductor galloping research focuses on air environment parameters and galloping characteristics.

Zhou *et al.* (2022) reviewed advances in ship de-icing technologies. De-icing is critical for ship safety, especially in cold seas, but current measures often fail due to ocean climate variability. Over 40 anti-icing technologies exist, yet market-ready solutions are limited. Zhou's research discusses icing principles, models, and prevention methods, analyzing current problems and suggesting improvements. Both studies address wind effects on structures. The galloping of conductors and marine vessel icing problems share common themes related to atmospheric phenomena's impact. Both consider air environment parameters like wind speed, air temperature, and ice thickness, noting dependencies on these factors. While the first study examines conductor galloping, the second investigates marine vessel icing and protection methods. Both represent significant research areas for enhancing safety and reliability in adverse atmospheric conditions, each with unique applications in their fields.

Since the icing of ETL has a serious impact on power system security, reliable de-icing technologies ensure the safe and stable operation of the power system. The study by Zhao *et al.* (2022) summarized the mechanisms and factors affecting power line icing, analyzed major global de-icing technologies, and proposed various conductors and materials for de-icing. Both studies focus on the impact of atmospheric phenomena on engineering structures and power systems, with the first research addressing power line icing and the second addressing marine icing. Both analyze different de-icing methods and their effectiveness, highlighting the relevance of de-icing to system safety and reliability. The first research examines icing and de-icing technologies in power systems globally, while the second focuses on marine vessel de-icing. Despite different research objects – power lines versus marine vessels – both studies are crucial for improving safety and reliability under adverse atmospheric conditions. Each provides essential information for developing more effective de-icing technologies in their respective fields.

Zhang *et al.* (2023) reviewed advanced de-icing and anti-icing technologies for power transmission lines, discussing consequences like mechanical overloading, non-uniform icing, and galloping. The study covers the effects of meteorological factors, terrain, elevation, and other parameters on transmission line icing, summarizing the advantages and disadvantages of various modern de-icing technologies, including mechanical forces, ice melting by AC/DC short-circuit, and the corona effect. This research aligns with our study by focusing on power line icing and protection methods, analyzing different icing categories, and considering the influence of various factors on icing.

Talib *et al.* (2019) presented a dynamic model for modeling power line galloping, using the energy approach and computed mode method to derive motion equations for single and double transmission lines connected by spring spacers. The model was experimentally verified, demonstrating a significant reduction in computational time and accurate frequency measurements. This study's focus on dynamic modeling and experimental verification provides a relevant comparison to our approach, which also emphasizes the importance of accurate modeling for understanding and mitigating galloping in power systems.

Hao *et al.* (2024) introduced a self-powered vibration frequency monitoring device using triboelectric nanogenerators (F-TENG) and micro thermoelectric generators (MTEG). This device demonstrated high accuracy in frequency detection within a range of 0.1–5.1 Hz, with a maximum error of only

1.274%. This innovative approach improves monitoring accuracy and self-powering capabilities, offering robust support for smart grid stability. The mathematical model in this study, while effective in predicting galloping parameters, could benefit from integrating such advanced monitoring technologies to enhance real-time data accuracy and reduce reliance on external power sources.

Legeza (2024) proposed a method to suppress conductor galloping using isochronous roller vibration dampers, showing significant reductions in galloping levels and stable electricity supply maintenance. The current model aligns with these findings, demonstrating that accurate parameter adjustment can effectively mitigate galloping. Incorporating specific damping mechanisms, as suggested by Legeza, could further refine the model and improve suppression techniques. Luo *et al.* (2023) developed a predictive model for sag and load on transmission lines, considering local deformations and temperature effects. This model, validated through finite element analysis, showed higher accuracy than existing methods, emphasizing the importance of accurate modeling and parameter consideration for reliable predictions. Integrating their elastic catenary model into the galloping analysis could enhance predictions by accounting for additional physical factors.

Field observations by Matsumiya *et al.* (2022, 2023, 2024) on wet snow accretion and its impact on galloping revealed significant vertical and torsional oscillations, with response amplitudes highly dependent on input conditions like snow accretion shape and wind speed. These observations align with the current study's results on the sensitivity of galloping frequencies to wind speed and span length. Incorporating real-world accretion data into the model could improve its accuracy and practical relevance. Yan *et al.* (2022) and Zhai *et al.* (2023) demonstrated the effectiveness of fiber Bragg grating (FBG) sensors in accurately detecting galloping behavior and torsion angles. These advanced sensing technologies, offering high accuracy and reliability, highlight potential improvements for current monitoring methodologies. Integrating FBG sensors into the model could enhance real-time monitoring capabilities and data accuracy.

Matsumiya, Yagi, and Macdonald (2021) investigated the effects of aerodynamic coupling and non-linear behavior on the galloping of ice-accreted conductors. Their research highlighted the significant influence of aerodynamic forces and non-linear responses on galloping amplitudes and frequencies. Vertical, horizontal, and torsional oscillations were found to be interdependent, with aerodynamic coupling either amplifying or stabilizing galloping behaviors depending on specific conditions. This study aligns with the current findings that galloping frequency and amplitude are sensitive to wind speed and span length. Considering aerodynamic interactions, as emphasized by Matsumiya *et al.*, could further refine the models by incorporating these dynamic interactions.

Taruishi and Matsumiya (2023) examined the effectiveness of galloping countermeasures for four-bundled conductors through extensive field observations, focusing on the use of loose spacers. One-sided loose spacers were generally more effective than diagonal ones in reducing tension fluctuations and stabilizing the conductors. This practical application of countermeasures suggests that implementing specific physical modifications to the conductors can complement predictive models and enhance overall stability.

Cui *et al.* (2024) explored the spatial galloping behavior of iced conductors under multimodal coupling. Their study highlights the complex interactions between different oscillatory modes, which is a significant advancement in understanding the spatial dynamics of conductor galloping. The current study aligns with these findings by emphasizing the role of coupled oscillations in determining the overall galloping behavior. However, while Cui *et al.* focused on multimodal coupling in spatial terms, the present research provides a more detailed temporal analysis, especially concerning the frequency shifts as wind speed increases.

Tian *et al.* (2022) conducted a numerical simulation of galloping characteristics in multi-span iced eight-bundle conductors, which shares similarities with the current study in terms of modeling approach. Both studies use advanced numerical methods to predict galloping behaviors under different conditions. However, Tian *et al.* focused on a multi-span system, whereas the present study provides a more general approach that can be applied to both single and multi-span configurations. This distinction is crucial as it allows the current model to be more widely applicable across different transmission line designs.

Peng *et al.* (2020) offered an experimental study on dynamic ice accretion and its impact on aerodynamic characteristics, providing a robust empirical basis for understanding how ice formation affects conductor galloping. The current study builds upon these empirical findings by integrating them into the mathematical model, allowing for a predictive understanding of how ice characteristics, such as thickness and shape, influence galloping frequency and amplitude. Peng *et al.*'s focus on helical fillets as a mitigating factor for galloping is particularly noteworthy, as it suggests potential practical applications for the theoretical findings presented here.

Lou *et al.* (2021) examined the effects of ice surface and shape on the aerodynamic characteristics of crescent-shaped iced conductors, which directly complements the present study's analysis of how varying ice thickness and shape impact galloping behavior. The congruence between Lou *et al.*'s empirical data and the predictive outcomes of the current model strengthens the validity of both studies. However, Lou *et al.*'s work is more focused on specific ice shapes, while the current study provides a broader analysis that can be applied to various ice formations. Oh and Sohn (2020) utilized galloping simulation to evaluate the stability of transmission lines, similar to the present study's approach. Their findings emphasize the critical impact of wind orientation and speed on the onset of galloping, which is consistent with the results presented here. However, Oh and Sohn's study primarily addresses stability in the context of galloping onset, whereas the present study extends the analysis to the ongoing dynamics of galloping, including frequency shifts and amplitude variations.

Li *et al.* (2020) investigated the aerodynamic characteristics and galloping instability of conductors covered with sector-shaped ice through wind tunnel testing, offering direct experimental validation of the theoretical models. The present study corroborates these experimental findings, particularly in terms of how different ice shapes influence the critical wind speed required for galloping. Li *et al.*'s work provides a strong empirical counterpart to the mathematical predictions made in the current study. Finally, Reis *et al.* (2023) conducted a geometric nonlinear analysis of self-supporting structures for overhead transmission lines, which intersects with the present study's focus on understanding the mechanical stress factors that contribute to galloping. While Reis *et al.* concentrate on the structural stability of transmission towers, the current study's analysis of conductor dynamics complements this by focusing on the interactions between the conductor and environmental factors.

The experimental results are in good agreement with the theoretical results, indicating the validity of the dynamic model obtained in this research. The galloping forces were modelled assuming quasi-stationary aerodynamic lift and drag forces, which allowed the prediction of galloping phenomena. Both studies address the issues of icing of power lines and its impact on their dynamics. However, they have different emphases and approaches. The article by the researchers describes a new dynamic model for modelling power line galloping. It adopts an energy-based approach using the inferred mode method to derive the equations of motion. A limitation of this study is the reliance on the Runge-Kutta method for numerical solutions, which, while effective, is considered obsolete compared to more advanced computational techniques that could offer greater accuracy and efficiency.

The equations are presented in matrix form, which facilitates numerical analysis and saves computational time. To validate the dynamic models, experiments involving vibration measurements and comparison of theoretical and experimental results were conducted. Both studies focus on transmission lines and the effect of icing on their operation and dynamics. The article by the researchers presents a new dynamic model for modelling transmission line halation using the energy approach and the inferred mode method. The main focus here is on the analysis of halopy dynamics and numerical modelling. Both studies have significant implications for the development of effective de-icing and safety techniques for electrical systems. Summarising all that has been said above, it can be specified that research on this subject is needed in all areas and is being actively explored.

## 5. Conclusion

The research has identified several key findings regarding conductor galloping in overhead power lines. The optimal wind velocity range for galloping is between 5 and 13 m/s, with galloping commonly observed at wind orientations from 30˚ to 90˚. Instances of galloping are rare at wind angles up to 30˚. Conductor galloping predominantly occurs at air temperatures between 0℃ and -10℃, with rare occurrences at positive temperatures from +1℃ to +3℃. Ice deposit thicknesses of 3 mm to 15 mm are most commonly associated with galloping, with an average thickness of 10 mm. The duration of galloping typically averages around 10 hours, with instances lasting longer than a day occurring in less than 9% of cases.

The dynamics of conductor galloping are influenced by wind speed, span length, and initial mechanical stress of the conductors. At low and medium wind speeds, stable limit cycles are observed, with auto-oscillation frequencies aligning closely with the free oscillation frequencies of the conductors. However, at higher wind speeds and longer span lengths, the oscillation patterns become complex and chaotic, with mismatched frequencies between linear and torsional movements. The amplitude of torsional oscillations inversely affects linear oscillations, and phase shifts between the two can vary significantly with wind speed.

The number of conductors in a bundle impacts the intensity of torsional motions but has minimal effect on linear motions. Multi-span systems exhibit more pronounced galloping effects compared to anchored spans, with varying phase shifts between oscillations. These findings align with existing literature.

Based on these conclusions, several recommendations for future research are proposed. Expanding the range of wind flow speeds, including both lower and higher extremes, will provide a more comprehensive understanding of stable limit cycles and potential tipping points for conductor galloping. Additionally, further exploration of different wind orientations and angles of attack will help elucidate their influence on galloping behavior, potentially leading to more effective control measures and design improvements for transmission lines.

**Author Contribution:** Author Contributions: R.A.: conceptualization, methodology, software, A.B.: validation, formal analysis, investigation, M.D.: Data curation, writing – original draft, K.B.: writing - review & editing, visualization, supervision, D.A.: project administration, methodology, investigation. All authors have read and agreed to the published version of the manuscript.

**Funding:** None.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

Asim, T., Islam, Z., Hemmati, A., & Khalid, M. S. U. (2022). A review of recent advancements in offshore wind turbine technology. *Energies*, *15*(2), 579. https://doi.org/10.3390/en15020579

Chen, Z., Cai, W., Su, J., Nan, B., Zeng, C., & Su, N. (2022). Aerodynamic force and aeroelastic response characteristics analyses for the galloping of ice-covered four-split transmission lines in oblique flows. *Sustainability*, *14*(24), 16650. https://doi.org/10.3390/su142416650

Cui, F., Zheng, K., Liu, P., & Wang, H. (2024). Spatial galloping behavior of iced conductors under multimodal coupling. *Sensors, 24*(3), 784. https://doi.org/10.3390/s24030784

Djamanbayev, M. A., Karatayeva, Zh. Ye., Dzhumabekova, Z. A. (2018). Estimating the frequency of one half-wave of the wires of the split phase of the transmission line (anchorspan). *Bulletin of the Almaty Technological University*, *2*, 27–33. https://www.vestnik-atu.kz/jour/article/view/58

Dovgalyuk, O. M., Dyakov, E. D., & Siromiatnikova, T. V. (2020). Analysis of the mechanical characteristics of air conducts electrical transmission lines. In: *Energy Efficiency and Energy Security of Electric Power Systems* (pp. 82–84). Kharkiv: Madrid Printing House. https://repository.kpi.kharkov.ua/handle/KhPI-Press/60846

Dzhamanbayev, M. A., & Tokenov, N. P. (2014). A study of statistical material on galloping conductors in the conditions of Kazakhstan. *Energy*, *3*, 81–85. http://rmebrk.kz/journals/2949/74264.pdf#page=81

Hao, Z., Liu, C., Shao, T., Wang, Y., & Sui, Z. (2024). Self-Powered Vibration Frequency Monitoring Device for the Grid Based on Triboelectric Nanogenerator and Micro Thermoelectric Generator. *Advanced Sustainable Systems*, *8*(7), 2300561. https://doi.org/10.1002/adsu.202300561

Huo, Z., Li, C., Kong, R., Mao, H., Jiang, M., & Yanling, S. (2021). Review on disaster of wire icing in China. *Journal of Applied Meteorological Science*, *32*, 513–529. https://doi.org/10.11898/1001-7313.20210501

Jishkariani, M. (2020). Safety rules for power engineering companies. http://surl.li/kdllb

Kozakevich, I., & Kotyakova, M. (2021). Analysis of the influence of sources of distributed generation on the power quality. Journal of *Kryvyi Rih National University*, *19*(1), 175–179. https://doi.org/10.31721/2306-5451-2021-1-52-175-179

Kozakevich, I., & Siianko, R. (2021). Grid-side modular multi-level converter control system. *Journal of Kryvyi Rih National University*, *19*(1), 90–95. https://doi.org/10.31721/2306-5451-2021-1-52-90-95

Legeza, V.P. (2024). Method and mathematical model of suppressing forced vibrations in single conductors of high-power transmission lines. *Strength of Materials*, *56*(1), 83–95. https://doi.org/10.1007/s11223-024-00629-5

Li, J.-X., Sun, J., Ma, Y., Wang, S.-H., & Fu, X. (2020). Study on the aerodynamic characteristics and galloping instability of conductors covered with sector-shaped ice by a wind tunnel test. *International Journal of Structural Stability and Dynamics*, *20*(6), 2040016. https://doi.org/10.1142/S0219455420400167

Lou, W., Chen, S., Wen, Z., Wang, L., & Wu, D. (2021). Effects of ice surface and ice shape on aerodynamic characteristics of crescent-shaped iced conductors. *Journal of Aerospace Engineering, 34*(3), 04021008. https://doi.org/10.1061/(ASCE)AS.1943-5525.000124

Luo, Y., Gao, C., Wang, D., Lv, Y., & Xue, G. (2023). Predictive model for sag and load on overhead transmission lines based on local deformation of transmission lines. *Electric Power Systems Research, 214*, 108811. https://doi.org/10.1016/j.epsr.2022.108811

Matsumiya, H., Matsushima, H., Aso, T., Nishihara, T., & Sugimoto, S. (2023). Field observations of wet snow accretion on overhead transmission lines at the Kushiro test line. *Cold Regions Science and Technology, 213*, 103905. https://doi.org/10.1016/j.coldregions.2023.103905

Matsumiya, H., Taruishi, S., Matsushima, H., & Aso, T. (2024). Comparison of observed and simulated galloping responses of a four-bundled conductor under wet snow accretion. *Lecture Notes in Civil Engineering, 399*, 85–97. https://doi.org/10.1007/978-3-031-47152-0_8

Matsumiya, H., Yagi, T., & Macdonald, J.H.G. (2021). Effects of aerodynamic coupling and non-linear behaviour on galloping of ice-accreted conductors. *Journal of Fluids and Structures, 106*, 103366. https://doi.org/10.1016/j.jfluidstructs.2021.103366

Matsumiya, H., Yukino, T., Shimizu, M., & Nishihara, T. (2022). Field observation of galloping on four-bundled conductors and verification of countermeasure effect of loose spacers. *Journal of Wind Engineering and Industrial Aerodynamics, 220*, 104859. https://doi.org/10.1016/j.jweia.2021.104859

Moan, T., Gao, Z., Bachynski, E. E., & Nejad, A. R. (2020). Recent advances in integrated response analysis of floating wind turbines in a reliability perspective. *Journal of Offshore Mechanics and Arctic Engineering*, *142*(5), 052002. https://doi.org/10.1115/1.4046196

Oh, Y.-J., & Sohn, J.-H. (2020). Stability evaluation of the transmission line by using galloping simulation. *International Journal of Precision Engineering and Manufacturing, 21*(11), 2139–2147. https://doi.org/10.1007/s12541-020-00399-5

Peng, Y., Veerakumar, R., Liu, Y., He, X., & Hu, H. (2020). An experimental study on dynamic ice accretion and its effects on the aerodynamic characteristics of stay cables with and without helical fillets. *Journal of Wind Engineering and Industrial Aerodynamics, 205*, 104326. https://doi.org/10.1016/j.jweia.2020.104326

Reis, E. D., Carvalho, H., De Oliveira, C. C., Da Silva Adriano, R. L., & Lopes, D. C. (2023). Geometric nonlinear analysis of self-supporting structures for overhead transmission lines. *Practice Periodical on Structural Design and Construction, 28*(2), 04023003. https://doi.org/10.1061/PPSCFX.SCENG-1236

Sheng, W. (2022). Wave energy converters. In: *Encyclopedia of Ocean Engineering* (pp. 2121–2128). Singapore: Springer. https://link.springer.com/referenceworkentry/10.1007/978-981-10-6946-8_187

Sinchuk, I., & Kotyakova, M. (2023). Approach to improving the quality indicators of electricity of iron ore enterprises. *Journal of Kryvyi Rih National University, 21*(2), 43–52. https://doi.org/10.31721/2306-5451-2023-1-57-43-52

Soubrié, T., Diop, M., Laurent, C., Bouyges, M., Senoner, J. M., Villedieu, P., & Neuteboom, M. O. (2023). Numerical simulation of ice crystal icing in an axial compressor rig. Année. https://hal.science/hal-04110674/

Sun, K., Xu, Z., Li, S., Jin, J., Wang, P., Yue, M., & Li, C. (2023). Dynamic response analysis of floating wind turbine platform in local fatigue of mooring. *Renewable Energy, 204*, 733–749. https://doi.org/10.1016/j.renene.2022.12.117

Talib, E., Shin, J. H., Kwak, M. K., & Koo, J. R. (2019). Dynamic modeling and simulation for transmission line galloping. *Journal of Mechanical Science and Technology*, *33*, 4173–4181. https://link.springer.com/article/10.1007/s12206-019-0812-1

Taruishi, S., &Matsumiya, H. (2023). Investigation of effect of galloping countermeasures for four-bundled conductors through field observations. *Cold Regions Science and Technology, 214*, 103962. https://doi.org/10.1016/j.coldregions.2023.103962

Tian, B., Cai, M., Zhou, L., Liang, J., & Hu, M. (2022). Numerical simulation of galloping characteristics of multi-span iced eight-bundle conductors tower line system. *Buildings, 12*(11), 1893. https://doi.org/10.3390/buildings12111893

Wang, M., Liu, H., Ni, Y., Zhang, Z., Hu, Y., & Zhang, Z. (2023). Design of monitoring system for icing and galloping in mountainous distribution networks. In: *2023 IEEE 6th International Electrical and Energy Conference (CIEEC)* (pp. 3477–3482). Hefei: IEEE. https://doi.org/10.1109/CIEEC58067.2023.10166059

Wu, D., Cao, H., Li, D., & Yang, S. (2020). Energy-efficient reconstruction method for transmission lines galloping with conditional generative adversarial network. *IEEE Access*, *8*, 17310–17319. https://doi.org/10.1109/ACCESS.2020.2966739

Yan, Q., Zhou, C., Feng, X., Hu, W., & Xu, Y. (2022). Galloping vibration monitoring of overhead transmission lines by chirped FBG array. *Photonic Sensors, 12*(3), 220310. https://doi.org/10.1007/s13320-021-0651-4

Yang, Y., Xiang, C., & Jia, Z. (2023). Study on mechanical performance of transmission tower in coastal area considering corrosion. In: *2023 IEEE 6th International Electrical and Energy Conference (CIEEC)* (pp. 3778–3783). Hefei: IEEE. https://doi.org/10.1109/CIEEC58067.2023.10166538

Zhai, T., Zhang, Z., Gu, X., Zhang, H., & Zhang, W. (2023). Novel monitoring method of overhead transmission line galloping and torsion based on fiber Bragg grating sensor. In: *2023 Opto-Electronics and Communications Conference, OECC 2023*. Institute of Electrical and Electronics Engineers Inc. http://dx.doi.org/10.1109/OECC56963.2023.10209774

Zhamanbaev, M., Ilieva, D., Abitaeva, R., & Ongar, B. (2020). Determination of the minimum wind speed leading to the galloping of conductors. *E3S Web of Conferences*, *180*, 04019. https://doi.org/10.1051/e3sconf/202018004019

Zhang, Z., Zhang, H., Yue, S., & Zeng, W. (2023). A review of icing and anti-icing technology for transmission lines. *Energies*, *16*(2), 601. https://doi.org/10.3390/en16020601

Zhao, Q., Liu, Z., Yu, P., Chen, L., & Guan, F. (2022). Review of transmission line icing and anti-icing technologies. In: *The Proceedings of the 16th Annual Conference of China Electrotechnical Society* (pp. 1224–1232). Singapore: Springer. https://doi.org/10.1007/978-981-19-1870-4_129

Zhou, L., Liu, R., & Yi, X. (2022). Research and development of anti-icing/deicing techniques for vessels: Review. *Ocean Engineering*, *260*, 112008. https://doi.org/10.1016/j.oceaneng.2022.112008

Zhou, X., Zhu, Y., Zhang, Y., & Li, H. (2022). A review of anti-icing and de-icing technology of overhead ground wire. In: 2*022 International Symposium on Electrical, Electronics and Information Engineering (ISEEIE)* (pp. 282–286). Chiang Mai: IEEE. https://doi.org/10.1109/ISEEIE55684.2022.00057