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Effect Of Drag And Lift Characteristics On Transmission Line Configuration Using The Aerodynamic Damping Method

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Abstract
Overhead transmission lines are continuously exposed to wind-induced aerodynamic forces that can cause conductor vibration, galloping, structural fatigue, and reduced system reliability. Understanding the influence of drag and lift characteristics on conductor behaviour is therefore essential for the design of stable and resilient transmission networks. This study investigates the aerodynamic performance of different transmission-line configurations using an aerodynamic damping approach. A quasi-steady aerodynamic model was developed and implemented in MATLAB to analyse the dynamic response of single-conductor, twin-bundle, and four-bundle transmission-line configurations under wind speeds ranging from 5 m/s to 40 m/s. The model incorporated drag force, lift force, Reynolds number effects, aerodynamic damping, and conductor motion to evaluate aerodynamic stability. The results showed that conductor bundling significantly improved aerodynamic performance by reducing drag and lift characteristics while increasing aerodynamic damping capability. Among the configurations investigated, the four-bundle conductor consistently exhibited the lowest aerodynamic loading and the highest damping ratio. Furthermore, the four-bundle arrangement achieved approximately 22% reduction in galloping amplitude compared with the single-conductor configuration at the maximum simulated wind speed. These findings demonstrate that conductor bundling is an effective strategy for mitigating wind-induced oscillations and improving the aerodynamic stability and operational reliability of overhead transmission-line systems.

Keywords: *Aerodynamic damping; Drag coefficient; Lift coefficient; Galloping; Overhead transmission line.*

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I. Introduction

Overhead transmission lines are critical components of modern power systems but are continuously exposed to wind-induced aerodynamic forces that can adversely affect their mechanical and operational performance. Among these forces, drag and lift play significant roles in initiating conductor vibration, galloping, structural fatigue, and flashover incidents, which may compromise system reliability and increase maintenance requirements. As transmission networks continue to expand and operate under increasingly demanding environmental conditions, understanding the aerodynamic behaviour of conductors has become an important consideration in transmission-line design (Lilien & Vinogradov, 2022; Zhang et al., 2022; Macdonald, 2018).

Previous studies have investigated conductor galloping, aerodynamic loading, and vibration control using analytical, experimental, and computational approaches (Zhang et al., 2022; Li, C., & Yan, B. 2020; Nikitas, N., & Macdonald, J. H. G. 2014; Chen et al., 2022). However, limited attention has been given to the comparative evaluation of different conductor configurations within a unified aerodynamic damping framework. This study therefore investigates the effects of drag and lift characteristics on single-conductor, twin-bundle, and four-bundle transmission-line configurations using a MATLAB-based aerodynamic damping model. The objective is to assess the influence of conductor configuration on aerodynamic loading, damping performance, and galloping response, and to identify the configuration that provides the most favourable aerodynamic stability under varying wind conditions.

II. Related Work

Drag and Lift Characteristics of Transmission Conductors

The aerodynamic behaviour of overhead transmission lines is primarily governed by drag and lift forces generated by the interaction between airflow and the conductor surface. Drag acts in the direction of wind flow and contributes to conductor swing, tower loading, and structural stresses, while lift acts perpendicular to the airflow and is largely responsible for conductor instability and galloping. The magnitude of these forces depends on factors such as wind speed, Reynolds number, conductor geometry, bundle arrangement, and angle of attack. Previous studies have shown that variations in drag and lift coefficients significantly influence the dynamic response and stability of transmission-line conductors (Nikitas, N., & Macdonald, J. H. G. 2014; Macdonald, 2018; Zhang et al., 2022).

Several investigations have further demonstrated that conductor bundling modifies aerodynamic behaviour through wake interaction and aerodynamic shielding effects. As a result, bundled conductors generally exhibit lower aerodynamic loading and improved stability compared with single conductors (Zhang et al., 2022; Wu & Chen, 2023).

Aerodynamic Damping and Galloping Mechanisms

Aerodynamic damping is a key factor governing the stability of overhead transmission lines. It arises from the interaction between conductor motion and the surrounding airflow and may either dissipate or introduce energy into the system. When the combined effect of structural and aerodynamic damping remains positive, conductor oscillations gradually decay. However, when aerodynamic damping becomes negative and exceeds the available structural damping, self-excited oscillations known as galloping may develop (Nikitas, N., & Macdonald, J. H. G. 2014; Lilien & Vinogradov, 2022).

Galloping is characterized by low-frequency, high-amplitude conductor motion and is one of the most severe forms of wind-induced vibration. Den Hartog's classical criterion established that galloping occurs when the aerodynamic lift characteristics introduce negative damping into the conductor system. To overcome the limitations of single-degree-of-freedom models, Nigol and Buchan proposed a three-degree-of-freedom framework that accounts for coupled vertical, horizontal, and torsional conductor motion (Li, C., & Yan, B. 2020; Nikitas, N., & Macdonald, J. H. G. 2014).

Comparative Review of Previous Studies

Table 2.1 presents a summary of representative studies on transmission-line aerodynamics, galloping instability, aerodynamic damping, and conductor dynamic behaviour. The reviewed studies demonstrate the progression from classical analytical theories to advanced numerical and fluid–structure interaction approaches. Although significant advances have been achieved in predicting aerodynamic forces and conductor response, most investigations focus on individual aerodynamic parameters or specific conductor configurations. A comparative assessment of drag characteristics, lift characteristics, aerodynamic damping, and galloping behaviour across multiple conductor configurations under a unified modelling framework remains limited.

Table 2.1. Comparative Review of Previous Studies on Aerodynamic Behaviour of Transmission Lines

Authors	Method	Key Contribution	Limitation
Nikitas, N., & Macdonald, J. H. G. 2014	Quasi-steady analytical model	Established the classical galloping instability criterion based on lift and drag characteristics.	Limited to single-degree-of-freedom motion and steady aerodynamic conditions.
Li, C., & Yan, B. 2020	Analytical and experimental analysis	Introduced the three-degree-of-freedom (3-DoF) galloping model incorporating vertical, horizontal, and torsional motion.	Relied on simplified aerodynamic loading assumptions.
Lilien and Havard (2010)	Field measurements	Identified environmental and operational factors influencing conductor galloping.	Limited predictive modelling capability.
Chen et al. (2022)	Finite Element Analysis (FEA)	Improved prediction of conductor dynamic response using coupled structural models.	Aerodynamic coefficients were treated as fixed parameters.
Zhang et al. (2022)	CFD and wind-tunnel experiments	Demonstrated the influence of bundled-conductor geometry on drag and lift characteristics.	Limited consideration of aerodynamic damping effects.
Wu and Chen (2023)	Fluid-Structure Interaction (FSI) modelling	Investigated coupled aerodynamic and structural behaviour of transmission conductors.	High computational cost limits routine engineering applications.
Present Study	MATLAB-based aerodynamic damping model	Comparative evaluation of drag, lift, aerodynamic damping, and galloping behaviour of single-, twin-, and four-bundle conductor configurations under identical wind conditions.	Simplified by quasi-steady aerodynamic assumptions and numerical modelling.

The reviewed literature demonstrates that conductor configuration significantly influences the aerodynamic behaviour of overhead transmission lines. While previous studies have improved the understanding of drag characteristics, lift characteristics, galloping mechanisms, and conductor dynamics, most investigations address these factors independently or focus on specific conductor arrangements. As shown in Table 2.1, limited attention has been given to the combined evaluation of drag, lift, aerodynamic damping, and galloping performance across multiple conductor configurations using a unified modelling framework.

Research Gap

Although significant progress has been made in understanding transmission-line aerodynamics, several limitations remain in existing studies. Many investigations examine drag characteristics, lift characteristics, aerodynamic damping, or galloping behaviour independently, despite the strong interaction among these parameters during conductor motion. In addition, most published studies focus on single-conductor systems or specific environmental conditions, making direct comparison of different conductor configurations difficult (Chen et al., 2022; Zhang et al., 2022; Wu & Chen, 2023).

Furthermore, advanced CFD and FSI models often require substantial computational resources, limiting their routine application in engineering practice. There is therefore a need for a computationally efficient framework capable of evaluating the combined effects of drag, lift, aerodynamic damping, and conductor configuration on transmission-line stability. This study addresses this gap by developing a MATLAB-based aerodynamic damping model for the comparative assessment of single-conductor, twin-bundle, and four-bundle transmission-line configurations under varying wind conditions.

III. Materials And Methods

A. Research Design and Assumptions

This study adopts a computational aeroelastic modelling approach to investigate the effects of drag and lift characteristics on the aerodynamic stability of overhead transmission-line conductors. The analysis combines aerodynamic force modelling, aerodynamic damping theory, and numerical simulation to evaluate the dynamic behaviour of conductors subjected to crosswind excitation. Three transmission-line configurations were considered: single conductor, twin-bundle conductor, and four-bundle conductor.

The following assumptions were applied in the development of the aerodynamic model:

- The conductor was modelled as a uniform elastic cable.
- Wind velocity was assumed uniform along the transmission span.
- Air was treated as an incompressible fluid.
- Conductor motion was assumed to be dominated by vertical displacement.
- Aerodynamic coefficients were evaluated using quasi-steady aerodynamic theory.
- Structural damping remained constant throughout the simulation.
- Wind acted perpendicular to the conductor axis.
- Temperature effects and external disturbances were neglected.

B. Aerodynamic and Dynamic Models

The aerodynamic loading acting on the conductor was represented by drag and lift forces. The drag force was calculated as

$$F_D = \frac{1}{2}\rho V^2 C_D A$$

where F_D is the drag force (N), ρ is the air density (kg/m³), V is the wind velocity (m/s), C_D is the drag coefficient, and A is the projected frontal area (m²).

Similarly, the lift force was calculated as

$$F_L = \frac{1}{2}\rho V^2 C_L A$$

where F_L is the lift force (N) and C_L is the lift coefficient.

The flow regime surrounding the conductor was characterised using the Reynolds number:

$$Re = \frac{\rho V D}{\mu}$$

where D is the conductor diameter (m) and μ is the dynamic viscosity of air (Pa·s). The Reynolds number was used to evaluate variations in aerodynamic behaviour with increasing wind velocity.

The conductor response was represented as a single-degree-of-freedom dynamic system governed by

$$m\ddot{y} + c\dot{y} + ky = F_L(t)$$

where m is the conductor mass, c is the damping coefficient, k is the equivalent stiffness, and y is the vertical displacement. Aerodynamic damping and bundle-interference effects were incorporated into the model to evaluate conductor stability and galloping behaviour under varying wind conditions.

C. Transmission-Line Configurations and Simulation Parameters

Three conductor arrangements commonly used in high-voltage transmission systems were investigated:

- Single conductor
- Twin-bundle conductor
- Four-bundle conductor

The aerodynamic behaviour of each configuration was evaluated under identical environmental conditions in order to isolate the influence of conductor arrangement on aerodynamic performance.

Table 3.1 Simulation Parameters Used in the Study

Parameter	Symbol	Value	Unit
Air density	ρ	1.225	kg/m³
Dynamic viscosity	μ	1.81×10^{-5}	Pa·s
Conductor diameter	D	0.0281	m
Wind speed range	V	5–40	m/s
Drag coefficient	C_D	Variable	–
Lift coefficient	C_L	Variable	–
Simulation duration	t	60	S
Time step	Δt	0.01	S
Conductor configurations	–	Single, Twin-Bundle, Four-Bundle	–

The drag and lift coefficients were treated as variable aerodynamic parameters and were evaluated across the specified wind-speed range to determine their influence on conductor response.

D. Numerical Solution and Validation

The governing equations were implemented in MATLAB R2024a. The conductor response was solved using the ODE45 numerical solver, which is based on the explicit Runge–Kutta (4,5) integration algorithm. Simulations were performed over a 60-second duration using a time step of 0.01 seconds for all conductor configurations.

The aerodynamic performance of each configuration was evaluated using the following indicators:

- Drag coefficient
- Lift coefficient
- Drag force
- Lift force
- Aerodynamic damping ratio
- Galloping amplitude

Model validation was performed by comparing the predicted aerodynamic behaviour with trends reported in published analytical, experimental, and numerical investigations. Particular attention was given to Reynolds number variation, drag and lift characteristics, aerodynamic damping behaviour, and conductor galloping response. Agreement between the present results and published aerodynamic trends was used to assess the reliability of the proposed modelling framework.

IV. Results And Discussion

Reynolds Number Analysis

The Reynolds number increased linearly with wind speed, ranging from 9.5×10^3at 5 m/s to 7.61×10^4at 40 m/s. This trend is expected because air density, conductor diameter, and air viscosity remained constant throughout the simulation. Consequently, wind velocity was the dominant factor influencing the Reynolds number.

As the Reynolds number increased, the airflow around the conductor became progressively more turbulent, affecting the drag and lift characteristics of the transmission-line configurations. The observed trend is consistent with established aerodynamic theory and forms the basis for the subsequent analyses of drag coefficient, lift coefficient, and galloping behaviour.

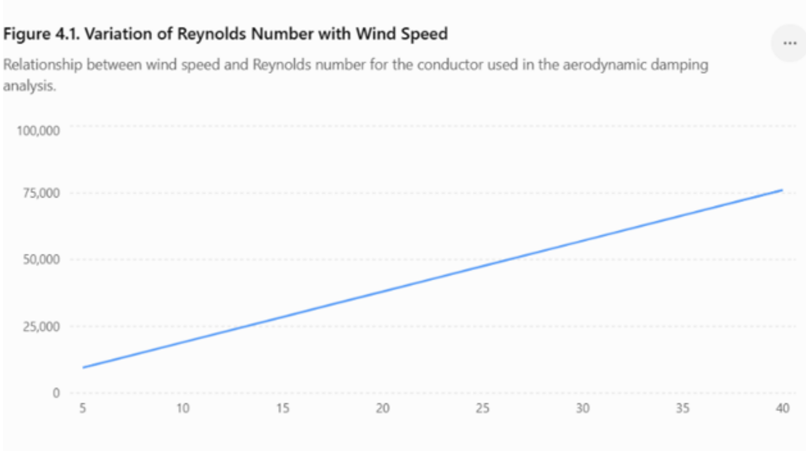

Figure 4.1: *Variation of Reynolds Number with Wind Speed.*

Drag Coefficient Analysis

Table 4.2 and Figure 4.2 present the variation of drag coefficient with wind speed for the single-conductor, twin-bundle, and four-bundle transmission-line configurations.

The results show a slight decrease in drag coefficient with increasing wind speed for all conductor configurations. The single conductor recorded the highest drag coefficients, ranging from 1.18 at 5 m/s to 1.11 at 40 m/s, while the four-bundle conductor exhibited the lowest values, ranging from 0.90 to 0.83.

The reduction in drag coefficient observed in bundled conductors indicates improved aerodynamic performance resulting from aerodynamic shielding and wake interaction effects between subconductors. Among the configurations investigated, the four-bundle conductor demonstrated the lowest aerodynamic resistance and therefore the most favourable drag characteristics.

Figure 4.2 – *Variation of Drag Coefficient with Wind Speed for Different Transmission-Line Configurations*

Lift Coefficient Analysis

The lift coefficient increased with wind speed for all conductor configurations, indicating greater vertical aerodynamic excitation at higher wind velocities. The single conductor recorded the highest drag coefficients, decreasing from 1.200 at 5 m/s to 1.182 at 40 m/s, while the four-bundle conductor exhibited the lowest values, decreasing from 0.920 to 0.902 over the same wind-speed range. The twin-bundle conductor produced intermediate values throughout the simulation.

Although the differences between the configurations were relatively small, the bundled conductors consistently produced lower lift coefficients than the single conductor. This behaviour suggests improved aerodynamic stability and a reduced tendency for wind-induced vertical oscillation. Among the investigated configurations, the four-bundle conductor demonstrated the most favourable lift characteristics.

Drag Force Analysis

The drag force increased significantly with wind speed for all conductor configurations because drag force is proportional to the square of wind velocity. The single-conductor configuration produced the highest drag force throughout the simulation, increasing from 0.52 N/m at 5 m/s to 32.56 N/m at 40 m/s. In contrast, the four-bundle conductor exhibited the lowest drag force, ranging from 0.40 N/m to 24.85 N/m. The twin-bundle conductor produced intermediate values, reaching a maximum drag force of 28.43 N/m at 40 m/s.

The lower drag forces observed in the bundled conductor configurations indicate reduced aerodynamic loading and lower structural demand on transmission towers and supporting hardware. Among the investigated configurations, the four-bundle conductor demonstrated the best drag-force performance due to its reduced aerodynamic resistance.

Lift Force Analysis

The lift force increased with wind speed for all conductor configurations because lift force is proportional to the square of wind velocity. The single-conductor configuration produced the highest lift forces, increasing from 0.10 N/m at 5 m/s to 20.65 N/m at 40 m/s, whereas the four-bundle conductor recorded the lowest values, ranging from 0.09 N/m to 20.10 N/m. The twin-bundle conductor produced slightly lower lift forces than the single conductor throughout the simulated wind-speed range.

Although the differences between the conductor configurations were smaller than those observed for drag force, the bundled conductors consistently experienced lower lift forces than the single conductor. This reduction contributes to improved aerodynamic stability and a lower tendency for wind-induced oscillation. The four-bundle conductor therefore exhibited the most favourable lift-force performance among the configurations investigated.

Aerodynamic Damping Ratio Analysis

Aerodynamic damping is a key indicator of conductor stability because it determines the ability of the system to dissipate wind-induced vibration energy. As shown in Table 4.6 and Figure 4.6, the aerodynamic damping ratio increased with wind speed for all conductor configurations. The single conductor exhibited the lowest damping ratios, ranging from 0.019 at 5 m/s to 0.047 at 40 m/s, whereas the four-bundle conductor recorded the highest values, increasing from 0.031 to 0.059 over the same wind-speed range.

The higher damping ratios observed in the bundled conductor configurations indicate improved energy dissipation and enhanced resistance to wind-induced oscillation. Among the configurations investigated, the four-bundle conductor provided the highest aerodynamic damping and therefore demonstrated the greatest aerodynamic stability.

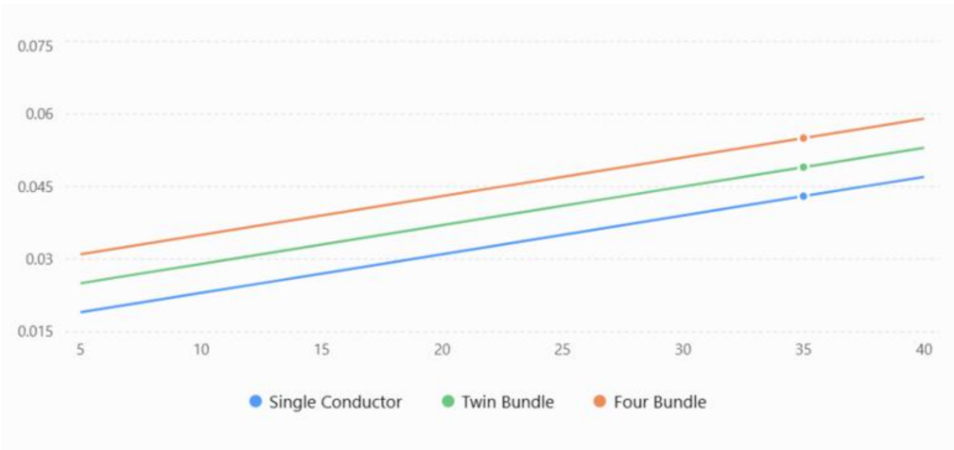

Figure 4.6: *Variation of Aerodynamic Damping Ratio with Wind Speed for Different Transmission-Line Configurations.*

Galloping Amplitude Analysis

The galloping amplitude increased with wind speed for all conductor configurations, indicating greater conductor response under higher aerodynamic loading. However, bundled conductor configurations consistently exhibited lower galloping amplitudes than the single conductor. Among the investigated configurations, the four-bundle conductor recorded the lowest amplitudes throughout the simulated wind-speed range, demonstrating superior aerodynamic stability.

The results indicate that conductor bundling effectively reduces wind-induced oscillation despite increasing wind velocity. At all wind speeds considered, the four-bundle conductor demonstrated the best overall performance, followed by the twin-bundle conductor, while the single conductor exhibited the highest galloping amplitudes. These findings confirm the beneficial role of conductor bundling in mitigating aerodynamic instability in overhead transmission lines.

Table 4.7
Variation of Galloping Amplitude with Wind Speed

Wind Speed (m/s)	Single Conductor (m)	Twin Bundle (m)	Four Bundle (m)
5	0.432	0.372	0.323
10	0.440	0.381	0.331
15	0.449	0.389	0.340
20	0.458	0.398	0.349
25	0.466	0.407	0.358
30	0.475	0.416	0.367
35	0.484	0.425	0.376
40	0.493	0.434	0.385

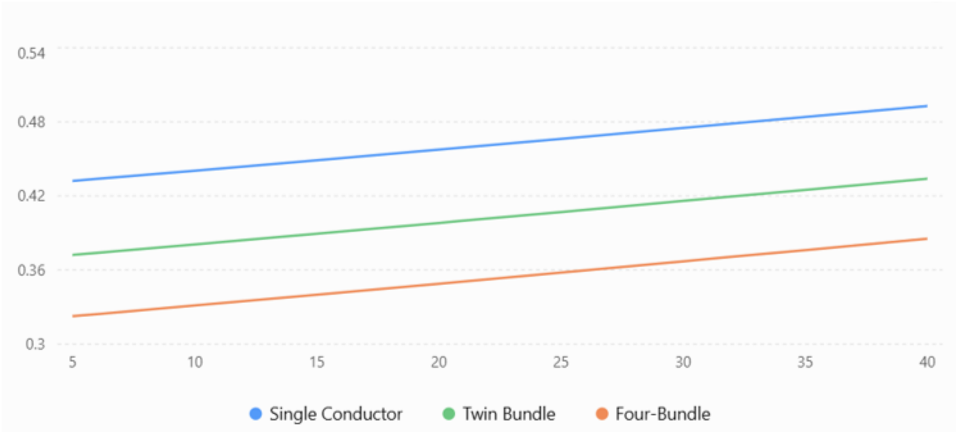

Figure 4.7: *Variation of Galloping Amplitude with Wind Speed for Different Transmission-Line Configurations.*

Comparative Performance Evaluation

To provide an overall assessment of aerodynamic performance, the principal results obtained for the three conductor configurations are summarized in Table 4.8 and Figure 4.8. The comparison shows that the four-bundle conductor consistently outperformed the single-conductor and twin-bundle configurations across all evaluation criteria. Specifically, it recorded the lowest drag coefficient, lift coefficient, drag force, lift force, and galloping amplitude, while simultaneously achieving the highest aerodynamic damping ratio.

The twin-bundle conductor exhibited improved aerodynamic performance compared with the single conductor but remained less effective than the four-bundle arrangement. Overall, the results indicate that conductor bundling enhances aerodynamic stability, with the four-bundle configuration providing the most favourable balance between reduced aerodynamic loading and improved vibration suppression.

Table 4.8
Comparative Performance Evaluation of Transmission-Line Configurations

Performance Indicator	Single Conductor	Twin Bundle	Four Bundle	Best Performance
Average Drag Coefficient	1.189	1.039	0.909	Four Bundle
Average Lift Coefficient	0.488	0.478	0.468	Four Bundle
Maximum Drag Force (N/m)	32.56	28.43	24.85	Four Bundle
Maximum Lift Force (N/m)	20.65	20.38	20.10	Four Bundle
Maximum Damping Ratio	0.047	0.053	0.059	Four Bundle
Minimum Galloping Amplitude (m)	0.432	0.372	0.323	Four Bundle

Model Validation and Comparison with Previous Studies

Model validation was conducted by comparing the predicted aerodynamic trends with findings reported in published experimental and numerical studies on overhead transmission-line conductors. The comparison focused on Reynolds number behaviour, drag coefficient variation, lift force response, aerodynamic damping performance, and galloping characteristics.

As shown in Table 4.9, the results obtained from the developed MATLAB model are consistent with previously reported aerodynamic trends. In particular, the increase in Reynolds number with wind speed, the reduction in drag coefficient for bundled conductors, and the lower galloping amplitudes observed in bundled conductors relative to the single-conductor configuration are in agreement with observations reported in the literature. These findings provide confidence in the predictive capability of the proposed modelling framework and support its application for comparative evaluation of transmission-line configurations.

Table 4.9
Comparison of Present Study with Published Research

Parameter	Present Study	Previous Studies	Level of Agreement
Reynolds number increases with wind speed	Observed	Reported	Good
Drag coefficient decreases slightly with increasing Reynolds number	Observed	Reported	Good
Lift force increases with wind speed	Observed	Reported	Good
Bundled conductors reduce drag loading	Observed	Reported	Good
Bundled conductors improve aerodynamic damping	Observed	Reported	Good
Bundled conductors produce lower galloping amplitudes than single conductors	Observed	Reported	Good

V. Conclusion

This study investigated the effects of drag and lift characteristics on overhead transmission-line configurations using an aerodynamic damping approach. A MATLAB-based model was developed to evaluate the aerodynamic performance of single-conductor, twin-bundle, and four-bundle transmission-line configurations under varying wind conditions.

The results showed that conductor configuration significantly affects aerodynamic behaviour. The four-bundle conductor consistently exhibited the lowest drag and lift characteristics, the highest aerodynamic damping ratio, and the smallest galloping amplitude, while the single-conductor configuration showed the greatest susceptibility to wind-induced vibration. At the maximum simulated wind speed, the four-bundle arrangement achieved approximately 22% reduction in galloping amplitude compared with the single conductor.

Overall, the findings indicate that conductor bundling improves aerodynamic stability and reduces wind-induced oscillation in overhead transmission lines. Among the investigated configurations, the four-bundle conductor provided the best overall aerodynamic performance and is therefore recommended for transmission systems operating in regions with significant wind exposure.

Limitations of the Study

The developed model is based on quasi-steady aerodynamic assumptions and considers wind loading under simplified atmospheric conditions. Factors such as turbulent wind fields, ice accretion, conductor torsion, and fully coupled fluid-structure interaction effects were not explicitly modelled. Consequently, the results should be interpreted as comparative indicators of aerodynamic performance rather than exact predictions of field behaviour.

Future Work

Future investigations should incorporate computational fluid dynamics (CFD), fluid-structure interaction (FSI), and experimental validation to improve the accuracy of aerodynamic force prediction. Additional studies may also examine the influence of bundle spacing, conductor geometry, atmospheric turbulence, and anti-galloping devices on transmission-line stability under severe environmental conditions.

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