Assessment approaches of climate factors influence for design of overhead transmission lines

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***Abstract*—A plan for the development of the electric power industry at the present stage has become impossible excluding climate change, especially when it comes to ensuring the sustainability of the power grid infrastructure. In this paper, it was carried out the analysis of the regulatory requirements of international, Russian and foreign standards for the power grid infrastructure design under the climatic factors influence. Comparative tables have been formed reflecting the consideration of climatic factors (wind and ice/snow) on the objects of the power grid complex with the designation of the main indicators that are evaluated for the choice of construction and materials for the execution of poles and wires of overhead transmission lines in Russia, the EU and the USA. Recommendations on improving the mechanisms for climatic factors in the design of overhead transmission lines were formed, a list of recommended adjustments of design loads, maps of climatic zoning and the period of repeatability for Russian reference documents was indicated. The results can be used to improve the regulatory framework and develop more effective strategies for the design and operation of power grid facilities.**

Keywords*—*overhead transmission lines, power grid, climate factors, reliability, design requirements, reference values, wind loads, ice and snow loads

I. INTRODUCTION

Providing a reliable, high-quality and safe power supply is an important task for electric grid companies. However, due to the large number of registered blackouts and technological disfunctions, it is not always possible to achieve a stable power supply. A significant number of technological disfunctions of electric transmission lines is due to the facts that, firstly, they are very long elements of the electrical grid, and secondly, they are affected by a large number of factors. Also a plan for the development of the electric power industry at the present stage has become impossible excluding climate change, especially when it comes to ensuring the sustainability of the power grid infrastructure [1-5]. The critical condition of power grids caused by a high degree of wear of the main technological equipment in combination with extreme weather conditions can be extremely dangerous for the economic and social stability of society [6-8]. For example, IPCC experts in the 6AR report [9] indicate the need to take into account such climate risks in the field of energy as increased wind loads, changes in climatic conditions, and an increase in the frequency of extreme weather events. IEA [10] and CIGRE [11] also identify a set of risks for power grid facilities associated with the influence of climatic factors, among which, in addition to the above, increased icy loads for wires and poles of overhead transmission lines, and increased intensity of atmospheric overvoltages are listed. Of course, from the reports of relevant international organizations, it can be concluded that the design of modern infrastructure facilities in the power industry should be aimed at ensuring the stability of the system in extreme weather conditions [12].

The dynamics of changes in the main dysfunctions of the normal working of the electrical grid complex's elements (overhead transmission lines and transforming substation equipment) over the past decade has a complex non-linear structure. This structure differs by the reasons of technological blackouts. However, the structure of technological violations exclusively for overhead transmission lines for the affected period because of climatic factors is described by a positive trend, and the number of accidents in most energy area increases every year.

Based on a review of statistical data on technological violations in the power grid complex, as well as annual reports on the activities of the largest companies in the Russia [13], China [14], USA and Canada [15], a structure of the accidents causes has been formed, which is shown in Fig.1.

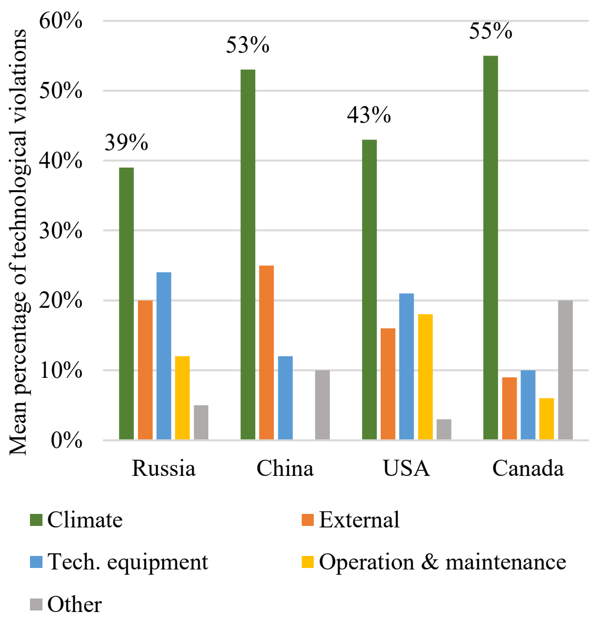

Fig. 1. Distribution of the technological disturbances causes in the power grid complex of various countries.

The share of the climatic factors contribution in the overall structure of the accident rate on power grid and substation equipment, regardless of the country, is the maximum and varies in the range from 39% to 55%. To date, there are requirements both in Russia and in the international community regulating the design and construction of power grid facilities under climatic factors. Studies aimed at analyzing these regulatory requirements can significantly improve the efficiency of designing new facilities and ensure the safe and stable functioning of the energy system in extreme weather conditions.

The relevance of the topic on the study of regulatory requirements for the design of power grid facilities in Russia is due, firstly, to actual changes in climatic conditions, which have growth rates exceeding global ones [16], and secondly, to the identification of potential solutions for adapting Russian power grids to new conditions on the basis of extensive practical foreign in this field, aimed at ensuring the reliability and safety of electrical networks. In addition, the analysis of foreign regulatory documentation can help in establishing uniform standards aimed at harmonized work and ensuring consistency in the energy sector. The process of attribution and analysis of individual causes and sub-causes of technological violations is carried out in accordance with Fig.2.

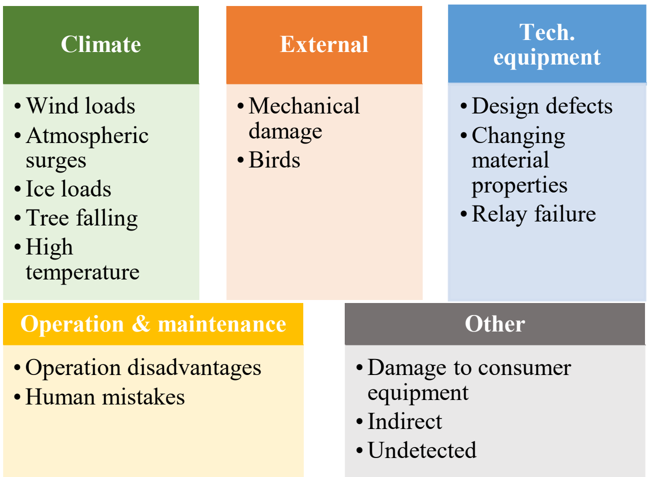

Fig. 2. Decomposition structure of causes and sub-causes of technological disturbances in the power grid complex.

The aim of this paper is to analyze the regulatory requirements of Russian and foreign standards for the design of power grid infrastructure facilities under the influence of climatic factors. Within the framework of this aim, the following tasks were set:

1) to investigate the regulatory requirements in Russia and foreign standards for assessing the impact of climatic factors on the reliability and design of overhead transmission lines and other objects of the power grid complex;

2) to analyze the features of the use of foreign standards in Russia;

3) to determine the possibility of using foreign standards for infrastructure projects in the Russian electric grid complex.

II. Methods and Materials

The research field in this work is national and international standards for the design of power transmission lines and official documents on this issue, shown in Fig.3 for individual countries. The choice of sources of initial data is due to the importance of a multilateral study of taking into account the climatic conditions influence in the overhead transmission lines design.

On the territory of the Russian Federation, in the tasks of designing power lines and their elements, PUE-7 [17], SP 20.13330 “Loads and impacts” [18] and [19] SP 131.13330 “Building climatology” [19] are used, regulating the climatic factors consideration. The process of establishing and calculating climatic loads is carried out both in accordance with all Russian reference documents [17-19], and on the basis of data from local weather stations.

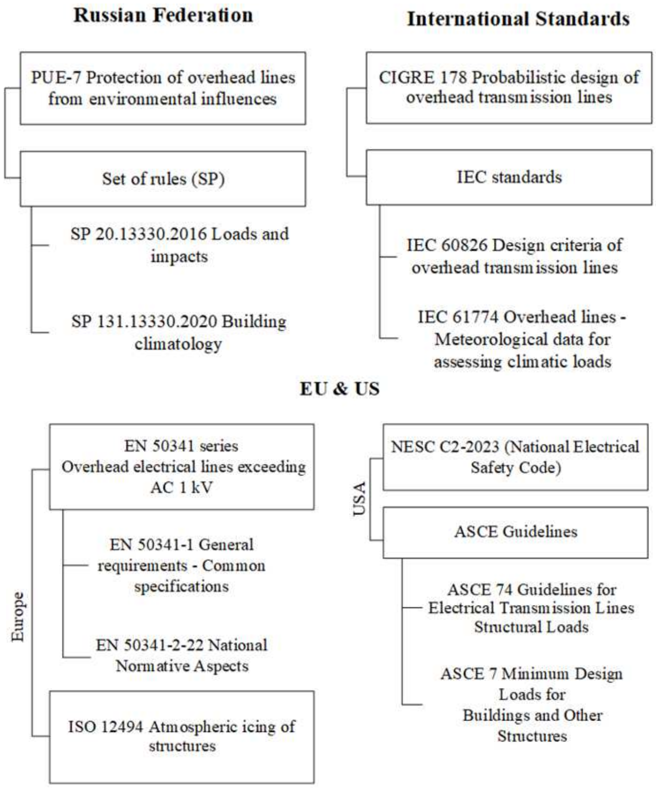

Fig. 3. Structure of reference documents with regulatory climatic requirements for reliability assessment in the design of power grid complex.

The main international standards that provides guidelines for evaluating design criteria, system reliability and the influence of climatic factors for power lines are IEC 60826 [21] and IEC 61774 [22], the feature of which is to determine the vulnerabilities of individual components: supports, foundations, wires and insulators.

In addition, the European standards EN 50341 series [22, 23] were analyzed, which establishes requirements and characteristics for overhead transmission lines with a voltage of more than 1 kV, and defines methods for assessing the impact of climatic factors on the reliability of power grid facilities, including reliability calculation methods and methods for estimating the cost of losses associated.

In the USA, the key documents containing recommendations on the placement, construction and operation of power grid facilities, as well as safety requirements under the influence of negative climatic factors are NESC C2 [24], ASCE 74 [25] and ASCE 7 [26].

Qualimetric and qualitative-quantitative methods were used as the approaches to conduct a comparative analysis of methods and standards for designing power grid facilities when considering national standards of various countries under climatic factors.

III. Results

When analyzing the Russian design standards [17-19], it was found that the main sections of these reference documents regulate the assessment of the impact of the following climatic factors:

- wind pressure on wires and supports (main wind load, peak values of wind load, resonant vortex excitation, aerodynamically unstable oscillations);
- icy loads depending on the thickness of the ice wall;
- combined effects of wind and icy deposits;
- thunderstorm activity;
- temperature climatic effects depending on the average daily temperatures of the warm and cold periods, the average monthly air temperatures in January and July.

Each of these factors and parameters affects the structural reliability of the overhead transmission line and its elements. For example, increased wind pressure is a load that a wire can withstand, which also depends on the thickness of the ice wall. The choice of power line wires brand, the type of supports and their material is determined by the calculations of normal and emergency conditions, necessarily taking into account various climatic factors individually and collectively. Currently, 8 climatic regions have been determined by wind pressure, by the thickness of the ice wall, by the wind load during ice, and by the number of thunderstorm hours per year – 7 districts. The differences between PUE-7 [17] and other SP [18, 19] are recorded when taking into account the temperature effect, which in turn depends on the standard temperatures of the warm and cold seasons, determined by zoning maps or reference values.

The international standards [20, 21] refer the following loads to the main impacts on power lines related to climate: dynamic wind pressure; icy load; combination of wind load with unfavorable temperature; combined wind and ice loads. One of the fundamental parameters for the preliminary determination of the reliability of power grid complex and its elements is the repeatability period. This is the reference level of a climatic phenomenon repeatability, and for IEC 60826 [20] this time interval is once every 50 years. For temporary overhead transmission lines and some wooden poles, the repeatability period can be assumed to be equal to 25 years. This standard additionally considers higher levels of reliability, where each level corresponds to its period of repeatability and determines the design reliability. It should be noted that intermediate values, for example 100, 200 or 400 years, can also be used in the design, if justified by local conditions or economic benefits, regarding the prediction of future damage.

It should also be emphasized that the IEC 60826 [20] provides methodological guidelines for calculating the influence of climatic factors on overhead transmission lines, but there is no guide for collecting data on weather (natural) phenomena. It was recommended to use the IEC 61774 [21] directly to quantify the actual levels of climatic loads for power transmission facilities and to form databases on retrospective load values, as well as to create climate maps. The main physical quantities that are natural (weather) parameters that are required to assess climatic impacts are indicated in Fig 4.

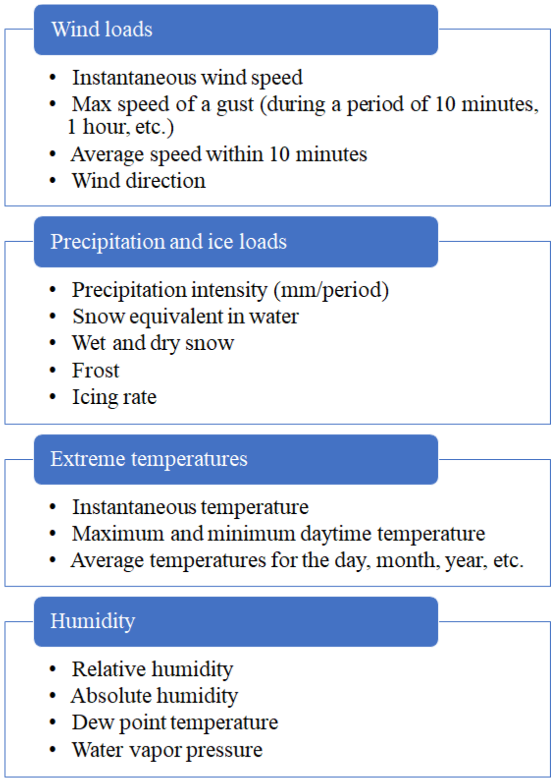

Fig. 4. The main physical quantities that are climate (weather) parameters that are required to assess climatic impacts.

The EN 50341 [22, 23] and US standards [25-27] also propose approaches similar to international ones, but it should be noted that when calculating wind pressure, a coefficient reflecting the dependence of air density on altitude and temperature is included. Additionally, NESC C2 [25] takes into account the reliability coefficient of responsibility, depending on the type of overhead transmission line being designed, capacity or responsibility.

It was formed comparative Tables I and II, reflecting the consideration of climatic impact key factors on the power grid complex objects with the designation of the main indicators that are evaluated for the choice of design and materials for the execution of poles and wires of power lines in the context of various regulatory and reference documents of Russia, the EU, the USA.

TABLE I. Impact of Ice and Snow Loads under Assessing the Reliability of Power Grid Complex Objects

Russia [14, 15]	**International [16]**	**EU [17]**	**USA [18]**
Linear load for circular cross-section elements: $i = \pi b k \mu_1 (d + b k \mu_1) \rho g 10^{-3}$	Ice loads: $g = 9.82 \cdot 10^{-3} \cdot \delta \pi t \cdot (d + t/10^3)$ δ – ice density (kg/m^3); t – radial thickness; d – diameter of the conductor.	Average wind pressure in icy conditions: $q_{lp}(h) = [1 + 7 I_v(h)] \cdot q_{lh}(h)$ $I_v(h)$ – turbulence intensity; $q_{lh}(h)$ – average wind pressure.	Weight of ice: $Wi = 0.0282(d + I_Z) I_Z$ I_Z – ice thickness; d – diameter of uninsulated wire.
Normative value of the surface ice load: $i^{`} = b k \mu_2 \rho g$			Cross-sectional area of ice: $A_i = \pi t_d (D_c + t_d)$ t_d –ice thickness; D_c – cross-section diameter.

TABLE II. IMPACT OF WIND LOADS UNDER ASSESSING THE RELIABILITY OF POWER GRID COMPLEX OBJECTS

Russia [17-19]	**International [20, 21]**	**EU [22, 23]**	**USA [24-26]**
Mean wind load: $w_m = 0{,}43 v_{50}^2 k(z_e) c$ v_{50}^2 – average wind speed over a 10-min interval with 50 yr repeatability; $k(z_e)$ – coefficient of wind pressure changes for altitude; c – aerodynamic coefficient.	Dynamic reference wind pressure: $a = \frac{1}{2}\tau\mu V_{Rx}^2 C_x G$ τ – correction coefficient of air density; $\mu =$ 1,225 kg/m^3 – mass of air per unit volume at a temperature of 15 ° C and an atmospheric pressure of 101.3 kPa; V_{Rx} – reference wind speed in the area category under consideration; C_x – resistance coefficient; G – combined wind factor taking into account (component effect).	$q_h(h) = \frac{1}{2}\rho v_h^2(h)$ ρ – air density in kg/m^3; v_h – average wind speed, in m/s at the initial height above the ground.	$L = 0.6 V_{m/s}^2 k_z G_{RF} C_f A$ k_z – coefficient of impact of pressure velocity; G_{RF} – the coefficient of reaction to wind gusts; C_f – resistance coefficient; A – area of wind impact.
Pulse wind load: $w_p = w_m \xi \zeta(z_e) v$ ξ – coefficient of dynamism; $\zeta(z_e)$ – wind pressure ripple coef/ for altitude.		Max wind pressure: $q_p(h) = [1 + 7 I_v(h)] q_h(h)$ $I_v(h)$ – turbulence intensity.	Wind force in the wind direction: $F = \gamma_w Q K_z K_{zt} V_{50}^2 G C_f$ γ_w – wind load coefficient, depending on the period of repeatability; Q – 0.613 K_{zt} – terrain coefficient; V_{50} – reference wind speed over a 50 yr repeatability, m/s G – coefficient of reaction to wind gusts for wires, lightning protection cables and structures
Peak wind load: $w_{+(-)} = w_0 k(z_e)[1 + \zeta(z_e)] c_{p+(-)} v_{+(-)}$ $c_{p+(-)}$ – peak values of aerodynamic coefficients; $v_{+(-)}$ – wind load correlation coefficients.		Loads for any object: $Q_{Wx} = q_p(h) G_x C_x A_x$ G_x – constructive factor; A_x – the area of component line projected onto a plane perpendicular to the wind.	

The periods of repeatability of the standards of Russia [17-19], Europe [22, 23], the USA [24-26] and the international level [20, 21] were analyzed and correlated, which are shown in Table III.

TABLE III. CROSS-CORRELATION OF REPEATABILITY PERIODS OF DIFFERENT STANDARDS

Name of the standard	**25 yr**	**50 yr**	**100 yr**	**150 yr**	**200 yr**	**400 yr**	**500 yr**
Russia [17-19]	+ reference	–	–	–	–	–	–
International [20, 21]	+	+ reference	–	+	–	–	+
EU [22, 23]	–	+ reference	–	+	–	–	+
USA [24-26]	+	+ reference	+	–	+	+	–

Also, as a result of the analysis of the categories of localities, it can be noted that in comparison with PUE-7 [17], in which only coastal areas are affected, the international standards IEC [20, 21] and European standards [22, 23], in addition to these, take into account the localities of seas, lakes and reservoirs. This document examines flat terrain in more detail and identifies two categories separately: 0 - separate seas and coastal zones; I – lakes and flat areas without obstacles. A cross-comparison of the categories of localities in the context of various power line design standards that take into account climatic influences is shown in Table IV.

TABLE IV. CROSS-CORRELATION OF TERRAIN CATEGORIES OF DIFFERENT STANDARDS

Russia [17-19]	**International [20, 21]**	**EU [22, 23]**	**USA [24-26]**
Open coasts, deserts, steppes, forest-steppes	A large area of water with a flat windward side and flat coastal areas	The sea and the coastal zone to it	Flat areas without obstacles and water surfaces
		Lakes or flat areas without obstacles	
Areas evenly covered with obstacles at least 2/3 of the height of the supports	Open terrain with very few obstacles	A plot with low vegetation, the distance between which is at least 20 times the height of the obstacles	Open terrain with scattered obstacles (include flat surfaces in hurricane-prone areas)
	Terrain with numerous small obstacles of small height	An area with obstacles, the distance between which does not exceed 20 times the height of the obstacles	Urban and suburban areas, woodlands, or other terrain with multiple closely spaced obstacles the size of a single-family house or larger
Areas with buildings more than 25 m high or trees more than the height of supports, orographically protected areas	Suburban areas or an area with a lot of tall trees	An area where at least 15% of the surface is occupied by buildings whose average height exceeds 15 m	

IV. DISCUSSION

Designing and assessing the condition of overhead transmission lines are extremely difficult tasks, despite the availability of zoning maps for various climatic parameters. It is determined that the information in the Russian reference documents [17-19] is outdated, and the zoning maps of Russia are not informative enough. For example, the information about climatic conditions on the map on the wire dance from PUE-7 [17] has not been edited since 2003, and the zoning map of the average number of crossings over 0°C per year is based on data for the period 1961-1990. A significant disadvantage of the Russian reference documents is the inability to establish the averaging period for the obtained normative values, as well as the inability to estimate the period of normative values application. In PUE-7 [17], regional reliability coefficients for calculating linear loads are deterministic in nature, which may be a problem for one of the main criteria of the standard - ensuring the reliability and economic efficiency of power lines. It should be noted that with probabilistic and semi-probabilistic approaches, there is a risk of exceeding loads. However, this risk is reduced to an acceptable level, depending on the level of reliability that is set for a specific task during design.

In international and foreign standards, when calculating reliability coefficients for determining loads on elements, three approaches are used, which include both probabilistic, semi-probabilistic, and deterministic models. Thus, the international standard IEC [20, 21] regulates the assessment of the overall strength of the line by determining the reliability of the least durable component, since any failure can lead to loss of capacity transmission capacity. In the European standards EN 50341 [22, 23], power transmission lines are designed in such a way that there is no cascade effect when one of the components of the line is disconnected, which also corresponds to the application of a probabilistic approach with the condition of element failures according to the N-1 principle. NESC C2 [24] takes into account the reliability coefficient of responsibility, depending on the type of power line being designed and power.

It is necessary to identify one of the main differences in Russian and foreign standards in terms of choosing a reference level of adverse climatic phenomena recurrence. If in Russian documents for all objects of the power grid complex this value is equivalent to a repeatability of 1 time in 25 years, then in all foreign standards the minimum estimate is equal to 1 time in 50 years (with the assumption of 1 time in 25 years for wooden poles). It is also worth noting that according to the materials of the CIGRE standard [27], for high-voltage lines or lines that, if they fail, can lead to a prolonged absence, it is proposed to use an even higher level of reliability equal to phenomena 1 time in 150 years.

Consequently, in international and other foreign standards, the implementation of better reliability is ensured by choosing a longer period of repeatability, and the implemented probabilistic approach is more elaborated in terms of reliability assessment and calculation of the safety margin, unlike the deterministic approach used in Russian documents. To improve the reliability of power grid, it is necessary to develop and take appropriate measures, including improving the mechanisms for taking into account climatic factors in the design. For Russian reference documents, adjustments may be made to already existing data on climatic loads or on zoning maps, taking into account local meteorological data and accident statistics. It can also be carried out the recalculation of the corrective design loads obtained on the basis of calculations of reliability, operational experience and working conditions in a particular climatic area, or the introduction of an additional adjustment factor that takes into account forecast climatic changes.

V. Conclusion

In the modern world, where climate change is becoming more and more noticeable, the issue of energy security is becoming an integral part of the sovereignty of the State. Any failures or malfunctions in the power supply caused by extreme weather conditions can have serious consequences for society and lead to disruption of the normal functioning of the main sectors of the economy. As part of a comparative analysis of domestic and foreign regulatory requirements for the design of power grid infrastructure facilities, it was concluded that from the point of view of the indicator reflecting the period of repeatability, it can be proposed to make an adjustment to Russian documents and change the current period of repeatability in 25 years to 50 years, which will reduce the risk of accidents due to climatic factors by an order of magnitude. In general, the results of this study can be used to improve the regulatory framework and develop more effective strategies for the design and operation of electric grid facilities, and can additionally be useful for specialists involved in the design and operation of electric grid infrastructure.

Acknowledgment

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