The effect of twisting of cable elements on its stress-strain state during bending

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Abstract. The paper considers the stress-strain state of cables of various designs under bending deformations. Using the Ansys program, the tribological interaction of cables with twisted and parallel-laid conductors is simulated, the contact interactions of its individual elements are determined. Analysis and comparison of the stress-strain state of cables will make it possible to assess the strength of materials and create the required cable design, depending on the operating conditions. These results can be used to create high-reliability cables at the design stage.

1. Introduction

Cables for various purposes and designs are used for power electric machines. Flexible or special cables are used for mobile machines, fixed cables - for stationary machines. Flexible cables designed for power mobile machines and mechanisms are subject to various types of deformation during operation [1]. Fixed cables are also subject to periodic bending when being reeled up on a drum. All cables of stationary and non-stationary laying during bending deformation are in a stress-strain state. In this case, contact stresses arise between the cable elements when exposed to external loads. Researchers from Tomsk State University of Architecture and Building (Tomsk) in the field of mechanics of flexible cables carried out work under a contract with the Sibkabel plant and the Tomsk Research, Design and Technological Cable Institute to increase the mechanical strength of flexible cables. The studies dealt with particular issues of the mechanical strength of cables, for example, in bending, stretching, compression and other types of deformation. They were aimed at increasing the reliability of cables used in a separate branch of the national economy [2].

In some works [3], the forces between the cable elements are determined in a theoretical way applying the conditions of equilibrium of composite rods, with the help of methods of structural mechanics. However, only an approximate solution of the problem posed was obtained [4]. There are works by the authors [5,6], who, using Kelly's experience, determined the stresses in a cable product. This method is experimental - theoretical and laborious. A parametric study of the structural damping of overhead cables is considered in [7]. All these studies deal with particular issues of mechanical strength and reliability of cable structures [5]. Works on the reliability and strength of ropes are considered in works [8-11]. The cable belongs to structurally heterogeneous structures, therefore the
results obtained for ropes with a structurally homogeneous structure cannot be used for cables. The work [12] considers the stress-strain state of a cable with parallel-laid conductors using the Ansys program. The difference between this work is the comparison and analysis of the results obtained in Ansys for twisted and non-twisted cables. The purpose of this work is to study the effect of twisting of cable elements on its stress-strain state during bending deformations using the Ansys computational program.

2. Body
At present, the problem of determining the stress-strain state of cables is out of the analytical solution. Despite the large number of experimental studies to determine the mechanical strength of cables, it is an impossible task to generalize them into a single whole to determine their stress-strain state. To solve this problem, like any engineering problem, the method of computer mathematical modeling is most suitable. The results of numerical methods make it possible to calculate and analyze a complex structure, like a cable.

The use of the finite element method makes it possible to determine the stress-strain state and to analyze the cable structure as a whole. For calculations in Ansys, cables with twisted conductors - flexible cables (KG) 3x2.5; 3x4; 4x2.5: 4x6 were selected for connecting mobile mechanisms to electrical networks with alternating voltage 660V and constant voltage 1000V for general industrial purposes. For comparison with twisted conductors and analysis, hypothetical cables with parallel laid elements were taken; standard values of elements and all technical characteristics of cables of KG 3x2.5; 3x4; 4x2.5: 4x6 were used. The geometrical dimensions of the structure of the elements of the KG cables are given in table 1 [1,12].

| Number of conductors and nominal cross-section, mm² | Diameter of TPG, mm | Thickness of TPG insulation, mm | Sheath thickness, mm | Outer cable diameter, mm |
|---------------------------------------------------|---------------------|---------------------------------|----------------------|--------------------------|
| 3x2.5                                             | 2.1                 | 0.9                             | 1.8                  | 12                       |
| 3x4                                               | 2.5                 | 1                               | 1.9                  | 13.7                     |
| 4x2.5                                             | 2.1                 | 0.9                             | 1.9                  | 13.2                     |
| 4x6                                               | 3.3                 | 1                               | 2.3                  | 17.37                    |

1 – current-conducting conductor

A three-dimensional model was built using first-order finite elements. During the simulation, an elastic contact is set among the interacting elements of the cable [13]. The radius of an absolutely rigid cylinder is assumed to be the minimum bending radius of the cable and is equal to 8D according to the technical specification. The problem is solved in a geometrically nonlinear setting using linear models of materials: copper with elastic modulus $E = 1.08 \cdot 10^5$ MPa, Poisson's ratio $\mu = 0.32$ and rubber, respectively, $E = 8$ MPa, $\mu = 0.47$, friction coefficient $f = 0.5$ [14,15,16].

The finite element mesh for the cable has been built (Figure 1). The elements of the cable are shown: the conductor, its insulation and the cable sheath, which have their own color and material (rubber, copper). The cable length is approximately equal to the twist pitch for twisted cable and for both constructions is 0.16 m. The right end of the cable is rigidly fixed; all cable elements are stationary along this section the conductors can be moved and rotated, which allows the cable to be completely wrapped around the rigid cylinder. To simplify the task, the current-conducting conductors are rigidly connected to each other at the end of the cable section; they were moved together as a single element. The following contacts of cable elements are considered: cable insulation - cylinder; conductor insulation and sheath; copper wire core and its insulation; insulation between near-end conductors.
Figure 1. Finite element mesh of the cable: a) Fragments of the KG 3x4 cable; b) Moving the KG 3x2.5 cable along the sections.

The reactions in the rigid termination at the left end of the cable have been determined. The units of measurement for the calculation results of all determined quantities are given in the SI system. The support reaction values in Ansys in anchorage for a 3x2.5 twisted cable are shown in table 2:

Table 2. Values of support reaction in fixing cable 3x2.5 with twisting.

| Support reaction | Fx,N  | Fy,N  | Fz,N  | Mx,Nm | My,Nm  | Mz, Nm |
|------------------|-------|-------|-------|-------|--------|--------|
| 1                | 0.52209 | -9.8613 | 4.7765 | 3.5366 | -0.21467E-01 | -0.35998E-01 |
| 2                | 0.39910 | -3.7641 | 2.3942 | 6.6336 | -0.13307E-01 | -0.30457E-01 |
| 3                | 0.13424 | -6.2269 | 3.2065 | 4.1996 | -0.51671E-02 | -0.97691E-02 |
| 4                | 0.57291 | 4.7401  | -164.45| -0.96410| -0.37753E-01 | -0.75062E-01 |

According to the theory of shifts during deformations, for example, bending, all elements of the cable structure are displaced relative to each other [13]. Computer simulation of cable deformation confirms the presence of shifts of the elements (in this case, fastened together) relative to the sheath.

3. Results

The results of determining the stress between the elements of the cable structure are obtained on the basis of the numerical method. Figure 2 shows the conductors of cables with and without twisting in a bending deformation state. The graphs of changes in contact stresses between core insulation and copper wires are shown. In the calculations of Ansys, equivalent stresses are determined; for simplicity, we will call them contact stresses, since these stresses appear at the contact points of the cable elements. Let's introduce designations on the graphs for each brand of KG cable: 1-3x2.5; 2-3x4; 3-4x2.5; 4-4x6. The maximum stresses in twisted cables arise in TPGs with a large cross section (Figure 2a). With large cross-sections of conductors, the compression pressure of the sheath of the conductors is greater than that of conductors with a smaller cross-section. For cables without twisting, the highest contact stresses are in TPZh with a smaller cross-section (Figure 2b). The compression pressure of the sheath without twisting is higher for conductors with a smaller cross-section. Both types of the cable meet the strength conditions for materials, since the calculated values are less than the permissible stress for rubber - 5 MPA [17].
Figure 2. Graphs of changes in contact voltages between copper conductors – conductors insulation for cables: a) with twisting; b) without twisting.

The greatest contact stresses in twisted cables occur in TPGs with a large cross section. For cables without twisting, the highest contact stresses are in TPG with a smaller cross-section (Figure 3). For the pairs considered above (Figure 2.3), the values of contact stresses vary from 0 to 2 MPa. In this case, the condition of strength for contact strength is also fulfilled; according to the reference book [17], the allowable bearing stress is 2 MPa.

Figure 3. Contact voltage sheath insulation - cable TPG insulation: a) with twisting; b) without twisting.

The regularity of the change in contact voltages for twisted cables is not observed when the insulation of the conductors is in contact with each other (figure 4a). The regularity that conductors with a smaller cross-section have large values of contact voltages does not remain when the conductors are in contact with each other for cables without twisting (figure 4b).
Figure 4. Contact voltage between insulations of TPG cable: a) with twisting; b) without twisting.

For 4x6 cables with twisted conductors, the values of contact voltages in contact with the cylinder are large (Figure 5a). For other cross-sections, the stress values have slight deviations from each other. Straight-free cables with a smaller cross-section have higher stress values in contact with the cylinder, on which the cable is bent (Figure 5b). The contact stresses have minimum values for cables with a large cross-section of conductors in a pair of cable sheath - rigid cylinder.

Figure 5. Contact voltage cable sheath - rigid cylinder.

The analysis of the stress-strain state of the cable shows that the contact stresses for pairs of copper conductors - conductor insulation, sheath insulation - TPG insulation for twisted cables increases with an increase in the cross-section of the conductors. For cables without twisting, the contact voltages for the same pairs are higher for conductors with a smaller cross-section. The values of contact voltages for a pair of TPG insulation - TPG insulation are higher for conductors with a smaller cross-section for twisted cables. This is due to the fact that a small contact area of the conductor has more load. For a cable without twisting for the same pair, it depends on the total area of the conductors. The larger the area of the cores, the greater the contact stresses. On average, the contact voltages for twisted cables are twice as high as for cables without twisting. This explains the appearance of additional stresses in the cable when twisting its elements.

In the event of relative shifts or its absence, it is possible, taking into account the stress-strain state and using work on cables [18-21], to select more durable materials for the elements of the cables.
4. Conclusion

For the first time, the calculation of the stress-strain state of cables with and without twisting has been performed using the Ansys program. The calculations made it possible to assess the stress-strain state of cables during bending and the contact strength of the cable structure elements. Comparison of the stress-strain state of twisted and non-twisted cables shows that the contact voltage is twice as much in twisted cables. Depending on the purpose and operating conditions at the design stage, one can choose the optimal dimensions and materials for the cable structure. Calculations in Ansys simplify calculations and give an overall picture of the stress-strain state of cables. It is impossible to solve this problem analytically.

From the results obtained, the conclusion can be made on the influence of structures with and without twisting on the contact stresses between the cable elements. They show also that the computer simulation is well correlated with physical studies in [18]. The results of this work can be used to create reliable cable structures.

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