Efficiency of Implementing Domestic Innovative High-strength and High-temperature Steel-aluminum Conductors

PJSC "Rosseti" maintains 44 thousand km of new conductor types or 1% of the total conductors' length (4.5 million km). Among these conductors are self-supporting insulated wires of various modifications (more than 41 thousand km or 0.9% of the total conductors' length) and bare conductors (less than 3 thousand km or less than 0.1% of the total conductors' length). In addition, Russian modern power grid is characterized by physical deterioration and obsolescence of equipment. As a result, low energy efficiency of power facilities takes place. The most important indicator of power system efficiency is the level of energy losses. With the growing power losses in electrical networks, the number of urgent problems increases. Reconstruction and technical re-equipment of electrical networks, application of advanced technical developments in design solutions, implementation of modern technologies and materials increasing reliability, durability and maintainability of power transmission lines are among these problems.

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INTRODUCTION

As of today, finding the ways for improving power grid energy efficiency is a pressing issue. One of the ways is the use of innovative conductors with better characteristics than steel-aluminum conductors. Increased transmission capacity, mechanical strength, resistance to high temperatures and resistance to aging and aggressive ambience are among these characteristics.

Power losses optimization in electrical networks requires accelerated implementation of the following activities:

– upgrading power grid equipment and implementation of new energy-saving technologies;
– conducting research, design and development works related to calculations, analysis, rationing and reduction of power losses in electrical networks.

The paper systematizes studies carried out in the framework of the project for developing high-temperature and high-strength conductors according to the relevant Agreement with PJSC "Rosseti". The task of the studies was to confirm the possibility of solving the basic problems of overhead lines construction and operation through the joint use of ASHT/ASHS conductors together with overhead ground wires, when keeping cost at a level of steel-aluminum conductors. The results are shown in table 1 and described in this paper.

Table 1. Possibilities of solving the main problems of overhead lines construction and operation through the joint use of ASHS / ASHT conductors

Problem	Solution based on ACSR application	Solution based on ASHS / ASHT application	Confirmation
Reducing corona losses and noise level, without increasing conductor's diameter	–	+	Experimental confirmation of "R&D Center "FGC UES", JSC and VDE (Germany)
Increasing lightning protection and resistance to short-circuit currents	–	+	Experimental confirmation of "R&D Center "FGC UES", JSC and VDE (Germany)
Significant reduction of elongation in operation	–	+	Experimental confirmation of "R&D Center "FGC UES", JSC
Reducing vibration, galloping and oscillations self-damping, while keeping conductor diameter	–	+	Experimental and computational confirmation of VSTU, JSC "VNIIZHT" and MPEI
Increasing span length and (or) sags, without increasing conductor's diameter	–	+	Design solutions
Replacing the conductor on the existing transmission poles, decreasing the load on all elements of overhead line and (or) increasing its transmission capacity	–	+	Design solutions
Decreasing wind pressure while keeping conductor diameter	–	+	Computational confirmation of VSTU and MPEI
Replacing the conductor in the ring networks and decreasing conductor diameter	–	+	Design solutions
Reduction of icing, while keeping conductor diameter	–	+	Computational confirmation of VSTU and MPEI
Keeping transmission capacity in areas with high air temperatures and solar activity, without increasing conductor's diameter	–	+	Design solutions and computational confirmation of VSTU and MPEI

RESEARCH OF CORONA DISCHARGE OCCURRENCE AS A FUNCTION OF VOLTAGE

An important point when using conductors with less diameter is the risk of corona losses and noise level enhancement. "R&D Center "FGC UES", JSC and then VDE (Verband der Elektrotechnik, Elektronik und Informationstechnik) conducted four studies for testing this problem. At the first stage, two conductors of the same diameter (18.8 mm) were taken for comparing and studying corona discharge. In total, four conductors were used within the experiment (Table 2). The tests were carried out in accordance with IEC 61284 recommendations.

Based on comparative tests results obtained at "FGC UES" R&D Center, it was established that ASHS 197/55 conductor manufactured by "Energoservis", LLC has corona discharge voltage (142.2 kV) by 5.7% higher than ACSR 185/29 conductor (134.5 kV) with the same diameter (18.8 mm).

Similar tests were carried out for ASHS 216/33 and ACSR 240/32 conductors with different diameters. Based on comparative tests results ACSR 240/32 conductor (21.6 mm in diameter) and ASHS 216/33 conductor (18.5 mm in diameter) have the same corona discharge voltage. However, continuous permissible current of the conductors being compared differs significantly (510 A for ACSR 240/32 conductor, 689 A for ASHS 216/33 con-

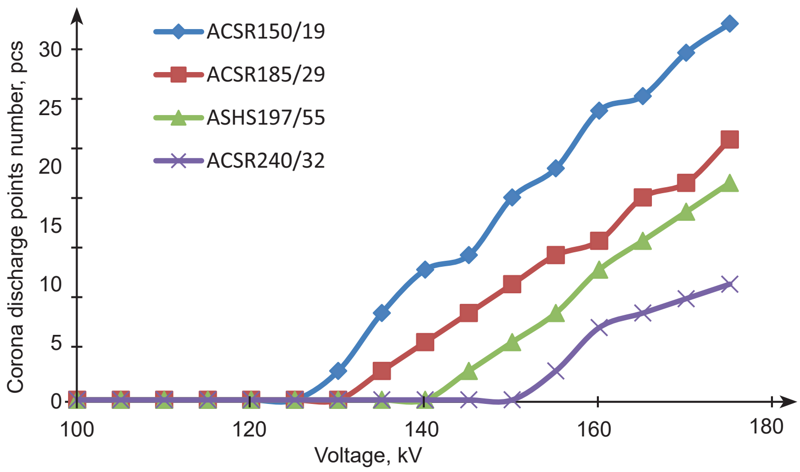

Fig. 1. Dependence of corona discharge points number on voltage

Table 2. Technical data of the tested conductors

Conductor model	Conductor diameter (external), mm	Number of aluminum wires in the conductor, pcs	Diameter of outer layer wires, mm	Continuous permissible current
ACSR 150/19	16,8	24	2,8	450
ACSR 185/29	**18,8**	**26**	**2,98**	**510**
ASHS/ASHT 197/55	**18,8**	**28**	**3,45**	**561/943***
ACSR 240/32	21,6	24	3,6	605

* t_{max}= 70°C for high-strength steel-aluminum conductors and t_{max} = 150°C for high temperature steel-aluminum conductors.

ductor (τ = 70 °C), and 1040 A for ASHT 216/33 conductor (t = 150 °C)).

The test voltage for inspecting visible corona on 220 kV overhead lines was determined by FGH Engineering & Test GmbH laboratory as 167.7 kV (phase voltage) and "R&D Center "FGC UES", JSC laboratory as 160.0 kV (phase voltage).

The test procedure in both laboratories was identical. Voltage levels and registered results when testing visible corona are shown in Table 3.

The tests of new ASHT 216/33-1 high-temperature conductor for visible corona inception were carried out in "FGC UES" R&D Center national testing laboratory and FGH Engineering & Test GmbH German testing laboratory. The tests were performed according to IEC 61284:1998 method and produced similar results for corona ignition voltage and streamer inception of corona discharge.

The differences in the results occur due to the conditions of conductor samples when testing. Conductor samples were taken directly from the drum when testing in FGH Engineering & Test GmbH laboratory. As to the tests of "FGC UES" R&D Center laboratory, the surface of conductor samples was additionally cleaned of dirt and small defects (related to the transportation and unwinding) that could cause corona discharge. It was done for studying immunity of new ASHT 19.6-216/33-1 conductors to corona discharge inception.

According to the tests results obtained by the laboratories, it was determined that streamer inception of corona discharge for ASHT 19.6-216/33-1 conductor is at the level of 139.7–150 kV (phase voltage). Based on corona discharge level, this conductor is recommended for use in domestic and foreign 110, 115, 138 and 150 kV electrical networks (in some cases the conductor can be used up to 220 kV).

Table 3. Results of visible corona discharge registration for ASHT-216 / 33-1 conductor

FGH Engineering & Test GmbH		"R&D Center "FGC UES", JSC	
Test voltage, kV	**Presence of visible corona discharge**	**Test voltage, kV**	**Presence of visible corona discharge**
41,9	Absence of visible corona discharge	100,0	Absence of visible corona discharge
55,9		105,0	
70,0		110,0	
83,8		115,0	
97,8	Corona ignition voltage	120,0	
111,8		125,0	
125,7		130,0	Scant glow of isolated corona discharge points
139,7	Streamer inception of corona discharge	135,0	
153,7		140,0	Stable ignition of corona discharge
167,7			
Increment — 10% of rated test voltage 167.7 kV (phase voltage)		150,0	Streamer inception of corona discharge
		155,0	
		160,0	
		165,0	
		Increment — 5 kV of rated test voltage 167.7 kV (phase voltage)	

Table 4. Calculated specific corona losses in good weather (220 kV overhead line)

Phase construction (conductor model; conductor diameter)	Annual average losses change
ACSR 240/32, Ø 21,6 mm	+ 26,67%
ACSR 300/39, Ø 24,0 mm	0,00%
ACSR 330/43, Ø 25,2 mm	–13,33%
ASHS 317/47, **Ø 22,3 mm**	–13,33%
ASHS 295/44, **Ø 21,5 mm**	–6,67%

Table 5. Calculated specific corona losses in good weather (330 kV overhead line with split phase consisting of 2 conductors with 40 cm spacing)

Phase construction (conductor model; conductor diameter)	Annual average losses change
2 × ACSR 300/39, Ø 24,0 mm	+ 18,52%
2 × ACSR 400/51, Ø 27,5 mm	0,00%
2 × ASHS 317/47, **Ø 22,3 mm**	–7,41%
2 × ASHS 295/44, **Ø 21,5 mm**	+ 3,70%

The calculated specific corona losses in good weather are presented in Tables 4, 5. Table 6 gives the average characteristics of overhead transmission lines in Russia.

ASHS conductors have advantages in terms of smaller corona losses in comparison with ACSR conductors of the same diameter. Also, ASHS conductors have comparable corona losses in regard to ACSR conductors with larger diameter and similar electrical and mechanical characteristics.

STUDY OF WIND PRESSURE

The direct influence of wind on overhead lines operation is its pressure on the conductors, ground wires and poles. In addition, wind increases conductors' tension through creating a transverse load. Additional bending forces on power line poles also appear. Wind pressure can cause breakage and fall of the poles with the pull out of bad fixed foundations. The results given below proves the necessity of replacing ACSR conductors with ASHS/ASHT ones on obsolete overhead lines.

Table 6. Average characteristics of overhead lines in Russia

Voltage, kV	220	330	500	750
Average length of overhead line, km	59	88	187	250
Average diameter of ACSR conductor, mm	25,6	25,6	27,4	26,1
Possible ASHT / ASHS conductor diameter in terms of corona discharge	22,4	22,4	24,5	24

COMSOL Multiphysics software package was used for simulating airflow behavior near the conductors. The software allows engineers to solve partial differential equations. Navier-Stokes equation was the model basis:

$$\rho(u \cdot \nabla)\, u = \nabla \cdot \left[-Pl + (\mu + \mu_T)(\nabla u + (\nabla u)^T) - \right.$$
$$\left. - \frac{2}{3}(\mu + \mu_T)\,(u \cdot \nabla)\, l - \frac{2}{3}\rho k l\right] + F,$$
$$\nabla \cdot (\rho\, u) = 0,$$
$$\rho(u \cdot \nabla)\, k = \nabla \cdot \left[(\mu + \mu_T \sigma_k^*)\,(\nabla k)\right] + P_k - \rho\, \beta_0^* k\, \omega, \qquad (1)$$
$$\rho(u \cdot \nabla)\, \omega = \nabla \cdot \left[(\mu + \mu_T \sigma_\omega^*)\,(\nabla k)\right] + a\,(\omega/k)\, P_k - \rho\, \beta_0\, \omega^2,$$
$$\mu_T = \rho\, k/\omega,$$
$$P_k = \mu_T \cdot \left[\nabla u\!: (\nabla u + (\nabla u)^T) - \frac{2}{3}(\nabla \cdot u)^2\right] - \frac{2}{3}\rho\, k \nabla \cdot u,$$

where u is the air velocity; ∇ is the del operator; ρ is the air density; μ is the dynamic viscosity; k is the turbulent kinetic energy; ω is the specific dispersion rate; a, σ_ω^*, σ_k^*, β_0, β_0^* are the coefficients of turbulent flow, l is the turbulence intensity.

The two-dimensional model was used to assess the wind impact on conductors with different cross-sectional shapes. The model's geometry is shown in Figure 2.

The following boundary conditions were chosen:

– wind speed direction is perpendicular to AB:

$$\nu_{AB} = \nu_0\,; \qquad (2)$$

– pressure equals zero on BC, CD and AD faces:

$$p = 0\,; \qquad (3)$$

– the boundaries of conductor's cross section are non-deformable walls.

The simulation was carried out at different values of ν_{AB} speed, which are typical for I, III and special wind zones according to 7-th edition of Electrical Installations Code [1].

The wind load acting on the conductor across the center was calculated as the sum of pressure X-components:

$$F = \int n \cdot P\, dl, \qquad (4)$$

where P is pressure, n is the unit vector along the X-axis.

The interactions of wind and conductors depending on wind speed and type of conductors' cross-section have been compared. The following conductors with similar diameters have been used for comparison: ASHS 128/37 and ACSR 120/19; ASHS 230/32 and ACSR 240/34; ASHS 277/79 and ACSR 240/56 (the cross-section area of aluminum and steel in mm^2 represent in the numerator and denominator respectively). The calculated wind load differs from P_W^H, standard wind load on conductors and ground wires, determined according to 7-th edition of Electrical Installations Code. The difference takes place due to ignoring the following facts: wind pressure change at various heights depending on terrain, the influence of span length on the wind load, wind pressure nonuniformity along overhead line span. The used approach allows engineers to determine clearly the contribution of conductor's contour to the change of wind load.

The view of conductors' contour after crimping was obtained by modeling steel-aluminum conductor plastic deformation process in the Abaqus/Explicit module of the SIMULIA/Abaqus software (Abaqus, Inc., USA). For all ASHS conductors aluminum wires of outer layer are tightly adjacent to each other without gaps. It provides a possibility to simulate the wind impact on a single conductor with one external contour by means of COMSOL Multiphysics.

The wind pressure acting on the conductors and air velocity distribution after flowing around ACSR conductors (according to GOST 839) and ASHS conductors (according to STO 71915393 – TU 120-2012) with 230 mm^2 aluminum cross section are shown in Figures 3 and 4. A smoother contour and the smaller diameter of ASHS conductors provide the reduction of pressure zone in front of the conductor (Figure 3b) and the stagnant zone behind it (Figure 4b). The maximum pressure on ASHS conductors is less by 3.5%, while the area with increased pressure is smaller regarding to ACSR conductors. The formation of several local areas characterized by air deceleration

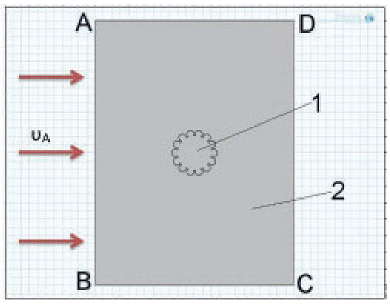

Fig. 2. Geometry of the used model: 1 – conductor cross-section, 2 – airflow

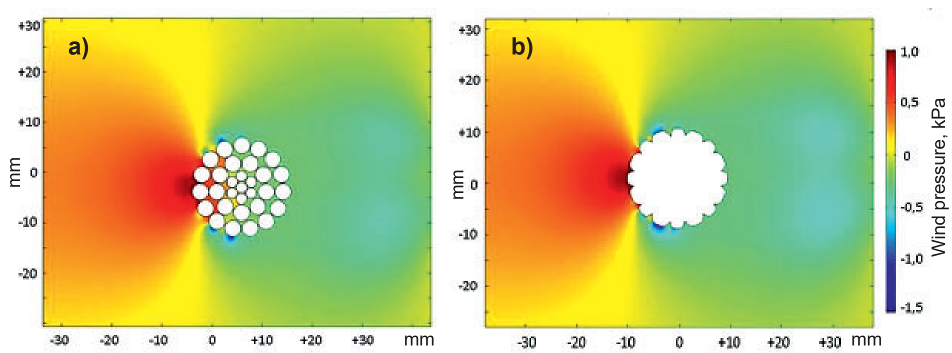

Fig. 3. Wind pressure acting on the conductors at the wind speed of 60 m/s (the first wind zone): a) ACSR 400/64; b) ASHS 477/66

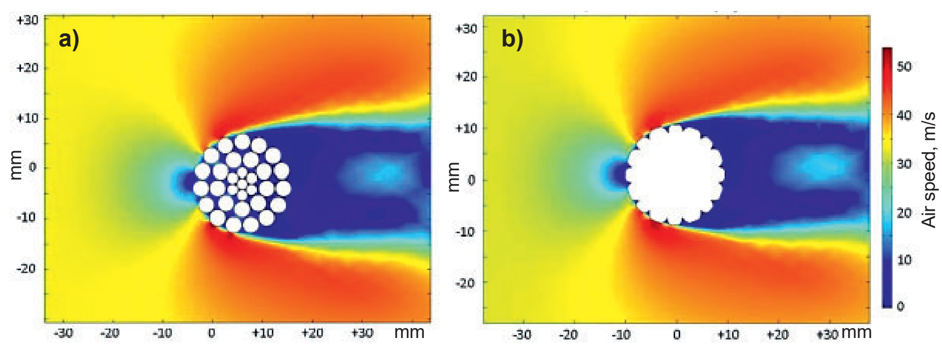

Fig. 4. Speeds distribution in the airflow at the wind speed of 25 m/s (the first wind zone): a) ACSR 120/19; b) ASHS 128/37

Table 7. Wind load for conductors with different cross-section contour depending on airflow speed

Airflow speed v_{AB}, m/s	Wind load acting on conductors, N / m					
	ASHS 128/37	ACSR 120/19	ASHS 216/32	ACSR 240/34	ASHS 277/79	ACSR 240/56
25	3,6	4,8	4,9	6,9	5,2	7,0
32	5,9	7,9	7,8	11,4	8,4	11,5
60	20,8	28,5	28,4	41,5	29,8	41,6

and reduced pressure is much more visible on the protruding turns of ACSR aluminum wires facing airflow front.

As can be seen from the data above, wind load on ASHS conductors having streamlined design is lower by 33% on the average. Reduction of wind load makes it possible to reduce the load on power transmission poles and to mount conductors with greater transmission capacity on existing towers during capital repairs. Also, the possibility to reduce the load on all elements of overhead line when keeping its transmission capacity appears.

REDUCTION OF VIBRATION LOADS AND OPERATING TENSION

Plastically crimped conductors have a number of advantages, which are usually typical for expensive conductors from profiled wires. Among these advantages are vibration loads reducing and oscillations self-damping.

Intensive gust-and-glaze loading of 6-750 kV overhead power lines is one of the urgent power industry problems in the countries with relevant weather conditions. Plastically deformed ASHS conductors have almost smooth outer surface (close to conductors from segmented Ω- and Z-shaped aluminum wires). Due to this, conductors vibration and galloping as well as ice coating can be reduced. At the same time, ASHS conductors should have greater torsional rigidity, reduced galloping probability, increased resistance to vibration, and self-damping ability even in comparison with conductors from segmented Ω- and Z-shaped aluminum wires, because ASHS conductors have developed contact surface of adjacent wires not only inside one layer, but also between layers [2].

Plastic deformation of conductors not only significantly increases the mechanical strength, but also several times reduces elongation during operation (regardless of the metal). The corresponding tests with products from different metals (from steel to copper) were carried out in JSC "VNIIZHT" and "R&D Center "FGC UES", JSC. Complete study is presented in [3].

INCREASE OF SPAN LENGTH WHEN CONSTRUCTING NEW FACILITIES

The plastically crimped ASHS and ASHT conductors allow engineers to increase the distance between overhead line poles up to 40% of the standard span (in the absence of restrictions related to line route). It is an urgent task when constructing new overhead lines.

For example, the comparative analysis of the span length for ASHS 128/37 conductor mounted on 110 kV overhead line and ACSR 120/27, TACSR 120, ACSR 120/19 conductors having the same cross-section and diameters has been fulfilled. Because of ASHS 128/37 conductors application the span length can be increased from 212 to 294 m compared with ACSR 120/27 conductor. ASHS 128/37 conductor has a higher content of steel (the ratio between aluminum and steel cross-section area is 3.45 for ASHS 128/37 conductor and 4.3 for ACSR 120/27 conductor), an equal diameter (15.2 mm), and increased transmission capacity (by 8% higher).

An example of ASHS/ASHT conductors application efficiency is the initial project of 150 kV Murmanskaya overhead line (Table 8 and Figure 5). ASHS 258/73 conductor is the most effective option when constructing new overhead line. In its turn, ASHS 216/33 conductor is the optimal option when reconstructing overhead line (replacing conductors on existing power transmission poles). 220 kV overhead line project developed by "FGC UES" R&D Center is also an illustrative example.

Proper use of developed conductors in combination with ground wires (TU 062-2008) or fiber-optic ground wires (TU 113-2013) for new construction and reconstruction of 35–750 kV overhead lines can significantly increase their transmission capacity, reduce capital and operating costs and enhance reliability when exposing entire range of climatic loads.

SUPPORTING TRANSMISSION CAPACITY IN THE REGIONS WITH HIGH AMBIENT TEMPERATURE WHEN KEEPING THE COST

Due to its design features, ASHT high-temperature conductor is cheaper by several times regarding to imported analogs with a long-term permissible temperature of 150 °C. Characteristics and features of ASHT conductor are confirmed during the Russian-German tests.

According to existing Electrical Installations Code, permissible current is determined taking into account the highest conductor's temperature (70 °C).

The calculation of the limit currents at the temperatures below 45 °C can be produced ignoring the influence of solar radiation. Absorbed solar radiation in the middle latitudes can heat conductors by 2–3 °C

Table 8. Indicators of ASHS/ASHT application on 150 kV Murmanskaya overhead transmission line

Conductor	Breaking load, kN	Maximum tension, daN	Conductor diameter, mm	Weight of conductor (1 km), kg	Span length, m
ACSR 240/32	75,05	3377,33	21,6	921	330
ASHS 258/73	151,533	6819,13	21,6	1296,5	**443**
ASHS 295/44	109	4905,05	21,5	1183	382
ASHS 218/63	130,096	5854,44	19,82	1106,7	424
ASHS 216/33	81,5	3667,51	**18,5**	**855**	352
ASHS 214/61	126,672	5700,33	19,6	1080,9	421

(for conductors operating in the temperature range of 60–70 °C and above).

ASHT conductor is capable to withstand a greater load under equal environmental conditions in comparison with ACSR conductor. The difference in permissible load for the compared conductors is 5%. The temperature of ASHT conductor is lower comparing to ACSR conductor, when increasing current load. The temperature difference is especially noticeable at high currents (around 5–7%).

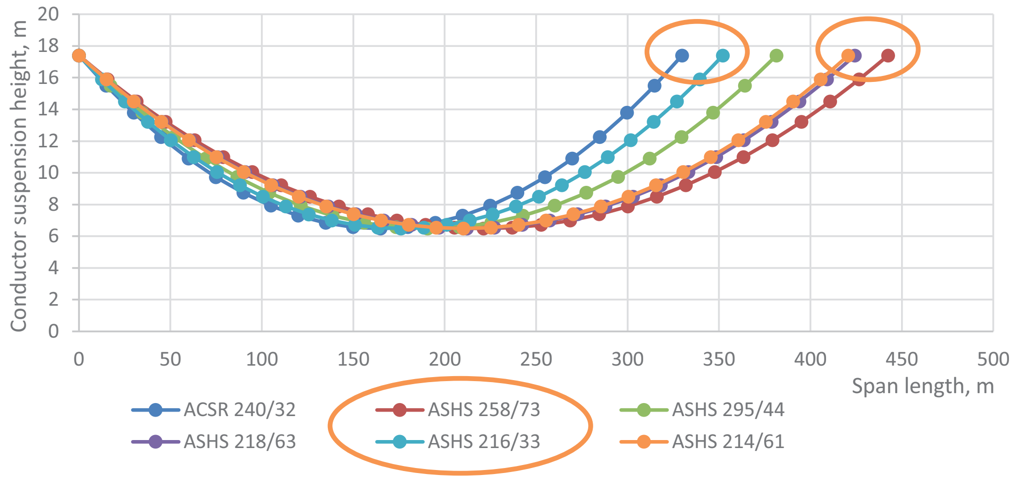

Fig. 5. Calculated spans for 150 kV Murmanskaya overhead transmission line

It should be noted that, according to the regulatory documentation, standard conductors are allowed to operate when their temperature is up to 90 °C. The permissible temperature for ASHT conductors is 150 °C.

Figure 6 represents the dependence of permissible current load on the air temperature (wind speed is 1.2 m/s) for ACSR and ASHT conductors in conditions of the maximum operating temperature of 80 °C and 150 °C, respectively. Continuous permissible current for high-temperature conductor is 30-35% higher than the value for standard conductor of the same diameter. Thus, innovative conductor can be used when significant enhance of transmission capacity, without increasing the cross-section, is required. Also, the innovative conductor can be implemented in the areas with high ambient temperatures.

CONCLUSIONS

1. Conducted studies have shown the following:
– ASHT conductors' application in electrical grid is the effective solution (the data on the ultimate loads, the reduction of heat release and magnetization of the conductors in operation have been obtained);
– ASHS conductors have corona discharge voltage higher, than ACSR conductors with the same diameter;
– the relative decrease of ASHT conductor magnetization in comparison with ACSR conductor is 3-10%.

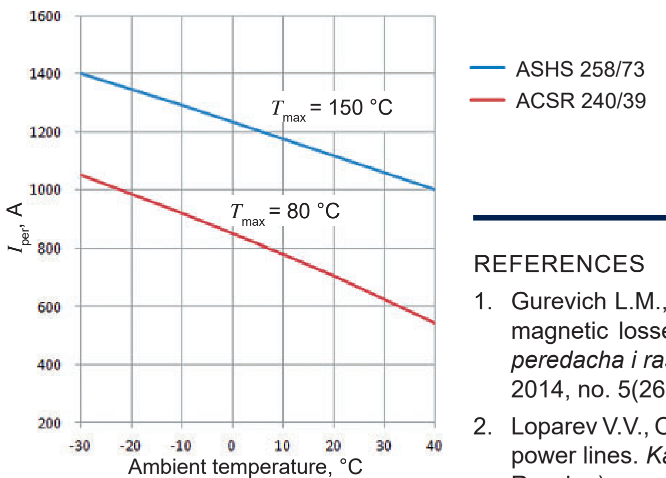

Fig. 6. Dependence of current load on ambient temperature for ACSR and ASHS conductors with the same diameter at a wind speed of 1.2 m/s

2. The obtained results show that innovative ASHT conductors' application is justified when significant increase of transmission capacity without increasing the cross-section is required. Also, the innovative conductor can be used in areas with high ambient temperatures.
3. Based on multivariate comparative analysis, the comparable cost of ACSR and ASHT/ASHS conductors does not increase costs of overhead lines construction and reconstruction.
4. The application of ASHT conductors provides corona losses decrease and span length enhancement. It reduces the total cost of overhead lines and ensures economic effect when reconstructing electrical networks.
5. Design features of ASHS/ASHT conductors reduce the load on all elements of overhead lines when replacing conductors on existing power transmission poles. Construction of new overhead transmission lines is necessary, taking into account that existing overhead lines operate more than 25–40 years and are obsolete. The discounted payback period for replacing standard conductors does not exceed 5 years per 1 km of 110 kV electrical network located in the Volgograd region.
6. The applied technology of plastic deformation provides a number of advantages noted by PJSC "Rosseti" Technical Council:
– increase in the fill factor of the conductor up to 92–97%;
– reduction of aerodynamic load (by 20–35%) and oscillations self-damping;
– reduction of icing (by 25–40%) and lowering of operating conductor elongation in several times. P

REFERENCES

1. Gurevich L.M., Danenko V.F., Pronichev D.V., Trunov M.D. Modeling of electromagnetic losses in various steel-aluminum conductors. *ELEKTROENERGIYa: peredacha i raspredelenie* [ELECTRIC POWER: Transmission and Distribution], 2014, no. 5(26), pp. 68-71. (in Russian)
2. Loparev V.V., Obraztsov Yu.V. On the features of modern conductors for overhead power lines. *Kabeli i provoda* [Cables and Wires], 2014, no. 6(349), pp. 9-15. (in Russian)
3. Kuryanov V.N., Sultanov M.M., Fokin V.A., Timashova L.V. Innovative high-effective conductors for power lines. *Energiya edinoy seti* [Energy of unified grid], 2016, no. 4(27), pp. 70–78. (in Russian)