Comparative analysis of the various types of structures for the electric transmission power cables supports’ static work in the software complexes implementing the finite elements method

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Abstract. The aim of the work was to conduct a comparative analysis of the static work of two structural types of steel poles of power lines (HVPC): in the form of a closed profile rods-shells with height-varying wall thickness and in the form of a trellised trihedral design made according to the patent [1]. In this case, both types of supports were considered for three different heights - under power lines of 10 kV - 9-11 m high, 35 kV - 20.6 m high and 110 kV - 22.5 m high, respectively. The bulk of the research was carried out at the ANSYS PC, where the joint work of the structural system “steel support of an overhead power transmission cable - a prefabricated and dismantled reinforced concrete foundation of a new type [2] - soil base” was considered. For this, the authors proposed a computer simulation technique that takes into account the spatial work of the structural system elements and the physical nonlinearity of the materials they are made of. At the same time, the Mises strength theory was used for steel, Williams-Warnake yield criterion was used for concrete, and Drucker-Prager yield criterion was used for the base soil. In addition, all the necessary geometric, power, and physical characteristics of the model were obtained on the basis of the current building codes for the energy facilities’ design. The auxiliary engineering calculations taking into account these codes were performed in the LIRA-SAPR 2017 PC in a linear formulation.

Introduction

The tasks associated with the search for the optimal structural forms of overhead power transmission line supports (HVPC) are relevant for the energy sector and the national economy of the country as a whole, since their solution will allow to save metal, reduce the anthropogenic load on the natural environment, and reduce the cost of generating a unit of electricity, which as a result, it will lead to a guaranteed reduction in prices for end-use products [11-14].

This article discusses the joint static work of the “support – foundation – soil base” construction system’s two new elements for which the corresponding patents have been obtained by the authors [1], [2]. Comparison of their technical and economic indicators with existing analogues shows a certain advantage and effectiveness of the proposed design solutions [3], [4]. These decisions have their own
characteristics, which cannot yet be reflected in the framework of the existing regulatory approach for the energy facilities’ design. In this regard, the problem of creating such a methodology for calculating the “support – foundation – soil base” system arises, which would take into account all the nuances of constructing the new supports [1] and foundations [2], as well as the features of their joint work under static and dynamic load.

The first step towards this can be the computer simulation. The universal tool for this is the finite element method (FEM), and the ANSYS program using this method is widely known and is popular among the engineers who are deeply involved in resolving the strength issues. Partially modeling the SSS of the structural system “support – foundation – soil base” has already been described in [5] using the example of an anchor-angle support SM10AU, manufactured according to the 3.407.2-181.09 series “Polyhedral steel supports of 6-10 kV overhead lines”. In continuation of this, in this article, a comparative analysis of the steel HVPC supports two structural types’ static work is carried out: in the rods-shells form of a closed profile with a wall thickness of variable height and in the form of a trellised trihedral design made according to the patent [1]. In this case, both types of supports were considered for three different heights - under power lines of 10 kV - 9-11 m high, 35 kV - 20.6 m high and 110 kV - 22.5 m high, respectively. Thus, a total of eight support options were considered:

SP-1 – is an anchor-angle support of the grade SM10AU (Fig. 1, a) of 10 kV, 9 m high, designed for a rotation angle of up to 1200, manufactured according to the series 3.407.2-181.09, suitable for operation in climatic conditions, including Kazan city (II-nd wind region, II-nd ice area); the support barrel is a thin-walled tubular rod with a wall thickness that is variable in height (in this case, changing the wall thickness is a distinctive feature of the support from the series 1, while the demarcation seam is made in the middle of the support barrel, and the lower part of the support has a larger wall thickness than the upper one);

SP-2 – is an anchor-angle support of the STR10AU brand (Figure 1, b) of 10 kV, 9 m high, designed for a rotation angle of up to 1200, manufactured in the form of a trihedral lattice structure for which a patent has been obtained [1];

SP-3 – is an intermediate support of grade SM10P (Figure 1, c) of 10 kV, 11 m high, manufactured according to the series 3.407.2-181.09; as in the first case, the support shaft has a variable wall thickness in height;

SP-4 – is an intermediate support of the STR10P grade (Figure 1, b) at 10 kV, 11 m high, manufactured in the form of a trihedral lattice structure;

SP-5 – is a double-chain intermediate bearing of the PM35-2f grade (Figure 1d) at 35 kW, 20.6 m high, manufactured according to the Metako-TSK.35.01 series, the shaft of the support has a variable wall thickness in height;

SP-6 – is an intermediate support of the STR35P brand (Figure 1, b) at 35 kV, 20.6 m high, manufactured in the form of a trihedral lattice structure;

SP-7 – is a single-chain intermediate support of the PM110-3FT brand (Figure 1, d) at 110 kV, 22.5 m high, manufactured according to the 3.407.2-182.09 series, the trunk has a variable wall thickness along the height of the support;

SP-8 is an intermediate support of the STR110P grade (Figure 1, b) at 110 kV, 22.5 m high, manufactured in the form of a trihedral lattice structure.

A general view of the listed supports is shown in Figure 1.
Figure 1. Types of simulated supports: a) anchor-angle support of the grade SM10AU; b) the three-edged trellised support of the brands STR10AU, STR10P, STR35P, STR110P; c) the double-chain intermediate grade support PM35-2f; d) the single-chain intermediate grade support PM110-3FT

The presented supports are designed for the suspension of non-insulated steel-aluminum wires according to GOST 839-80, as well as self-supporting insulated wires of the SIP-3 (SAX) type according to TU 16.K71-272-98. Of the wires presented in the standards, AS 185/29 brand wire has the greatest load on the pore, which is accepted for calculation (the area of the aluminum part is 185 mm², the steel core is 19 mm², the wire diameter is 18.8 mm, the linear mass is 7.28 kg / m, breaking strength is 62.1 kN).

The second element of the considered structural system - the foundation - is collapsible and is performed according to the patent [2]. The general view of the foundation is shown in Figure 2. Its
economic efficiency can be ensured not only due to the low laboriousness during installation, dismantling and the low transportation costs - this is stated in the patent’s text, but also by the calculation method when assessing the SSS of the system “steel support – foundation – soil base” taking into account their collaboration.

![Diagram of collapsible foundation](image)

**Figure 2. General view of a collapsible foundation [2]**

The third element of the system under consideration — the base soils — can be different at the installation site of the supports; we will take the worst case scenario that the Code of Practice 22.13330.2011 “Soil bases of Buildings and Structures” allows: the type of soil is clay, non-slip, non-swelling; with the porosity coefficient 0.95; strain modulus is $E = 8$ MPa; flow rate is $IL = 0.5$; the soil adhesion is $c = 15$ kPa; the angle of internal friction is $\varphi = 170$; the rated resistance is $R0 = 150$ kPa; the coefficient of the base rigidity (bed coefficient) is $k = 10$ MPa / m (The Designer’s Guide Vol.2, edited by A. Umansky, 1973. - P. 307).

Since we are interested in working with the foundation only for a single support, we can consider it without wires, replacing their action with the corresponding load. Otherwise, it is necessary to consider the entire so-called “anchor span” up to 3 km long, within which several intermediate supports would be located; all the supports would then be connected with the wires having a certain sag (which depends on the wire type, the intermediate spans’ length and the ambient temperature). Thus, the design schemes of the supports are shown in Figure 3.

The essence of the modeling technique of the “support - foundation - soil base” system is as follows:

1 - determination of the system elements’ loads (based on the provisions of Code of Practice 20.13330.2011 “Loads and effects” and PES-7 “The rules for the electrical tools’ installation”);

2 - a static calculation of a steel support separately, as a rigidly canted cantilever rack of a hollow or lattice section (as a result of which the load on the foundation edge is determined) is performed in the Lira-SAPR 2017 PC in the elastic setting;

3 - the base dimensions’ determination of the foundation based on the load on it in accordance with the engineering methodology of Code of Practice 22.13330.2011 “Foundations of buildings and structures”;
4 - modeling of a single system “support – foundation – soil base”, the definition of VAT in it in the PC “ANSYS”;

5 - checking the system elements for strength, stability and deformability (respectively, according to the 1st and 2nd groups of limit states) based on the provisions of Code of Practice 16.13330.2017 Steel Structures, Code of Practice 63.13330.2012 Reinforced Concrete Structures and Code of Practice 22.13330.2011 “Foundations of buildings and structures”.

Figure 3. The HVPC supports’ design schemes: a) the supports of the SM10AU and STR10AU brands; b) supports of the brand SM10P and STR10P; c) the supports of the PM35-2f and STR35P brands; d) the supports of the PM110-3FT and STR110P brand

The calculation takes into account the following types of loads:

1 - depending on the action direction:
   - horizontal (wind on a support, wind on wires and cables, from pulling wires and cables) and
   - vertical (dead weight of the support, weight of insulator strings (with fittings), weight of wires and cables, ice load, mounting load (weight of the fitter with tools));

2 - depending on the action duration:
   - constant (dead weight of the support, weight of wires);
   - temporary (wind, ice load on wires and cross beam, mounting load).

Separate load - temperature. Since we do not consider the cables’ operation, therefore, we do not take this load into account in the calculations.

The self-weight of the steel mast is set automatically in the ANSYS PC and the Lira-SAPR 2017 PC, provided that the material density is entered. Moreover, the reliability coefficient is $\gamma_f = 1.05$.

The design schemes for the series supports are shown in Fig. 3, for the corresponding lattice supports, the load application scheme is similar (for the SP-2 support, the scheme corresponds to SP-1, for OP-4 - OP-3, etc.).

According to PES-7, steel supports are designed for the following loads combinations:

1 circuit (normal mode): Wires and cable are not broken and free from ice. The wind is directed along the axes of the traverse.

2 circuit (normal mode): Wires and cable are not broken and covered with ice. The wind is directed along the axes of the traverse.

3 circuit (emergency mode): One wire (on the right / left side) is broken, giving torque to the support.

4 circuit (emergency mode): Two wires are broken, giving maximum torque to the support.
The “support – foundation - soil base” system includes the elements formed from the materials with qualitatively and quantitatively different physical and mechanical properties. To simulate them in the ANSYS PC, the corresponding types of finite elements and the laws of deformation were used. Their list is presented in Table 1.

**Table 1.** Toward the construction of a finite element model.

| FE model parameter | Steel support | Reinforced Concrete Foundation | Base soil          |
|---------------------|---------------|---------------------------------|--------------------|
| Geometrical dimensions | In cross section a polygonal pipe of variable cross section and wall thickness with a variable height | A regular hexagon in plan with a side of 1.8 m, a height of 0.6 m, consisting of prisms with a base in the form of a regular triangle with a side of 0.6 m. | Array 10x10x10 m |
| The Finite Element Type | Shell 181 | Solid 65 | Solid 45 |
| Deformation law | Two-line diagram, kinematic hardening with the Bauschenger effect | Curved diagram by Radaykin O.V. [6] | Determined by the strength theory |
| Strength theory | Mises | William Warnake | Drucker Prager |

Figure 4 shows the material deformation diagrams used to create the model.

**Figure 4.** Diagrams of deformation of materials: a) curvilinear diagram by Radikin O.V. under tension [6]; b) the same - in compression; c) two-line diagram, kinematic hardening with the Bauschenger effect.

The mathematical expressions describing the diagrams in Fig. 4, a-b have the form:

\[
\sigma_{\text{fr}} = a_f (1 - b_f D_{sf})^{\gamma} E_{\text{id}} e_{\text{id}},
\]

\[
\sigma_b = a_b (1 - b_b D_b)^{\gamma} E_p e_p,
\]

(1)
where \( D_\text{bt} = \frac{\varepsilon_\text{bt}}{\varepsilon_\text{bt2}} \) is the deformation criterion of damage to tensile concrete; \( \varepsilon_\text{bt}, \varepsilon_\text{bt2} \) - are the current and ultimate relative deformations for stretched concrete, respectively; \( D_\text{b} = \frac{\varepsilon_\text{b}}{\varepsilon_\text{b2}} \) is the damage deformation criterion to compressed concrete; \( \varepsilon_\text{b}, \varepsilon_\text{b2} \) - are respectively, the current and ultimate relative deformations for compressed concrete;

\[
a_i = \frac{2.7R_\sigma}{E_b}, \quad b_i = \frac{1}{50R_\sigma}, \quad c_i = 50R_\sigma \frac{\varepsilon_\text{b2}}{\varepsilon_\text{b0}} - 1, \quad a_c = \frac{2.7R_\sigma}{E_c}, \quad b_c = \frac{1}{50R_\sigma}, \quad c_c = 50R_\sigma \frac{\varepsilon_\text{b2}}{\varepsilon_\text{b0}} - 1
\]

- are the calculated coefficients that nevertheless have a clear physical meaning;

\( \varepsilon_\text{b0}, \varepsilon_\text{b0} \) - are the relative strains corresponding to vertex stresses in tension and compression.

As a law of deformation for steel, a bilinear diagram of kinematic hardening was adopted (see Fig. 4, c). The law assumes that the different signs stresses’ sum during loading and unloading in the \( \sigma - \varepsilon \) diagram is always equal to twice the yield strength \( \sigma_y \), that is, the Bausinger effect is taken into account. The model is recommended for elastoplastic problems with small deformations of a material that satisfies the Mises flow condition:

\[
\sigma_{eq} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \leq \bar{\sigma}_\text{m},
\]

where \( \sigma_{eq} \) - is the equivalent stresses von Mises, \( \sigma_1 \geq \sigma_2 \geq \sigma_3 \) - are the principal stresses, \( \bar{\sigma}_\text{m} \) - is the standard average plasticity limit taking into account the variation coefficient of 5%.

Thus, the physical law of a thin-walled shell deformation was described by four parameters: the elastic modulus \( E=206 \cdot 10^3 \text{ MPa} \), tangent module \( E'=75 \cdot 10^3 \text{ MPa} \), yield strength \( \bar{\sigma}_\text{m} = 355 \text{ MPa} \) and the Poisson’s ratio \( \nu=0.3 \).

To determine the foundation dimensions, a single support was previously calculated as a rigidly fixed cantilever rack, that is, without taking into account the foundation and soil base. This calculation was made in the PC “Lira-SAPR 2017”, taking into account all the Code of Practice features for the HVPC poles design. As a result, we obtained the load on the edge of the foundation, according to which, using the formulas Code of Practice 22.13330.2011 “Foundations of buildings and structures”, the required dimensions of the foundation were calculated (see Table. 2).

**Table 2.** The results of the foundation dimensions’ preliminary calculation.

| SP Brand | Hexagon side, m | Number of prefabricated elements | Sketch |
|----------|----------------|---------------------------------|--------|
| SP-1, SP-2 | 4.2         | 294                             |        |
Further, to reduce the volume of the article, we present the results of computer simulation using the supports SP -1 and SP -2 as examples. A general view of FE models is shown in Figure 5.

|   |   |   |
|---|---|---|
| SP -3, SP -4 | 3 | 150 |
| SP -5, SP -6 | 4.2 | 294 |
| SP -7, SP -8 | 4.2 | 294 |
Figure 5. The finite-element model of the “support – foundation – soil base” system: a) for the SP-1 support; b) for the SP-2 support.

The results of determining the equivalent stresses in the considered supports are shown in Figure 6.

Figure 6. The SP-1 (a) and SP-2 (b) supports’ computer simulation results.
The SSS analysis Figure 6 shows that the strength and stability of the supports in both options is provided. The corresponding utilization rates turned out to be close to 0.912 and 0.837. Despite this, the SP-1 support (with a solid wall of the barrel) has significant underutilized reserves of strength in comparison with the time SP-2 (with a lattice wall). Therefore, the forces are distributed more evenly in the lattice structure, and, therefore, it is reasonable to expect noticeable metal savings due to the use of this design solution for the high-voltage transmission cables’ construction, especially for high heights (over 20 m).

Results
1. The computer modeling technique previously proposed by the authors in the ANSYS PC [5,16] of the design system “steel support of the high-voltage power lines - collapsible foundation of a new type [2] - soil base” has been improved. The methodology, as before, takes into account the spatial work of structural elements and the physical nonlinearity of the materials they are made of. In addition, it gives an opportunity to consider the trihedral support lattices made according to the patent [1], as well as to set the nonlinear properties for concrete using the deformation diagrams [6], constructed on the deformation damage criterion basis.
2. A program for the numerical research of the high-voltage power cables steel supports which includes 8 series of supports, differing in the trunk design (with a solid wall or lattice), height (from 9 to 22.5 m), purpose and the corresponding loading scheme (angular or intermediate anchor), has been developed.
3. The first results obtained within the framework of this publication show that the strength and stability of the supports of the first two series are ensured (these are the supports with a solid wall (SP-1) and lattice (SP-2), 9 m high). The corresponding utilization rates turned out to be close - 0.912 and 0.837. Despite this, the SP-1 support has significant underutilized reserves of strength in comparison with the SP-2. Therefore, in the lattice structure, the forces are distributed more evenly and, therefore, it is reasonable to expect noticeable metal savings due to the use of this design solution for the construction of high-voltage transmission cables, especially for high heights (over 20 m).

Summary
In further publications, it is planned to illuminate the results of SSS all series supports modeling, on the this basis to determine the rational scope of trihedral lattice supports [2], as well as to obtain an engineering methodology for their calculation and design.

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