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Estimate of Maximum Expected Intensity of One-Half-Wave Lines Dancing

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***Abstract*—**In this paper, the regression dependence of dancing intensity from wind speed and length of span was established due to the statistic data obtained from multi-year observations on line wires dancing accumulated by power systems of Kazakhstan and the Russian Federation. The lower and upper limitations of the equations parameters were estimated, as well as the adequacy of the regression model. The constructed model will be used in research of dancing phenomena for the development of methods and means of protection against dancing and for zoning plan of the territories of line wire dancing.

***Keywords*—**Power lines, line wire dancing, dancing intensity, regression equation, dancing area intensity.

I. Intrduction

UNDER certain conditions, there is a mechanical oscillation of wires on overhead power lines, characterized by relatively low and a significant part of the amplitude. These fluctuations were called "dancing" of wires. Dancing of icy wires is one of the main problems in design and operation of overhead power lines in areas (countries) where this is a phenomenon. It essentially affects the size, cost and reliability of lines. In this regard, there is a need for a comprehensive study (statistics, theory, and experiment) of the dancing phenomenon of overhead wires.

The main objective of the theoretical development of dancing [1]-[5] is to create a common mathematical model allowing under specified conditions to determine the main characteristics of the oscillatory process - the dancing intensity, number of half-waves, frequency, dynamic load and conditions of aerodynamic instability of wires with icy sediment of wind stream. Statistic data summarized from the experience of electric networks operation is the main criterion for the evaluation of possible exposure to overhead line dancing, as well as the intensity (amplitude) of dancing. The results of these studies should ultimately serve to improve reliability of overhead power lines.

The paper deals with the estimation of possible intensity of line wire dancing. For this purpose, were taken the initial statistic data which was accumulated by energy systems based on multiyear observations of line wire dance during operation of overhead lines. Issues on dancing intensity estimate in a different way are presented in [5]-[10]. A distinctive feature of this work is the fact of taking into account of the effects of dancing on the intensity of such basic factors as wind speed and angle of attack of the wind flow on the line.

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II. One-Half-Wave Dance

As you know, the greatest danger in terms of the reliability of lines is one-half-wave dancing, and below only this type of dancing is displayed. The total number of observations is 67 cases. Among which, 42 cases are recorded dances in power systems of Kazakhstan, 20 cases in power systems of the Russian Federation [9], [11] and 5 cases are the results of experimental data recorded at the experimental field of the Kazakh Scientific Research Institute of Energy (KazNIIE).

Graphic images of the initial statistical observations are shown in Fig. 1, where along the ordinate axis are given intensities of one-half-wave lines dance A_p, and the axis of abscissa is an independent variable X, which is a product of the span length ℓ and the vertical component of the wind speed $V_{\perp}$, i.e.

$$X = \ell V_{\perp} \tag{1}$$

Here $V_{\perp} = V\,Sin\alpha$ where V - wind speed, α - the angle of wind flow attack to the line.

Regression Equations

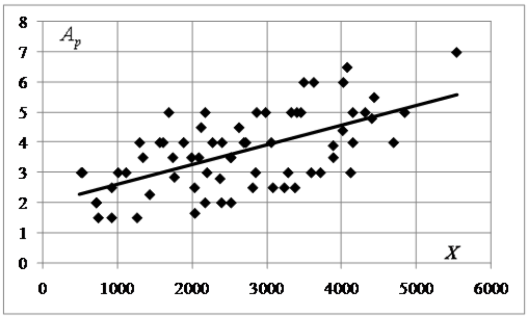


Fig. 1 Graphic images of the initial statistical observations
• observation data, ________ regression line

Based on Fig. 1, we obtain the following linear model

$$A_p = b_0 + b_1 X \tag{2}$$

According to the least squares method (LSM - method) in order to estimate the parameters of the function b_0 and b_1 we use a set of equations [12], [13].

$$b_0 = \frac{\sum_1^n x_i^2 \sum_1^n A_{pi} - \sum_1^n x_i \sum_1^n x_1 A_{pi}}{n\sum_1^n x_i^2 - \left(\sum_1^n x_i\right)^2} \tag{3}$$

$$b_1 = \frac{n\sum_1^n x_i A_{pi} \sum_1^n - \sum_1^n x_i \sum_1^n A_{pi}}{n\sum_1^n x_i^2 - \left(\sum_1^n x_i\right)^2} \tag{4}$$

where the total number of observations $n = 67$.

The results of calculations: $b_0 = 1{,}96$ and $b_1 = 6{,}5 \cdot 10^{-4}$.

III. Empirical Dependence of the Dance Intensity

It is useful to take into account the information on possible intensity (amplitude) of wire oscillations, depending on wind speed and the characteristics of the lines while developing for wire dancing exclusion and for design of power transmission lines (PTL). This information can be obtained from long-term statistical observations acquired by energy systems on wire dance during power lines operation.

As it can be seen from the analysis of statistical data on overhead wires dancing of the energy systems of West Kazakhstan region, wire dancing occurs regardless its class of voltage, design modification of lines, its length of span and value of mechanical stresses in wire. Moreover, fluctuations in wires occur with different number of half-waves in the span [11].

This part of the paper deals with the empirical dependence of the dancing intensity on wind speed, angle of attack of wind flow in the lines, length of span and number of half-waves. Selected materials cover one half-wave (18 cases), two half-wave (15 cases) and three half-wave (5 cases) dancing. Total number of observations is equal to $n = 38$. According to the selected material, the minimum span length is 90 m and the maximum is 367 m.

In order to establish the empirical relationship we take the following variables:

$$A_P = \begin{pmatrix} A_{P1} \\ \cdot \\ \cdot \\ A_{P38} \end{pmatrix}, \quad X = \begin{pmatrix} 1 & x_1 \\ \cdot & \cdot \\ \cdot & \cdot \\ 1 & x_{38} \end{pmatrix},$$

where A_p is observation vector, the dimension (38×1), $X = \tilde{\lambda} V_\perp$ is the matrix of independent variables, the dimension (38×2), $\tilde{\lambda} = \frac{\ell}{m}$ (ℓ is the length of the span), x_i are components of the independent variables X. This, A_p determines the dancing intensity, $V_\perp$ - the vertical component of the wind speed, $\tilde{\lambda}$ - the length of half-waves, m is the number of half-waves in the span.

$$b = \begin{pmatrix} b_0 \\ b_1 \end{pmatrix}, \tag{5}$$

where b is the vector of parameters of evaluation, the dimension (2×1).

$$E = \begin{pmatrix} e_1 \\ \cdot \\ \cdot \\ e_{38} \end{pmatrix}, \tag{6}$$

where E is the vector of errors (remaining's), the dimension (38×1).

The models we represent in the matrix form

$$A_p = Xb + E \cdot \tag{7}$$

By the least squares method of evaluation (LSM - method) for b [2].

$$b = \begin{bmatrix} b_0 \\ b_1 \end{bmatrix} = \left(X^T X\right)^{-1} X^T A_p \,, \tag{8}$$

where "T" is the symbol of transposition.

As a result of calculations based on the acquired statistical data, we should obtain a linear regression model of the first order.

$$A_p = b_0 + b_1 \tilde{\lambda} V_\perp = b_0 + b_1 \frac{\ell}{m} V \cdot Sin\alpha \,, \tag{9}$$

where the parameters of the equation are $b_0 = 1{,}785$; $b_1 = 0{,}0011$.

IV. Study of the Regression Equation

Assessment of the adequacy of the regression model is made by F - Fisher criterion. Estimated (actual) value of F is according to [12]-[14].

$$F_{фак} = \frac{\sum_1^n (A_{pi}^{т} - \overline{A}_p)^2}{s^2} \tag{10}$$

Here

$$s = \sqrt{\frac{\sum_1^n (A_{pi} - A_{pi}^{T})^2}{n-2}}\,; \quad \overline{A}_p = \frac{1}{n}\sum_1^n A_{pi},$$

where A_{pi}^{T} is a theoretical (predicted) value, S is an estimation of the dispersion adequacy.

Results of the comparison of the actual value Fact = 37.8 and tabulated Ftab $\approx$ 3.98, where Fact>Ftab show the reliability of the regression equation. Tabulated value is defined for the significance level of 0.05 and the degree of freedom n - r = 65, (or is the number of coefficients of the regression equation).

Estimate of the significance of the coefficients b_j is made by t - Student criterion [12], [13].

$$t_{b_0} = \frac{b_0\sqrt{n}}{s}\sqrt{\frac{\sum_1^n (x_i - \bar{x})^2}{\sum_1^n x_i^2}};$$

$$t_{b_1} = \frac{b_1\sqrt{\sum_1^n (x_i - \bar{x})^2}}{s}, \tag{11}$$

where $\bar{x} = \frac{1}{n}\sum_1^n x_i$ (x_i – independent variables)

Tabulated value of tα – criterion calculated for the level of significance $\alpha = 0{,}05$ and degrees of freedom are65, which is equal to $t_\alpha \approx 2$. As $t_{b_0} > t_\alpha$ and $t_{b_1} > t_\alpha$, the corresponding coefficients of the regression equation are considered to be significant.

The confidential intervals $100(1-\alpha)$ %for a free term $b_0 \pm \Delta b_0$ and angular coefficient $b_1 \pm \Delta b_1$ can be obtained by calculating the marginal error for each parameter [13].

$$\Delta b_0 = \frac{t_\alpha s}{\sqrt{n}}\sqrt{\frac{\sum_1^n x_i^2}{\sum_1^n (x_i - \bar{x})^2}};$$

$$\Delta b_1 = t_\alpha \frac{s}{\sqrt{\sum_1^n (x_i - \bar{x})^2}}; \tag{12}$$

The calculated values: $\Delta b_0 = 0{,}61$ and $\Delta b_1 = 0{,}00021$.

Taking into account the numerical values of the marginal error it can be said that the confidential intervals for b_0 and b_1 with 95% of confidential level are in the range of

$$1{,}35 \le b_0 \le 2{,}57 \text{ and } 0{,}00044 \le b_1 \le 0{,}00086. \tag{13}$$

The obtained equation for observation within a certain range of variable X can provide quite adequate representation. The equation is, of course, cannot be applied to the X values, beyond these boundaries, as it cannot provide them a reasonable prediction. Variable X depends in turn on other variables: the length of span, wind speed, and angle of attack. Therefore, the restrictions imposed on X can be achieved by a reasoned choice of ranges of the length spans, wind speed, and angle of attack.

According to the materials of observation, the lowest span length is generally equal to 120 m (length 82 m and 103 m can be met once). The major span length can be of 430 m. The range of attack angle to wind flow lines can be from 350to 900. The range of wind speed is from 5 m/sec to 20 m/sec. This, a higher speed corresponds mainly to a small length of the span and vice versa. And, according to the observation data for $\ell = 120\,\mathrm{m}$ the maximum vertical velocity component does not exceed $V_\perp = 17\,m/\sec$, and for $\ell = 400\,\mathrm{m}$ the speed is reduced to $V_\perp = 13{,}8\,m/\sec$, that is, for every span there is a critical speed.

In general, the critical speed causing line wire dancing is determined by considering the aerodynamic instability of icy wires in a wind flow. In this case, the critical velocity for any span within the range $100\,m \le \ell \le 450\,m$ in the first approximation can be established by the interpolation method. As we know, for a linear interpolation at a given segment arbitrary function is approximated by a linear function and it's graph (straight line) passes through two nodal points. In this case, the coordinates of nodal points are the corresponding lengths of spans and the wind speed, i.e. (120; 17) and (400; 13.8).Knowing the coordinates of points, we determine the equation of the line passing through these points.

$$\begin{vmatrix} 120-400 & 17-13{,}8 \\ \ell - 120 & V_\perp - 17 \end{vmatrix} = 0\cdot$$

Expanding the determinant, we obtain the desired limitation $V_\perp \le 15{,}6 - 0{,}01\cdot\ell$.

V. Conclusion

We obtained the analytical dependence which allows estimating (with the imposed limitations) the maximum (minimum) of possible dancing intensity depending on the length of span, wind speed and direction:

The upper limitation of the maximum expected dancing intensity

$$A_p^{\max} = 2{,}57 + 8{,}6\cdot 10^{-4}\,\ell V\,Sin\alpha \tag{14}$$

The lower limitation of the minimum expected dancing intensity

$$A_p^{\min} = 1{,}35 + 4{,}4\cdot 10^{-4}\,\ell V\,Sin\alpha \tag{15}$$

Limitations on the independent variables (the ranges of change in the lengths of span are a little extended):

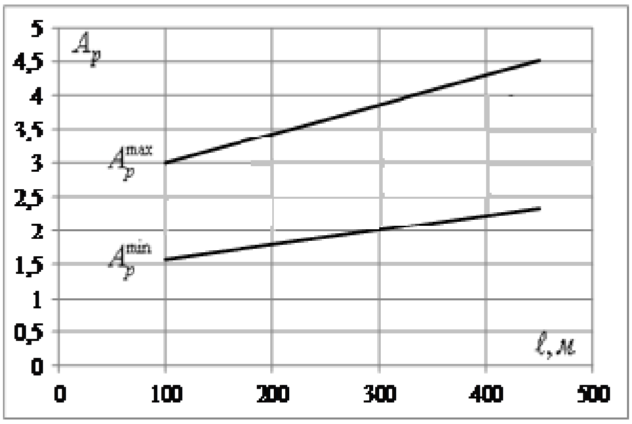
$$\begin{aligned} &100\,m \le \ell \le 450\,m \\ &V_\perp \le 15{,}6 - 0{,}01\cdot\ell \end{aligned} \tag{16}$$

$$35^0 \le \alpha \le 90^0$$

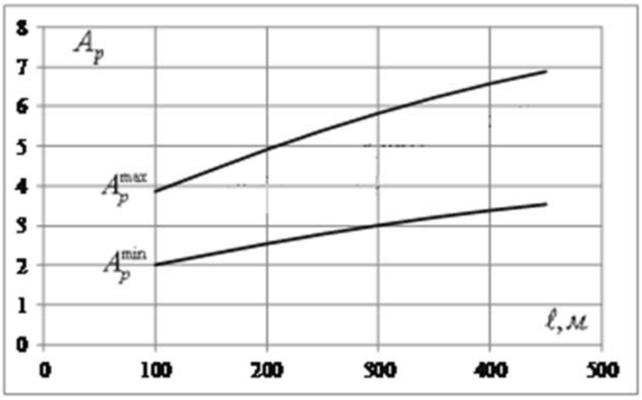
where $V_{\perp} = V\,Sin\alpha$.

In Fig. 2 is constructed an example of the area of the expected dancing intensity of line wires at various lengths of span and wind speed. Maximum vertical(critical) speed is determined from the equation

$$V_{\perp} = 15{,}6 - 0{,}01 \cdot \ell \qquad (17)$$



(a)



(b)

Fig. 2 Area of the expected dancing intensity (a) for $V_{\perp} = 5m/\sec$ (b) for the critical velocity

The constructed model will be used for investigation of the dancing phenomena, for the development of methods and means of protection against dancing and for zoning plan of the territories of line wire dancing.

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