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Scientific and methodological support for tower structures creation and improvement

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Abstract. In accordance with the decree of the President of the Russian Federation No. 899 of July 7, 2011, a list of critical technologies has been approved in our country, among which there are “technologies for creating energy-saving systems for the transportation, distribution and energy use” [1]. First of all, we are talking here about electrical energy, and in the composition of these systems it is possible to distinguish not only the electrical part, but also the component associated with the construction infrastructure organization. For the economy development in the technological area under consideration, appropriate scientific and methodological support is necessary, personnel who have mastered this support, then the formation of new or the use of the existing relevant organizational structures in the ministries of construction and energy, in the design business and in production, and ultimately all of the above-mentioned follows consolidate at the laws and standards’ level. The place of the authors’ research in this development strategy is the development of scientific and methodological support for the creation of tower structures for energy sector. The intermediate result of these studies is the monograph [2]. The topic was further developed in the articles [3-16].

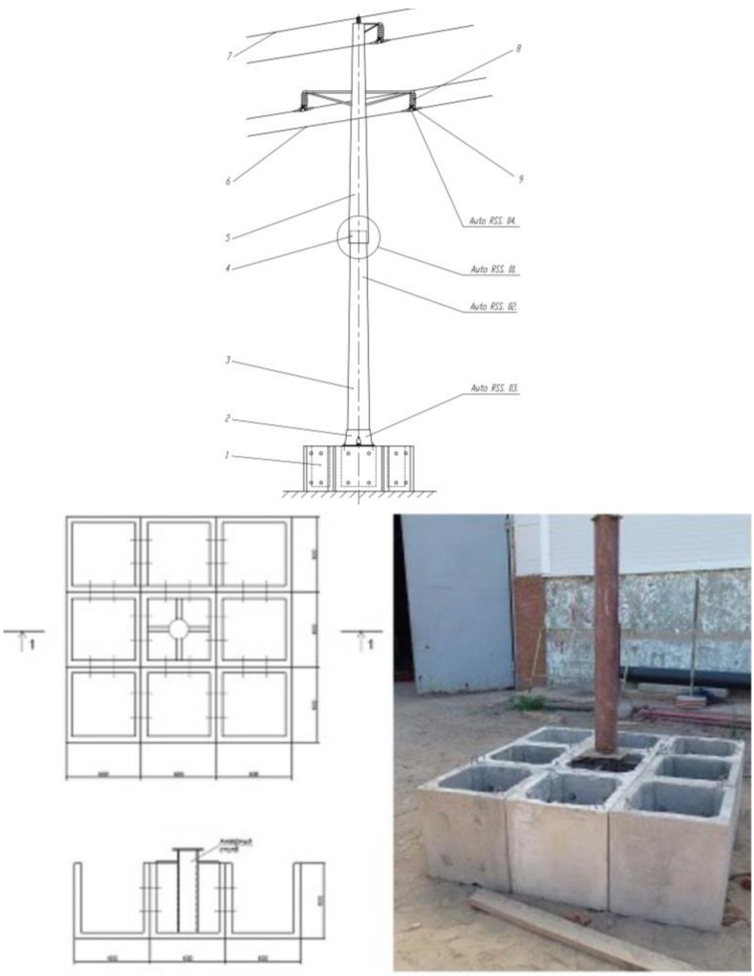
1 Introduction

By scientific and methodological support, we mean a set of theories, hypotheses, models, methods, techniques and experimental and regulatory framework, built into a logically consistent interconnected structure that gives a possibility to create, introduce into production and operate new, more advanced products. In our case, these are the tower structures for the energy sector. This understanding of the issue implies the presence of a certain sequence of actions, the beginning of which is fundamental research, and the end is the use of this sequence results in the form of mass production for mass consumption. Applied research, experimental design, creation of technical and technological regulations, other regulatory documents, etc. can serve as the sequence stages.

2 Main part

The traditional approach to the design of tower structures is a separate consideration of its elements and the solution for each of them a certain set of particular engineering problems.

In contrast to this approach, the fundamental principle of the proposed scientific and methodological support is the joint consideration of the tower structure, as an integral system, in the form of a trunk (steel or reinforced concrete), which gives the most general idea of the structure, foundation (usually reinforced concrete), base soil, all kinds of docking points, created taking into account the conditions of their work under load and purpose, as well as the load-bearing elements of the electrical part - wires, suspensions, etc. The listed tower structures are illustrated in Fig. 1 on the ETL support example.



a) b)

Fig. 1. Information diagram of the research of tower structures: a) ETL support (1 - foundation; 2 - support node; 3 - the lower part of the barrel - a tubular rod of a larger diameter; 4 - joint of tubular rods of different diameters; 5 - the upper part of the barrel - a tubular rod of a smaller diameter; 6, 7 - current-carrying wires performing a power carrying function; 8 - insulator; 9 - assembly for attaching wires to the insulator); b) general diagram and view of the "support stand-foundation-base soil" system

Nevertheless, the main provisions of the traditional approach in this consideration are preserved in the form of an initial approximation to determine the optimal structural parameters of a structure, and for this, in the previously published works of the author, it was developed:

1 - for a solid-walled structure shaft - pos. 3.5 (Fig. 1, a) - the calculated shear model and the mathematical apparatus for finding the stress-strain state (SSS) based on the A.A. Umansky's theory improvement, on the basis of which an engineering method for calculating forces and stresses was further obtained, which is implemented in software «AutoRSS.02» [4];

2 – for the support unit - pos. 2 (Fig. 1) - it was proposed to replace the supporting ribs made of plates with a special conical insert of optimal shape (a patent was obtained [3]), the effectiveness of which was substantiated by the calculation, on the basis of which an engineering method for calculating forces and stresses was further obtained, which was implemented in software «AutoRSS.03» [5]; in addition, for the case of a flange joint, a computational model of a stiffener and a mathematical apparatus for finding its SSS are proposed;

3 – for a docking unit of two pipes of different diameters - pos. 4 (Fig. 1) – the new solutions are proposed in the form of a pipe-in-pipe joint, a computational model and mathematical apparatus for finding the stress-strain state of such a joint, and on the basis of this, an engineering technique for calculating the forces and stresses in it has been developed, which is implemented in software «AutoRSS.01» [6];

4 – for the docking station of wires with the mast of the power transmission line support - pos. 9 (Fig. 1) - a design model of the joint was proposed, on the basis of which the optimal shape of the transition element between the wire and the insulator was obtained (a patent was obtained [7]), and then an engineering method was developed for calculating the forces and stresses in the joint, which was implemented in software «AutoRSS.04» [8];

5 – for the foundation - pos 1 (a collapsible foundation with high performance was proposed (a patent was obtained), in the subsequent chapters, on the basis of computer modeling, its joint work with a steel support was studied).

At the first stage of creating the authors' approach, a research problem was considered on the joint work of a steel support-support and a precast reinforced concrete foundation (a patent was obtained [9]) by an experimental method and using a mathematical FEM - modeling [4].

Experimental and theoretical studies of the system (Fig. 1, b) showed that its limiting state occurs simultaneously due to the loss of strength of the leg member (in the form of the residual plastic deformations appearance) and the base soil. At the same time, the concrete elements' destruction of the cells and their connections was not recorded. It was also found that the rack joint work with the foundation is ensured. The compliance of the conjugation of the prisms that make up the foundation did not have a significant effect on the SSS of the system as a whole. Based on the above-said, it is recommended that a new type of collapsible foundations [9] be used in real conditions in the construction of cellular towers PMG-30.

At the next stage of the research, apparently for the first time, a joint consideration of the tower structure as an integral system was carried out in the form of computer modeling in [10]. It considers a multifaceted steel support as a trunk ETL for 10 kV according to series 3.407.2-181.09 (Fig. 2a).

The foundation is also collapsible, but it is made according to another patent [9] (Fig. 1, b). Unlike the previous version, it consists of concrete prisms not with a square, but a triangular base.

The essence of the modeling technique for the system under consideration was as follows:

1 – determination of structural loads (based on provisions BC 20.13330.2011 "Loads and Impacts" and PUE-7);

2 – static calculation of a steel support separately, as a rigidly embedded cantilever column of a hollow section (as a result of this, the load on the foundation edge is determined);

3 – determination of the size of the foundation base on the load on it;

4 – modeling of a single system "support-foundation-soil", the SSS definition in it;

5 – verification of system elements for strength, stability and deformability (respectively, for the 1st and 2nd groups of limiting states).

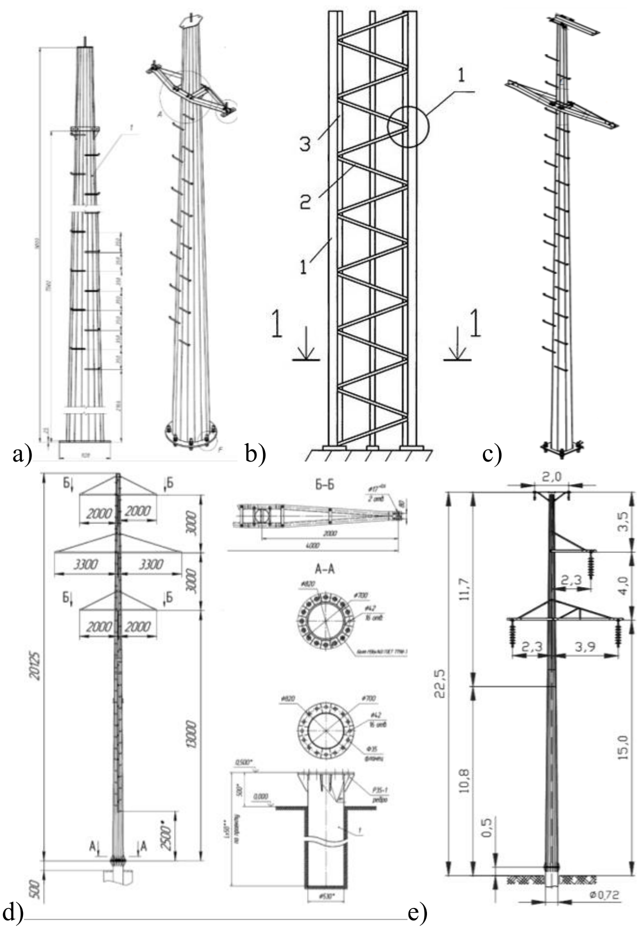


Fig. 2. Types of simulated support structures ETL: a) support anchor-angle mark SM10AU; b) three-guard lattice support of stamps STR10AU, STR10P, STR35P, STR110P; c) double-chain intermediate support PM35-2f; d) single-chain intermediate support PM110-3FT

The "support-foundation-soil" system includes the elements formed from the materials with qualitatively and quantitatively different physical and mechanical properties. For their modeling, the corresponding types of finite elements and the laws of deformation in software «Ansys» were tested. Their list is presented in Table 1.

The development of the research carried out was a comparative analysis of the static operation of various types of steel supports for the power lines based on computer modeling of the system “support-foundation-foundation soil” [11]. Two structural types of ETL steel supports were considered: in the form of rods-shells of a closed profile with a wall thickness variable in height and in the form of a lattice triangular structure manufactured according to the patent [12]. At the same time, both types of supports were considered for three different heights - for 10 kV power lines - with a height of 9-11 m, 35 kV - with a height of 20.6 m and 110 kV - with a height of 22.5 m, respectively. Thus, a total of eight support options have been considered. The general view of the listed supports is shown in Fig. 2.

The following are the results of computer modeling using the example of supports OP-1 and OP-2. General form FE- models are shown in Fig. 3.4.

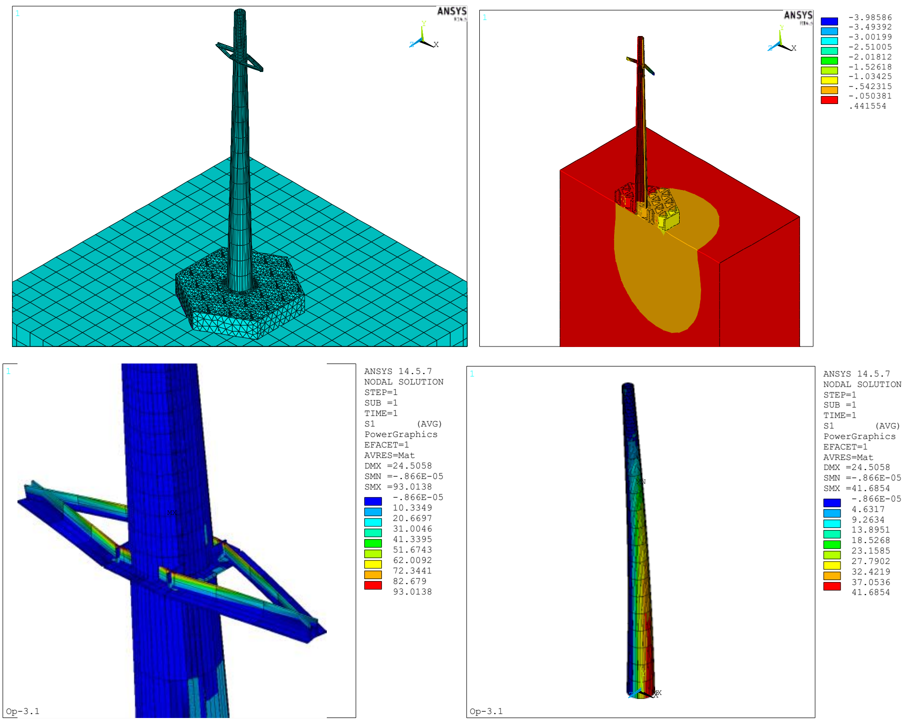


Fig. 3. SSS assessment for the systems "support-foundation-soil" type OP-1

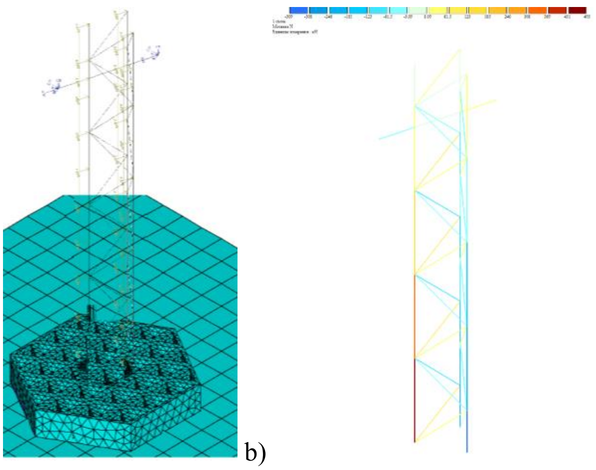
SSS analysis shows that the strength and stability of solid-wall and lattice sections’ structures is ensured. The corresponding utilization rates turned out to be close to - 0.912 and 0.837. Despite this, the support OP-1 (continuous) has significant underutilized reserves of strength in comparison with sometimes OP-2 (lattice). Consequently, in the lattice structure, the forces are distributed more evenly and therefore, one should reasonably expect a noticeable saving in metal due to the use of this constructive solution for the construction of tower structures, especially for high heights (over 20 m). The results of determining the equivalent stresses in the considered supports are shown in Fig. 3 (OP-1) and Fig. 4 (OP-2).

In further publications it is planned to highlight the simulation results supports’ SSS of all series, on the basis of this, to determine the rational area of trihedral lattice supports application [12], as well as to obtain an engineering method for their calculation and design.

As challenging as the study of ETL supported systems, is the question of developing methods for designing wind turbine towers. This is the subject of our publications [13-16].

In these articles, the joint static work of the elements of the building system "combined tower - reinforced concrete foundation - foundation soil" is considered by the WTT example. At the same time, a combined tower in the article means a high-rise structure, consisting of two parts: the lower one is made of pipe-concrete, the upper one is in the form of a thin-walled rod-shell of a closed profile. In both cases, a weakly tapered pipe acts as a shell. Analysis of the literature has shown that there is currently no complete methodology for calculating such a system. And when developing it, the following factors should be taken into account most fully:

– physical nonlinearity of material properties;
– geometric nonlinearity of system elements (blades, etc.);
– cyclic fatigue of materials - steel and concrete;
– dynamic effects;
– resonant phenomena;
– friction between concrete and steel shell and between concrete and soil.



a) b)

Fig. 4. Finite element model of the "support-foundation-soil" system: a) for support OP-2; b) results Mh, kN

It is not possible yet to analytically describe the influence of all these factors, which is reflected in the existing design standards of WTT [17,18] and educational literature [19]. However, it is possible to use a powerful tool - computer simulation in software «Ansys» for this. In the article [11], we have already used this tool to study the joint operation of the system "steel support of power lines - foundation - foundation soil". Moreover, in contrast to it, the system considered here takes into account the following features:

– wind load on the swept area of rotating blades, an important characteristic of which is not the pressure, but the wind flow speed;
– presence of concrete at the tower bottom;
– frictional forces between steel shell and concrete core.

The last two circumstances transform the lower part of the tower barrel into a so-called tube-concrete structure, which, due to a number of advantages [20, 21], significantly increases the operational properties WTT, including strength, reliability and durability. Use pipe concrete as part of a combined tower WTT, most likely, the author proposed for the first time.

As an example, let us consider WTT Acciona AW-82/1500 class IEC IIIB for 1,5-2 MW from [22,23] - Fig. 5.

The foundation for the tower is made of massive cast-in-place concrete of class B25, reinforced with steel reinforcement in terms of a circular cross-section foundation.

Structural WTT loads take into account the load safety factors γ_f=1,0 and the reliability of the structure γ_n=1,0. Table 2 GOST P 54418.1-2012 8 design cases are registered for WTT calculation. The most characteristic is the first one - "Electricity generation" - calculation using the model of normal turbulence.

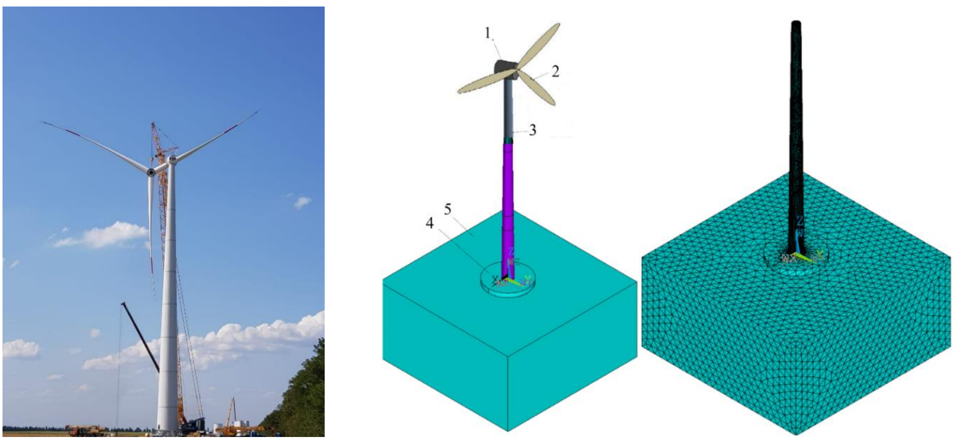
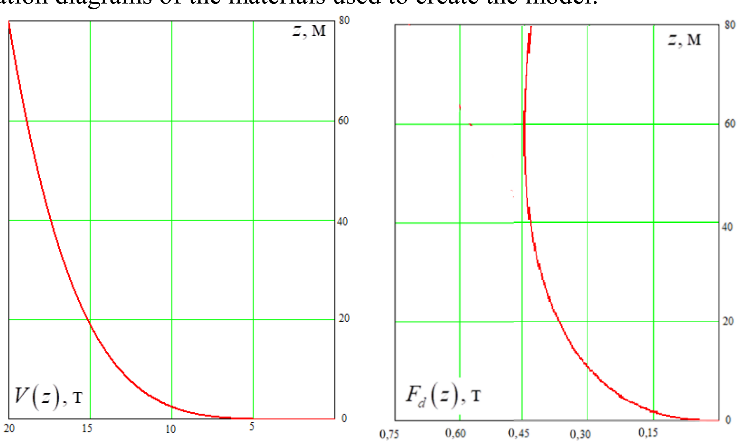


Fig. 5. Structural diagram (computer model in software «Ansys») WTT for 2 MW: 1 - nacelle; 2 - rotor blades; 3 - tower; 4 - collapsible foundation; 5 - base soil

The considered design includes the elements formed from the materials with qualitatively and quantitatively different physical and mechanical properties. Fig. 7 shows the deformation diagrams of the materials used to create the model.



a) b)

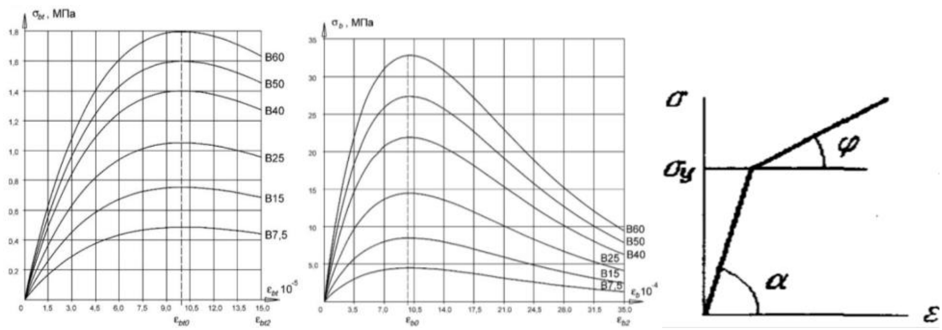
Fig. 6. Distribution of wind speed *V* (a) and wind load F_d (b) in height

Mathematical expressions describing the diagrams in Fig. 8, a-b are given in the article [24]. The bilinear diagram of kinematic hardening was taken as the deformation law for steel (see Fig. 7, c). The law assumes that in the diagram «σ-ε» the sum of opposite sign stresses during loading-unloading is always equal to twice the value of the yield stress σ_y, that is, the Bauschinger effect is taken into account. The model is recommended for elastoplastic problems with small deformations of the material satisfying the von Mises yield condition.

Thus, the physical deformation law of a thin-walled shell was described by four parameters: the elasticity modulus E=206·10^3 MPa, tangent module E'=75·10^3 MPa, yield point σ_{el}=355 MPa and Poisson's ratio ν=0.3.

To determine the dimensions of the foundation, the tower was previously calculated as a rigidly embedded cantilever post, that is, without taking into account the foundation and base soil:

As a result, loads on the foundation edge were obtained, according to which, using the formulas BC 22.13330.2011 "Foundations of buildings and structures", the required dimensions of the foundation were calculated: 18 × 18 m, height 1.8 m.



a) b) c)

Fig. 7. Diagrams of materials' deformation: a) curvilinear diagram of Radaikin O.V. when stretched [24]; b) also - when compressed; c) two-line diagram, kinematic hardening with the Baushanger effect.

The results of determining the equivalent stresses in the tower are shown in Fig. 8.

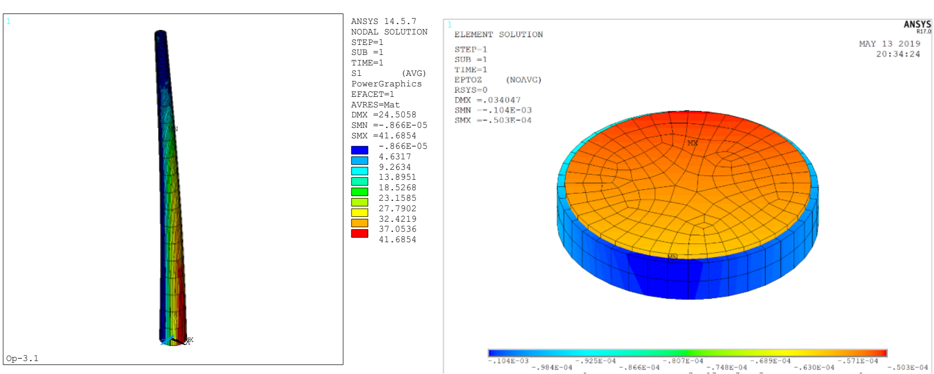


Fig. 8. Results of the tower computer simulation

Comparison of the calculation results with the data of [22] showed that the breaking load of the tower increased by 37% due to filling its lower part with concrete, which indicates the proposed solution effectiveness. In this case, the destruction of the tower with and without a concrete core occurred from the loss of the steel shell local stability at the junction of the tower with the foundation (with a compressed zone). The results obtained on the bent pipe concrete efficiency correlate with the experimental data of [25], which indicates the validity of the approach proposed in this article. A more detailed consideration of the stressed deformed soil massif, foundation, contact interaction between the concrete core and the steel shell will be devoted to subsequent publications.

3 Conclusion

1. In this publication, a generalization of the research previously carried out by the authors has been made, which allows us to speak of an integral scientific and methodological support for the creation of new, more advanced tower structures for the energy sector. This support includes a set of theories, hypotheses, models, methods, techniques and experimental and regulatory framework, built into a logically consistent interconnected structure that gives an opportunity to create, introduce into production and operate new, more advanced products [26].
2. Two of the most representative types of tower structures - supports ETL and supports WTT – have been considered; each in the form of a single "support-foundation-foundation soil" system. This approach made it possible to take into account the joint work of all the system components and the redistribution of efforts between them, taking into account the physical nonlinearity of the materials' properties.
3. In the perspective of the author, a small group of generalized (integral) criteria for the onset of one or another limiting state for the entire system under consideration "support-foundation-foundation soil" has been developed, which, in the authors' opinion, can be done on the basis of the reliability theory and the energy theory of deformation and destruction of construction facilities and structures.

References

1. Decree of the President of the Russian Federation of July 7, 2011 No. 899 "On approval of priority directions for the development of science, technology and technology and the list of critical technologies of the Russian Federation".
2. N.F. Kashapov, L.S. Sabitov, Stress-strain state of thin-walled shell rods of a closed profile (Publishing house: University, Kazan, 2019).
3. I.Z. Gatiyatov, L.S. Sabitov, I.L. Kuznetsov, V.Yu. Yudin, A.K. Mezikov, A.I. Nikiforov, Patent for invention RU 2620625 C1, 29.05.2017. Application No. 2016130488 from 25.07.2016. Joint assembly of pipes of different diameters:
4. L.S. Sabitov, I.L. Kuznetsov, I.R. Badertdinov, O.V. Radaykin, Bulletin of civil engineers **6 (71),** 37-44 (2018).
5. L.S. Sabitov, I.L. Kuznetsov, V.Yu. Yudin, Certificate of registration of the program for PC RU 2017662991, 22.11.2017. Application No. 2017617847 from 21.07.2017. «AUTORSS.03»
6. L.S. Sabitov, I.L. Kuznetsov, S.I. Sabirov, Certificate of state registration of the program for PC №2013611451 from 18.01.2013 «AutoRSS.01». Application No.2012661265 from 18.12.2012.
7. I.L. Kuznetsov, L.S. Sabitov, Yu.M. Strelkov, A.K. Mezikov, A.I. Nikiforov, Patent for invention RU 2615178. Russian Federation. Method of protecting steel-aluminum wires of overhead power lines from fatigue vibrational damage at the exit from the supporting clamp /; declared 02/10/2016; publ. 04/04/2017. Bul. No. 10. 12 p.

8. L.S. Sabitov, I.L. Kuznetsov, Yu.M. Strelkov, Certificate of registration of the program for PC RU 2017662990, 22.11.2017. Request No. 2017617846 from 21.07.2017. AUTORSS.04
9. L.S. Sabitov, I.L. Kuznetsov, D.M. Khusainov, S.I. Sabirov, Z.R. Akhunova, Yu.M. Strelkov, Patent for invention RU 2633604 C1, 13.10.2017. Application No. 2016134679 dated 08.24.2016. Collapsible foundation under support
10. Yu.M. Strelkov, L.S. Sabitov, N.F. Kashapov, I.R. Gilmanshin, O.V. Radaykin, Energy saving. Science and education. Collection of the international conference reports, 424-434 (2017).
11. Yu.M. Strelkov, O.V. Radaykin, L.S. Sabitov, I.L. Kuznetsov, Comparative analysis of the power lines steel various types of supports' static operation based on computer modeling of the "support - foundation - foundation soil" calculation of structures **1 (282),** 71-79 (2019).
12. L.S. Sabitov, I.L. Kuznetsov, I.R. Badertdinov, Yu.M. Strelkov, Patent for invention RU 2641354 C1, 17.01.2018. Application No. 2016145699 dated November 22, 2016. Triangular lattice support.
13. L.S. Sabitov, Yu.G. Konoplev, O.V. Radaykin, Bulletin of the Volgograd State University of Architecture and Civil Engineering. Series: Building and architecture **1 (78),** 345-355 (2020).
14. L.R. Mayilyan, M.A. Zubritskiy, O.Yu. Ushakov, L.S. Sabitov, Construction materials and tools **3 (1),** 14-20 (2020).
15. Yu.M. Strelkov, L.S. Sabitov, I.L. Kuznetsov, O.V. Radaykin, L.Sh. Akhtyamova, Effective structures, materials and technologies in construction, 116-127 (2019).
16. L.S. Sabitov, Yu.G. Konoplev, Scientific and technical bulletin of the Volga region. **12,** 210-213 (2019).
17. K.N. Umesh, P. Bharath, Mohamed Farzath Iyaz, Mechanical and Production Engineering **4 (10),** 13-17 (2016).
18. Ch. Chantharasenawong, P. Jongpradist, S. Laoharatchapruek, *Preliminary Design of 1.5-MW Modular Wind Turbine Tower,* AEC17, 2nd TSME International Conference on Mechanical Engineering, 19-21 October 2011.
19. E.M. Fateev, Wind engines and wind turbines (Selkhozgiz, Moscow, 1948).
20. V.V. Elistratov, A.A. Panfilov, Design and operation of non-traditional and renewable energy installations. Wind turbines: a tutorial (SPb., Polytechnic University, 2011).
21. I.A. Duvanova, I.D. Salmanov, *Concrete columns in the construction of high-rise buildings and structures*, Construction of unique buildings and structures. SPb., Peter the Great St. Petersburg Polytechnic University together with the Venture Production, Research and Design Institution **6 (21)**, 89-103 (2014).
22. A.I. Kikin, R.S. Sanzharovsky, V.A. Trull, Structures from steel pipes filled with concrete (Stroyizdat, Moscow, 1974).
23. M.E. Deich, Technical gas dynamics. 2nd edition, revised (Gosenergoizdat, Moscow – Leningrad, 1961).
24. O.V. Radaykin, Bulletin of civil engineers, SPb., SPbSACEU **6,** 71-78 (2017).
25. V.I. Efimenko, Strength and deformations of flexible pipe-concrete elements: PhD Thesis, Poltava, 1989.
26. L.R. Mailyan, O.V. Radaykin, L.S. Sabitov, A.L. Mayilyan, S.B. Yazyev, Yu.M. Strelkov, The act on the scientific research results' implementation on the topic:

"Development of scientific and methodological support for the design and construction of new building systems" steel tower (support) -reinforced concrete foundation-soil foundation", issued by JSC "Wind power separate generating company" organization of the state corporation Rosatom, No. 347-70 / 478 of 25.02.2020.

27. R.K. Mukhametrakhimov, L.V. Lukmanova, Civil Enginering Journal **102 (2),** 10206 (2021).
28. R.K. Mukhametrakhimov, L.V. Lukmanova, IOP Conference Series: Materials Science and Engineering. Institute of Physics Publishing **890 (1)** 2020.