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Stability of the bearing terminals for harness conductors in overhead power lines

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--***ABSTRACT***--
The paper presents a research on stability of suspension of harness conductors to the bearing terminals of overhead power lines, taking into account the impact of the influencing factors. A methodology has been developed for determining the maximum deviation of the bearing terminals at different degrees of unevenness of the loads on the harness conductors. A first-order mathematical model is obtained after conducting a saturated screening design experiment and a subsequent simplex screening design for six influencing factors. The proposed methodology makes it possible to determine the level of stability of the bearing terminals for harness conductors when examining the reliability of overhead power lines by mechanical parameters.
KEYWORDS:overhead power line, harness conductor, bearing terminal, insulator circuit, stability
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I. INTRODUCTION

The main objective in designing overhead power lines (OPL) according to mechanical parameters is to achieve high reliability and economy. OPL construction costs are reduced when using insulator circuits (IC) with minimum construction height [1,2]. The construction height of an IC is reduced when bearing terminals (BT) with a minimum vertical dimension are used for suspending harness conductors (HC). This makes it necessary to determine the maximum deviation angles of the IC at different dimensions of the BT.

II. EXTERNAL LOADS ON THE BEARING TERMINALS FOR A HARNESS CONDUCTORS

The magnitude of deviation of the HC to the IC is not relevant for violation of the permissible distances from the conductor to the non-conducting parts, because, when building the OPL, capacitive rings are installed between the IC and the BT for HC.

The second reason why it is necessary to study the magnitude of deviation of the HC from their initial position is the significant influence of the dynamics of the conductor on the change of some electrical parameters (the inductive resistance of the conductor, for example).

In practice, two main types of HC deviation are observed under the action of ice and wind loads:

- simultaneous deviation of both the HC and the IC due to wind with a direction, perpendicular to the axis of the OPL;
- twisting of the HC around its axis relative to the point of suspension of the BT to the IC in case of uneven icing.

The magnitude of deviation of the HC from its stable position depends on the combination of ice and wind loads on it, on the geometric dimensions of both the terminal and the conductor, as well as on the wind and weight span lengths.

The combination of the external loads on the BT for a HC with two conductors per phase is given in Fig. 1a, and for a HC with five conductors per phase - in Fig. 1b, where the following designations are adopted: Gi - the weights, respectively, of the i-th conductor in the bundle (i=1,2,...,n);Ei - the wind loads on the i-th conductor (i=1,2,...,n);n - the number of conductors in the bundle.

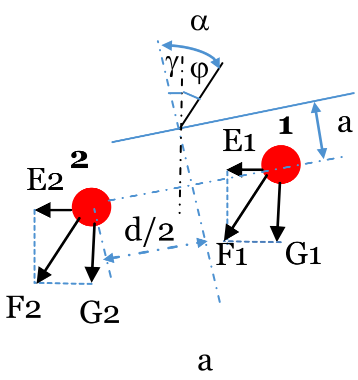
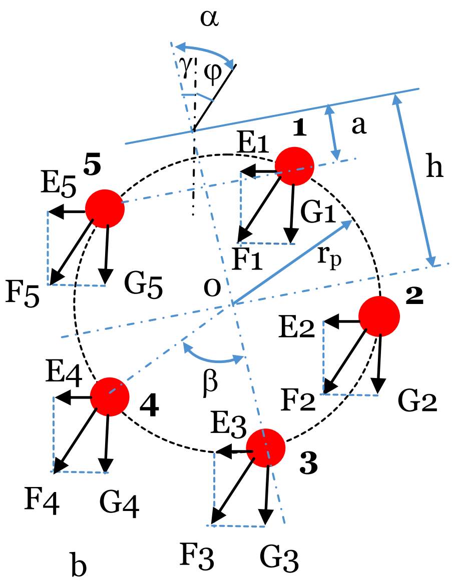


Fig.1.External loads on the BT for a HC with: a - two conductors per phase; b - five conductors per phase



A stable position of the BT is observed when the forces E_i are equal and when the conductors in the bundle are uniformly iced (equality of G_i forces). When the F_i -forces equalities are violated, real conditions are created for: deviation of the IC; stability violation of the system; and obtaining the maximum value of the angle α at a certain ratio of the F_i forces (Fig. 1).
The rotation angle (α) of the BT relative to the axis of the IC is determined by the equilibrium equations of the system

(1) $$\alpha = \delta + \tau,$$

where δ is the deviation angle of the IC;τ - the angle of rotation of the terminal relative to the vertical.
The calculation expressions for the angles δ and τ for two and five conductors in the bundle, respectively, are given in table 1, where the following notations are adopted: m is the coefficient with which the possible cases of reducing the load due to the weight of the conductor, are taken into accountat different suspension heights of the supporting poles (it is assumed that m =0.75 for the supporting poles, while for all other types of poles m =1) [3]; G_k - the weight of the BT;r_p - the radius of the circumference along which the axes of the conductors in the bundle are located; - $\beta = 2\pi / n$ - the angle between the two conductors in the bundle, measured relative to its center;a - the distance from the suspension point of the BT to the center of the bundle.

	n=2	**n=5**
$tg\,\theta$	$\dfrac{E_1 + E_2}{G_1 + G_2}$	$\dfrac{\sum_{k=1}^{n} E_k}{m.\sum_{k=1}^{n} G_k + \dfrac{G_u}{2}}$
$tg\;\tau$	$\dfrac{0,5(G_1 - G_2).d + (E_1 + E_2).a}{0,5(E_1 - E_2).d - (G_1 + G_2).a}$	$\dfrac{\sum_{k=1}^{n} E_k B_k + \sum_{k=1}^{n} G_k C_k}{\sum_{k=1}^{n} E_k C_k - \sum_{k=1}^{n} G_k B_k}$ $B_k = h - r_p\{1 - \cos[k\beta - (\beta/2)]\};$ $C_k = r_p.\sin[k\beta - (\beta/2)];$ $h = a + r_p.\cos(\beta/2).$

Table 1. Determination of the angles θ and τ

The forces F_i (i=1,2,…,n), acting on the BT from Fig.1 and Fig.2 in normal mode are determined by equation [4]

(2) $$F_i = \sqrt{G_i^2 + E_i^2},$$

where

(3) $$G_i = \gamma_{3i}\, s\, l_T;$$

(4) $$E_i = \gamma_{5i}\, s\, l_B,$$

where $\gamma_{5i}$are the relative wind loads on the i -th conductor in the bundle;- γ_{3i} - the relative loads from the iced conductors in the bundle;s - the section of the conductor;l_B and l_T - the wind and weight span lengths, respectively.

The relative loads γ_{3i} from equation (3) depend on the thickness of the ice wall, on the ice density, on the cross-section, diameter and relative load, resulting from the corresponding conductor weight.

The relative loads $\gamma_{5i}$from equation (3) depend on the geometrical dimensions of the conductor, the span length, the thickness of the ice cover of the conductor, the coefficient of uneven wind pressure, the wind speed in the case of an icy conductor, the anglebetween the OPL axis and the wind direction.

In such a complex situation, when the influence of a large number of variables has to be investigated, the possibilities are: to carry out an a priori ranking by the random balance design method or to perform a saturated screening design experiment [5].In this case the second research approach is appropriate to be applied.

The following sequence of work is used to obtain the combination of those adverse conditions, in which the angle α has a maximum value:

- The factors, influencing the BT stability for a HC are divided into groups, combining the mutually independent factors (Table 2).
- A screening experiment is performed in order to obtain a priori information about the studied parameter.
- A first-order saturated design is constructed by minimizing the largest of all variances of the regression coefficient estimates.According to this criterion, the first-order simplex designs are optimal.

№	Factor	Limits of change	
		lower	upper
1	Thickness of the ice wall, b,m	0,01	0,04
2	Wind speed at icing, v1, m/s	17,5	20,0
3	Span length, l, m	200	660
4	Geometric dimensions of the terminal (Fig. 1) c,m a,m	 0,25 0,15	 0,45 0,40
5	Design parameters of the conductor d,m s,mm^2.10^{-6} γ_1, N/m.mm^2	 0,027 441,5 33370	 0,0302 541,5 35500

Table 2. Factors, influencing the magnitude of angle τ

The geometric dimensions of the terminal (a and c at n=2, respectively h and a at n=5) are mutually independent factors, which necessitates the implementation of a simplex design for the number of influencing factors k=6. Table 3 shows the coded values of the influencing factors, and table 4 presents the simplex design for k=6 at n=2.

The experiments at each point of the experimental design shown in Table 4 are performed with specially developed software while varying the influencing factors within the limits, given in Table 2. The results from the numerical experiments for α are given in Table 4, and the values of the coefficients b_i (i=0,1,…,k) can be seen in Table 5.

Code	X_1	X_2	X_3	X_4	X_5	X_6		
Factor	b,m	v_1,m/s	L,m	c,m	a,m	D,m	s, $mm^2.10^{-6}$	γ_1. $N/m.mm^2$
-1	0,01	17,50	300,0	0,250	0,1500	0,0272	441,5	33370,00
$-a_{62}$	0,0162	18,01	373,8	0,291	0,2012	0,0278	462,0	33806,65
a_{63}	0,0271	18,92	505,2	0,364	0,2925	0,0289	498,5	34584,10
a_{61}	0,0348	19,56	597,0	0,415	0,3562	0,0297	524,0	35127,25
a_{64}	0,037	19,75	624,0	0,430	0,3750	0,0299	531,5	35287.00
+1	0,04	20,00	660,0	0,450	0,4000	0,0302	541,5	35500,00

Table 3. Coded values of the influencing factors

№	X_1	X_2	X_3	X_4	X_5	X_6	φ, grad	γ,grad	α,grad
1	-1	-1	a_{61}	$-a_{62}$	1	a_{63}	34,52	0,95	35,47
2	-1	a_{61}	$-a_{62}$	1	a_{63}	-1	37,77	0,89	38,66
3	a_{61}	$-a_{62}$	1	a_{63}	-1	-1	19,38	10,48	29,86
4	$-a_{62}$	1	a_{63}	-1	-1	a_{61}	26,50	4,81	31,31
5	1	a_{63}	-1	-1	a_{61}	$-a_{62}$	19,54	15,43	34,97
6	a_{63}	-1	-1	a_{61}	$-a_{62}$	1	19,75	10,48	30,23
7	a_{64}	a_{64}	a_{64}	a_{64}	a_{64}	a_{64}	18,42	19,37	37,79

Table 4. Simplex design for k=6 at n=2

Coefficient	b_0	b_1	b_2	b_3	b_4	b_5	b_6
Value	34,042	-5,268	1,864	-0,113	1,236	3,348	-0,767

Table 5. Coefficients of the first-order regression equation

The screening experiment shows that the factors X_3 and X_6 are insignificant. Since the conclusions about the influence of the factors are valid only for the investigated intervals of change, it follows that the factor X_6 turns out to be insignificant, due to its small interval of change. Therefore, in further investigations of the factorial influence, it is advisable to carry out the studies for a specific type of conductor, and to enter its geometric dimensions as input data. The conclusion of the screening experiment, referring to the insignificance of the X_3 factor, gives reason to set only the overall span length when determining the forces.

Analogous results regarding the degree of influence of the factors on the angle α are obtained at n=5.

III. RESULT VIEW

The determination of the maximum value max $\alpha=f(X_i)$ is greatly simplified after taking into account the results of the screening experiment. The design parameters for each conductor type are set as input quantities. The calculations are carried out with the accepted normalized values of the climatic factors - the thickness of the ice wall, the wind speed during icing, the maximum wind speed at a given overall span length (l_r) and with modeling of different conditions of load unevenness on the HC. In the developed software, this unevenness is expressed by 20% and 40% of fallen ice from one conductor in the bundle at n=2. By increasing the number of conductors in the bundle, the probability of load unevenness and simultaneous ice falling from all conductors in one span length significantly reduces. Therefore, for research purposes, the angle α is checked when the ice falls from 1, 2 or at most 3 conductors in the bundle. For that reason, at n=5, six of the possible load unevenness options, given in Table 6, are included in the algorithm.

With the developed software, calculations of the angles τ, θ and α were carried out for the HC type 5 xAC 400 at a= 0.1 and 0.4 m for the 3rd climatic region with an overall span length l_r=420 m and the obtained values are given in Table 6. It can be seen that the most severe load unevenness mode occurs when the ice falls from conductors 1, 2 and 3, according to their numbering in Table 6. The maximum value of the angle α is obtained at minimum dimensions of the BT.

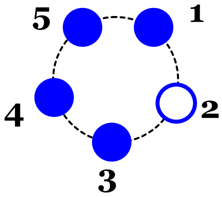
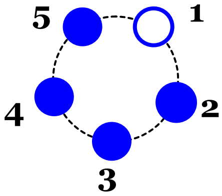
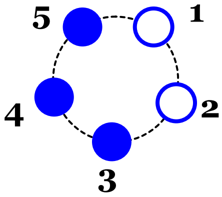
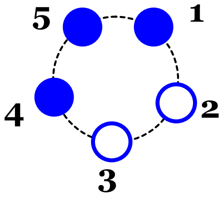
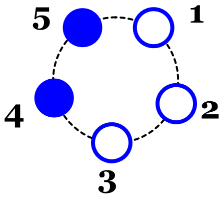
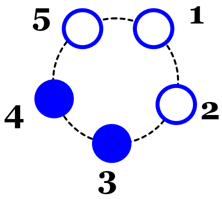
Load scheme	a,m	α, grad	φ, grad	γ, grad
	0,1	40,76	25,06	15,70
	0,4	33,38	25,06	8,32
	0,1	43,26	25,06	18,20
	0,4	34,93	25,06	9,87
	0,1	41,37	24,92	16,45
	0,4	33,99	24,92	9,07
	0,1	41,05	24,92	16,13
	0,4	33,51	24,92	8,59
	0,1	47,36	24,74	22,62
	0,4	36,96	24,74	22,62
	0,1	46,18	24,74	21,44
	0,4	36,48	24,74	11,74

Table 6. Values of the angles α,φ and γ for different variants of load unevenness due to icing at n=5 (with notation: λ- iced and μ - ice-free conductor)

In [2] it is stated that for n>3 always $\tau < 10^{o}$.The results, presented in Table 6 show that in complex consideration of the action of the influencing factors on the maximum deviation of the BT, the values of the angle τ reach 15-22^{o}. Therefore, the error from not taking into account the joint action of all factors on the angle τ size can reach from 25% to 50%.

IV. CONCLUSIONS

- When studying BT suspension stability, it is necessary to take into account the complex action of the influencing factors, observed in real conditions. Neglecting some of the factors influencing on the BT deviation leads to significant errors.
- It is expedient to conduct the study of BT stability for a specific type of conductor. When determining the forces, acting on the conductors, for the purposes of the study it is sufficient to work with the overall span length.
- The proposed methodology allows to determine the maximum deviation of the BT at different degrees of unevenness of the loads on the HC and the span length and taking into account the influence of all essential factors.
- The methodology makes it possible to determine the BT stability for the HC when examining the reliability of OPL by mechanical parameters.

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