UDC 621.3.013 https://doi.org/10.20998/2074-272X.2024.5.09

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Analytical solution of conductor tensile force in asymmetrical spans used in overhead power lines and substations with influence of tension insulators

Introduction. *Designing electrical substations involves analyzing the horizontal tensile force in flexible tension conductors under varying temperatures. These temperature changes affect the conductor's length and forces.* ***Problem.*** *Existing methods for calculating horizontal tensile force in conductors often focus on symmetric spans or require complex finite element modeling (FEM), which is impractical for routine substation design. Asymmetric spans with tension insulators present a more complex challenge that current solutions do not adequately address.* ***Purpose.*** *Universal analytical solution and algorithm for calculating the horizontal tensile forces in conductors in asymmetric spans with tension insulators used in power substations or short overhead power line spans. The solution is designed to be easily implementable in software without requiring complex tools or extensive FEM.* ***Methodology.*** *The methodology involves deriving an analytical solution based on the catenary curve formed by the conductor between attachment points at different heights. The analysis includes calculating the conductor's length for a given tensile force and using a state change equation to determine forces under new temperature conditions. Validation is performed using FEM calculations.* ***Results.*** *The proposed solution was validated against FEM models with varying height differences (5 m and 15 m) and conductor temperatures (–30 °C, –5 °C, +80 °C). The results showed a minimal error (less than 0.15 %) between the analytical solution and FEM results, demonstrating high accuracy.* ***Originality.*** *This paper presents a novel analytical solution to the problem of calculating tensile forces in asymmetric spans with tension insulators. Unlike existing methods, our solution is straightforward and easily implementable in any programming language.* ***Practical value.*** *The solution is practical for routine design tasks in electrical substations or short overhead power lines. Especially in power substations, accurate tensile forces are needed not only for mechanical design and sag calculations but also for calculating the dynamic effects of short-circuit currents.* References 23, tables 4, figures 3.

Key words: **substation, asymmetrical span, tension section, state change.**

Вступ. *Проєктування електричних підстанцій включає аналіз горизонтальної сили, що розтягує, в гнучких натяжних провідниках при різних температурах. Ці зміни температури впливають на довжину провідника та сили.* ***Проблема***. *Існуючі методи розрахунку горизонтальної сили, що розтягує, у провідниках часто орієнтовані на симетричні прольоти або вимагають складного моделювання методом скінченних елементів (FEM), що непрактично для звичайного проєктування підстанцій. Асиметричні прольоти з натяжними ізоляторами є складнішим завданням, яке існуючі рішення не вирішують належним чином.* ***Мета***. *Універсальне аналітичне рішення та алгоритм розрахунку горизонтальних сил, що розтягують, у проводах несиметричних прольотів з натяжними ізоляторами, що застосовуються на силових підстанціях або коротких прольотах повітряних ліній електропередачі. Рішення розроблено таким чином, щоб його можна було легко реалізувати в програмному забезпеченні, не вимагаючи складних інструментів або моделювання методом FEM.* ***Методика*** *передбачає отримання аналітичного рішення на основі контактної кривої, утвореної провідником між точками кріплення на різній висоті. Аналіз включає розрахунок довжини провідника для заданої розтягуючої сили і використання рівняння зміни стану для визначення сил в нових температурних умовах. Перевірка здійснюється з використанням розрахунків методом FEM.* ***Результати***. *Запропоноване рішення було перевірено на моделях FEM з різною різницею висот (5 м та 15 м) та температурою провідника (–30 °C, –5 °C, +80 °C). Результати показали мінімальну помилку (менше 0,15 %) між аналітичним рішенням та результатами FEM, демонструючи високу точність.* ***Оригінальність***. *У цій статті представлено нове аналітичне рішення задачі розрахунку зусиль, що розтягують, у несиметричних прольотах з натяжними ізоляторами. На відміну від існуючих методів, наше рішення є простим та легко реалізованим будь-якою мовою програмування.* ***Практична цінність***. *Вирішення практично для рутинних завдань проєктування електричних підстанцій або коротких повітряних ліній електропередачі. Точні сили, що розтягують, необхідні, особливо на силових підстанціях, не тільки для механічного проєктування та розрахунку провисання, але і для розрахунку динамічних ефектів струмів короткого замикання.* Бібл. 23, табл. 4, рис. 3.

Ключові слова: **підстанція, несиметричний проліт, натяжна ділянка, зміна стану.**

Introduction. One of the basic calculations in the design of overhead power lines (OPL) and electrical substations is the analysis of the horizontal tensile force acting on the tensioned current-carrying conductor in various temperature states [1, 2]. These temperature states result from the natural cooling and heating of the conductor due to ambient temperature, induced wind, irradiation, currents in the conductors, etc. [3]. As a result of a change in conductor temperature, the length of the conductor and the forces acting on the conductor also change. These forces need to be analyzed in the design phase to ensure long-term safe operation and prevent unwanted damage or breakage of the conductors [4]. For this purpose, a tensioned conductor's state change equation is used. The state change equation makes it possible to determine the forces acting in the conductor in any second state given the known value of force and temperature in the defined first state [5].

This article deals with a general problem of horizontal tensile force calculation in a stranded conductor connected at two points with rigid insulators at both span ends, typically used for busbars in power substations. For spans where the weight of the conductor is much higher than the insulators' weight, the tension insulator's influence and the number of conductors in the bundle can be neglected for calculating the horizontal tensile force F_h acting on the conductor. These are typical tension sections of OPL and long spans [6, 7].

Long spans are typically characterized by the condition where the mass of the insulators is considerably less than that of the conductor, resulting in the formation of an almost ideal catenary shape when the span is observed. Solution for long span mechanics is well described in [8] or in [5] by state change equation for long spans and is widely used in power line design practice today [8]. Conversely, assessing the catenary curve for short spans is a more intricate task due to the substantial influence of insulator weights at the span ends [9]. Short spans are typical, for example:

- short tension sections of OPL (approx. less than 150 m);
- dead end of OPL and their connection to an electrical substation;
- tensioned sections in electrical substations, busbars, spans with termination on transformers (Fig. 1).

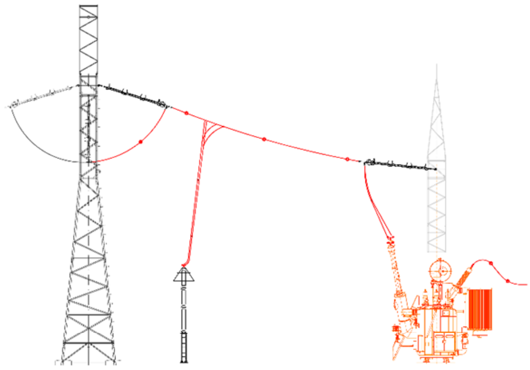

Fig. 1. Example of a short asymmetric span in an electric substation

The mentioned examples of short spans are, in most cases, asymmetrical, which mean that the heights of the suspension points of the insulators are different. Results of mechanical calculations of asymmetric short spans are practically necessary for the following:

- design of tensioned spans [10, 11];
- control of deflections and permitted distances between conductive parts in electrical substation [12];
- calculation of dynamic effects of short-circuit currents in electrical substations [13–15];
- dynamic line rating implementation of OPL or electrical substations [16, 17];
- determination of the intensity of electric field [18];
- determination of magnetic flux density [19, 20].

A symmetric solution to the problem without considering bundle conductors was processed in [8]. An extended solution of the symmetrical span under the influence of bundle conductors is presented in [9].

Solution for asymmetric span win tension insulators using the Finite Element Method (FEM) is presented in [21]. The authors proposed an iterative process based on the mutual calling of MATLAB and ANSYS software. Although it is a valid solution to the problem, it can only be rarely applied in substation design practice due to the need for complicated FEM modelling and complex software.

In another paper by the same group of authors from 2022, they presented a more general solution of the state change equation with the influence on non-uniform load. Authors presented the application of their solution on ultra-high voltage OPL sag calculations [22].

In [23] was presented software for sag-tension substation calculation. Their solution was again purely symmetric. These few studies represent the only relevant sources of information on the topic. We therefore consider it necessary to provide a straightforward solution to the mentioned problem.

The goal of the paper is to presents a clear, comprehensible and universal analytical solution to the mechanics of unsymmetrical spans with consideration of tension insulators. The presented solution is easy software implementable in any programming language and does not require complex tools and programs. The solution was validated using FEM, and the results show a high agreement of the analytical results with the numerical model.

Methodology. Consider a stranded aluminum conductor steel reinforced (ACSR) conductor connected between attachment points (AP I and AP II) and sagged with a horizontal tensile force F_h, and ignoring the insulators. The conductor shapes itself in a catenary curve. If points AP I and AP II are at the same heights, the span is considered a symmetric span. Most spans are asymmetric and have insulators on both ends, which cannot be omitted in the calculation in case of short spans, approximately under 150 m. Figure 2 shows a general short asymmetrical span with tension insulators. The investigated system consists of two attachment points for insulators (API I and API II) and two attachment points of conductors (APC I and APC II, Fig. 2), on the opposite sides of the span. We assume identical rigid insulators on both ends.

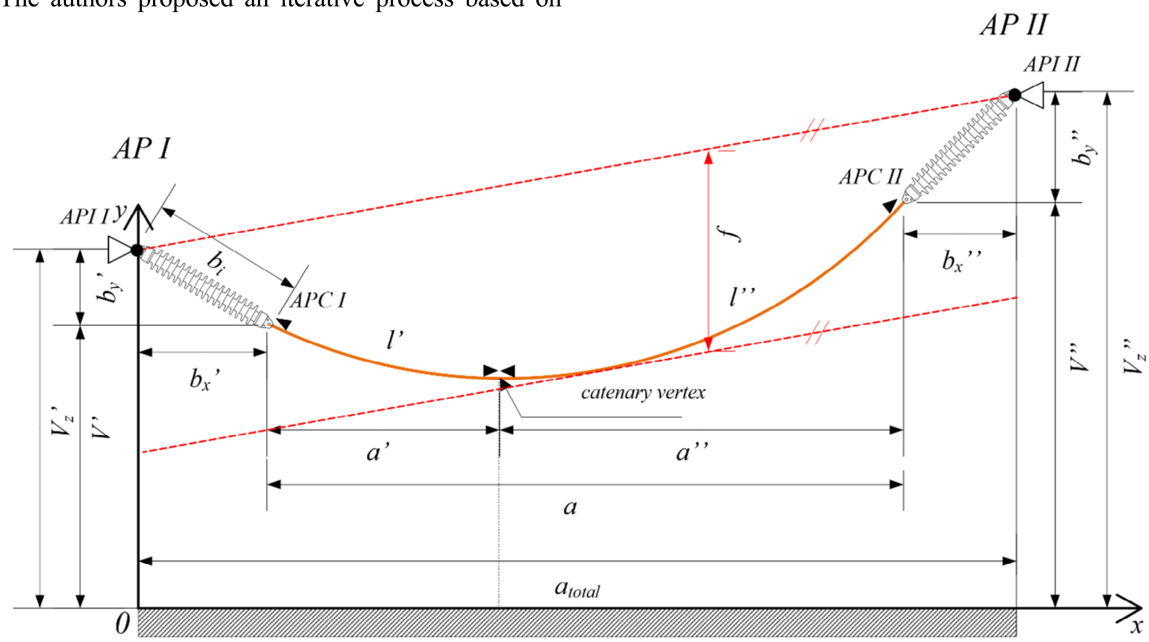

Fig. 2. General short asymmetrical span with tensile insulators

Typical conductor used for tensioned busbar in substations is ACSR conductor. The conductor is freely attached to the insulator on both sides, forming a natural cattery curve with a defined parameter c. Distance from the APC I to the vertex of the catenary is a'. Similarly, a'' equals the distance from the vertex to the APC II.

Total span length a_{total} is a known parameter and equals length from the API I to the API II. Table 1 shows the list of known parameters.

Table 1

Known parameters of the span

Symbol	Description
V_z'	Height of insulator placement at APC I
V_z''	Height of insulator placement at APC II
b_i	Insulator length
W_i	Insulator weight
n_b	Number of conductors in a bundle
a_{total}	Span length with insulators
α	Thermal coefficient of conductor expansion
E	Young modulus of elasticity of the conductor
S	Cross-section of the conductor
w_c	Conductor unit weight
F_h	Horizontal tensile force in a single conductor

We assume that horizontal tensile force F_h acting in a conductor is a known defined parameter. From this, a catenary parameter c is given as:

$$c = \frac{F_h}{w_c n_b g}, \tag{1}$$

where g is the gravitational acceleration.

The analytical solution, state equations calculation, of the presented system, consists of two steps:

- calculation of the length of the conductor for a given F_h;
- calculation of state change equation for a set of state quantities.

Length of the conductor. In general, without considering a specific attachment point, it applies that in a steady state, the sum of the torques of the given system, the insulator and the conductor equals zero (Fig. 3).

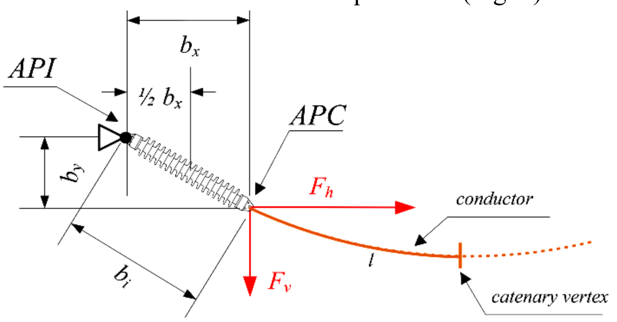

Fig. 3. Forces acting on the conductor on a one side of the span

In such a case, the insulator of length b_i and weight W_i settles in a position with horizontal deflection b_x and vertical deflection b_y. We can write the torque condition as follows:

$$F_v b_x - F_h n_b b_y = 0, \tag{2}$$

where F_v is the vertical force and F_h is the horizontal force acting on the conductor; n_b is the number of conductors in the bundle; F_v is the function of the length of the conductor l and insulator properties.

F_v equals the sum of the weight of the conductor acting on the length from the APC to the vertex of the catenary and the weight of the insulator acting on half the length of the insulator projection b_x. The weight of the conductor is considered as the weight of the conductor per unit of length F_v as a function of l equals:

$$F_v(l) = \frac{1}{2} W_i g + w_c z n_b l\, g. \tag{3}$$

Torque condition now equals:

$$\left(\frac{1}{2} W_i + w_c l\, n_b\right) b_x g - F_h b_y = 0. \tag{4}$$

The length of the insulator b_i equals by Pythagorean theorem:

$$b_i^2 = b_x^2 + b_y^2. \tag{5}$$

The equations (4), (5) represent two equations with two unknown parameters. Their positive solutions for insulator deflections, b_x b_y, as a function of F_v are given following equations:

$$b_x(F_v) = \frac{b_i F_h n_b}{\sqrt{(F_h n_b)^2 + F_v^2}}; \tag{6}$$

$$b_y(F_v) = \frac{b_i F_v}{\sqrt{(F_h n_b)^2 + F_v^2}}; \tag{7}$$

For clarification, all quantities related to AP I have a superscript «′» and all quantities related to AP II have a superscript «″». For the sake of simplicity, the relations for AP I will be presented in the following section. The vertical component of the conductor force F_v' at APC I is a sum weight force of the insulator and conductor at length l' (Fig. 2):

$$F_v'(l') = g\left(\frac{1}{2} W_i + w_c n_b l'\right). \tag{8}$$

Similarly, F_v'' at APC II. Solving the length of the conductor is an iterative calculation when in the first step, a random estimate is made for the deflection of the insulators b_x', b_x'' and b_y' and b_y'' (e.g. $b_x' = b_x'' = b_i$ and $b_y' = b_y'' = 0$). The length of the conductor span is given as:

$$a(b_x', b_x'') = a_{total} - (b_x' + b_x''). \tag{9}$$

The heights of the suspension points of conductors V' in APC I and V'' in APC II are equal to the difference in the height of the AP I insulator and the vertical deflection of the insulator:

$$V'(b_y') = V_z' - b_y'. \tag{10}$$

Similarly, V'' at APC II. The horizontal distance from the APC I to the vertex of the catenary a' equals:

$$a'(V', V'', a) = a - c \cdot \left[\operatorname{arcsinh}\left(\frac{V'' - V'}{2c \cdot \sinh\left(\frac{a}{2c}\right)}\right) + \frac{a}{2c}\right]. \tag{11}$$

Horizontal distance from the APC II to the vertex of the catenary a'' equals:

$$a''(a') = a - a'. \tag{12}$$

Length of the catenary l_t' from the APC I to the vertex of the catenary equals:

$$l_t'(a') = c\sqrt{\sinh^2\left(\frac{-a'}{c}\right) + 1} \cdot \operatorname{tgh}\left(\frac{a'}{c}\right). \tag{13}$$

Similarly, l_t'' at APC II. As a result of the force F_h, the length of the conductor will contract. The total conductor lengths l' will be equal after this shortening:

$$l'\left(l'_t\right) = l'_t - \frac{F_h l'_t}{E \cdot S}, \quad (14)$$

where E is the Young modulus of elasticity; S is the cross-section of the conductor.

Similarly, l'' at APC II. Now, it is possible to determine the vertical force acting in both attachment points $F'_v(l')$ $F''_v(l'')$ from (8). From the vertical forces, the new insulator deflections, b_x' b_x'' equation (6) and b_y' and b_y'', equation (7) are determined.

The calculation is repeated until the difference between newly calculated deflection equals or exceeds user-defined precision ε. The length of the conductor is then calculated as follows:

$$l(a', a) = -c\sqrt{\sinh^2\left(\frac{a-a'}{c}\right)+1} \cdot \mathrm{tgh}\left(\frac{a'-a}{c}\right) + c\sqrt{\sinh^2\left(\frac{a'}{c}\right)+1} \cdot \mathrm{tgh}\left(\frac{a'}{c}\right). \quad (15)$$

General form of state-change equation. Subscript 0 defines the primary state, and subscript 1 defines a new state of the conductor. The calculation assumes that the span parameters are known (Table 1) together with the force F_{h0} at the conductor temperature ϑ_0. The calculation aims to determine the horizontal tensile force in the new state of the conductor, which is characterized by a change in state variable ϑ_1.

Change in conductor temperature from ϑ_0 to ϑ_1 causes change in the length of the conductor Δl_ϑ:

$$\Delta l_\vartheta = l_0 \alpha\left(\vartheta_1 - \vartheta_0\right), \quad (16)$$

where l_0 is the length of the conductor at state 0 and α is thermal coefficient of expansion. Change of conductor length due to temperature, Δl_ϑ, results in a change in conductor sag and, therefore, a change in horizontal tensile force in the conductor. This change of force causes the opposite change in the conductor length Δl_F:

$$\Delta l_F = \frac{l_0}{E \cdot S}\left(F_{h0} - F_{h1}\right). \quad (17)$$

The total change in conductor length is equal to:

$$\Delta l = l_1 - l_0; \quad (18)$$

$$\Delta l = \Delta l_\vartheta - \Delta l_F. \quad (19)$$

By combining (18), (19) with (16), (17) we get general state change equation of the conductor:

$$l_0\left(\alpha\left(\vartheta_1 - \vartheta_0\right) + \frac{1}{E \cdot S}\left(F_{h1} - F_{h0}\right)\right) + l_0 - l_1 = 0. \quad (20)$$

Calculation. The following iterative algorithm is used to calculate the conductor length. Known parameters are listed in Table 1 together with the force F_{h0} at conductor temperature ϑ_0. The iterative algorithm consists of the following steps:

1) calculate the length of the conductor l_0 in state 0;

2) make the initial guess of $F_{h1}^{(k)} = F_{h0}$, where k iteration step equals $k = 0$;

3) calculate the length of the conductor $l_1^{(k)}$ in state 1;

4) calculate the steady state equation error $U_\varepsilon^{(k)}$:

$$U_\varepsilon^{(k)} = l_0\left(\alpha\left(\vartheta_1 - \vartheta_0\right) + \frac{1}{E \cdot S}\left(F_{h1}^{(k)} - F_{h0}\right)\right) + l_0 - l_1^{(k)}; \quad (21)$$

5) compare error results:

$$\left|U_\varepsilon^{(k)}\right| \le \varepsilon. \quad (22)$$

- If (22) is True then $F_{h1}^{(k)}$ is the resulting force in state 1 and calculation is over.
- If (22) is False then continue to 6).

6) define new $F_{h1}^{(k+1)}$ according following rules:

- If $k = 0$ then $\Delta F_{h1} = 0.9 \cdot F_{h1}^{(0)}$;
- If $k \neq 1$ then $\Delta F_{h1} = 0.5 \cdot F_{h1}^{(k)}$;
- If $U_\varepsilon^{(k)} > 0$ then $F_{h1}^{(k+1)} = F_{h1}^{(k)} - \Delta F_{h1}$;
- If $U_\varepsilon^{(k)} < 0$ then $F_{h1}^{(k+1)} = F_{h1}^{(k)} + \Delta F_{h1}$.

7) increment k and repeat from step 3).

Validation and results. Presented analytical solution for the general state change equation of conductor with tensile insulators on both ends was validated by calculating identical problem using FEM. FEM model was prepared as a transient structural analysis representing the process of assembling and tensioning the conductors (or bundled conductors) for a defined span in the gravitational field, respecting all given material properties and boundary conditions of the model. The model consists of a fine mesh of link elements that can form ideal sag from the mathematical and physical point of view. In addition, the model involves the link elements for insulators and auxiliary damping elements that ensure a converged model state in time. Result comparison was made for the following models:

- two height differences, ΔV: 5 m and 15 m;
- three temperatures in state 1: –30 °C; –5 °C; +80 °C;
- single conductor and three conductor bundle arrangement.

ACSR conductor 758-AL1/43-ST1A was considered in the calculation. This is a typical, most common ACSR conductor used in a substation in Slovak and Czech Republic region. In all models and calculations, the span length a_{total} was 30 m and force in primary state F_{h0} was 4500 N. Temperature at state 0 was –5 °C. A summary of the model and conductor parameters are in Table 2.

Table 2

Conductor and span specification

Quantity	Value	Unit
b_i	6.64	m
w_c	2.432	kg/m
W_i	425	kg
F_{h0}	4.5	kN
S	801.2	mm^2
a_{total}	30	m
ΔV	5; 15	m
n_b	1; 3	–
α	$2.11 \cdot 10^{-5}$	1/°C
E	62300	MPa
ϑ_0	–5	°C
ϑ_1	–30; –5; +80	°C

Tables 3, 4 show the results of calculated horizontal tensile force in state 1 for different ΔV, temperatures and number of conductors in the bundle. For all calculations, the error of the analytical solution to the FEM was determined as:

$$error = \left|\frac{F_{h1_{FEM}} - F_{h1_{an}}}{F_{h1_{FEM}}} \cdot 100\right|. \quad (23)$$

Table 3

Comparison of horizontal tensile forces in the conductor, ΔV = 15 m, determined using FEM and analytical solution of the state equation

n_b	ϑ_1, °C	F_{h1FEM}, N	F_{h1an}, N	*error*, %
1	–30	4524.89	4525.31	0.009
	–5	4499.23	4500.00	0.017
	80	4414.87	4416.79	0.043
3	–30	4632.08	4638.67	0.142
	–5	4497.11	4500.00	0.064
	80	4111.94	4106.47	0.133

Table 4

Comparison of horizontal tensile forces in the conductor, ΔV = 5 m, determined using FEM and analytical solution of the state equation

n_b	ϑ_1, °C	F_{h1FEM}, N	F_{h1an}, N	*error*, %
1	–30	4518.26	4518.13	0.003
	–5	4499.92	4500.00	0.002
	80	4438.90	4439.67	0.017
3	–30	4585.83	4586.12	0.006
	–5	4499.71	4500.00	0.006
	80	4238.50	4239.01	0.012

Discussion. FEM itself also contains a certain amount of error, because the conductor or bundle of conductors is not considered a continuous continuum, but a finite link of elements representing the conductor. This error can be seen in $F_{h1\text{FEM}}$ for temperature in state 1–5 °C. The expected value is 4500 N because no actual change of conductor state happened. However, the resulting values of F_h in state 1 are approximately 0.002–0.06 %. We consider this error to be insignificant, but it is necessary to keep it in mind when comparing it with the analytical solution.

As can be seen from the results, the analytical solution achieves a minimal insignificant error compared to the solution of the problem using FEM. The error of the analytical solution is at the level of the internal error of the FEM calculation itself. Results also show that error rises with a higher difference of attachment points. Again, the value of this error is in the order of 0.1 %, which is considered highly tolerable.

The primary benefit of the analytical solution in practical applications is its speed. This solution can be readily integrated into the software tools that designers currently use. Conversely, addressing the issue of asymmetrical spans with tension insulators through the FEM method is time-consuming and inefficient for project planning in real-world scenarios.

Conclusions.

1. We have presented a comprehensive analytical solution to the mechanics of asymmetrical spans with the influence of rigid tension insulators on both ends witch are typically. These are the typical tensioned spans used in electrical substations, short overhead power line sections or dead end of overhead power line and its connection to an electrical substation. Our analytical approach is valuable for a range of applications, including the project phase of tensioned spans, the control of deflections and permitted distances between conductive parts in electrical stations, the calculation of dynamic effects of short-circuit currents in electrical substations, and the implementation of dynamic line ratings in electrical substations.
2. The presented solution is easily implementable in any programming language and does not require complex tools or software.
3. We validated this solution by comparing it with finite element method calculations, and the results showed a high agreement between the analytical results and the numerical model.
4. Overall, this work contributes to a better understanding of the mechanics of overhead power lines and tensioned busbars in electrical substations, especially in cases involving non-uniform load distribution and the influence of tension insulators.
5. It offers a valuable tool for engineers and designers in power transmission and distribution, facilitating more accurate and reliable designs for these critical infrastructure components.
6. The motivation for publishing our solution is the lack of a solution to the problem that is understandable and easily implementable in software.
7. The presented work and issues can be expanded in the future by implementing insulator chains connected in series instead of single rigid ones.

In summary, this analytical solution provides engineers and designers with a practical and efficient method for calculating the horizontal tensile force in conductors equipped with tension insulators in overhead power lines and electrical substations.

Conflict of interest. The authors declare no conflict of interest.

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Received 25.02.2024
Accepted 19.04.2024
Published 20.08.2024

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How to cite this article:
Bendik J., Cenky M., Paulech J., Goga V. Analytical solution of conductor tensile force in asymmetrical spans used in overhead power lines and substations with influence of tension insulators. *Electrical Engineering & Electromechanics*, 2024, no. 5, pp. 64-69. doi: https://doi.org/10.20998/2074-272X.2024.5.09