Comparative analysis of evaluation approaches for the climatic factors influence on power grid facilities reliability

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***Abstract*— This paper provides an overview of the main accidents causes in the power grid complex of various countries in recent years, which showed that one of the key causes of failures is the climatic factors influence. The aim of the study is to determine the most significant indicators and initial data to take into account the level of climatic factors influence on the reliability of overhead transmission lines. It was carried out a review of requirements for the structural integrity of electric grid facilities, as well as a comparative analysis of Russian and foreign studies from the point of view of reliability from the influence of climatic factors. The results of the study show the need to update the existing requirements for the structural integrity and strength of power grid facilities, taking into account current and projected changes in climatic loads, as well as the relevance of the preparation of standards governing the calculation of reliability indicators.**

Keywords*— *power grid facilities, overhead lines, transmission lines, reliability, climate changes, wind loads, extreme weather conditions

I. INTRODUCTION

The assessment of the meteorological factors influence in various climatic zones on the power systems functioning is analyzed by researchers around the world [1, 2]. The CIGRE [3-5] and IEA [6] reports note that due to climate change, there is an increase in the number of adverse meteorological phenomena, and as a result, an increase in the accidents risk [7–9] and a decrease in the reliability of power grid equipment in general. The analysis of accidents in the power grid complex shows that one of the key causes of failures are climatic factors [10, 11].

Both abroad [12, 13] and in Russia [14-16], a lot of work is being done on meteorological and climatological support for the design and operation of power grids, however, estimates of observed and even more expected changes in climatic characteristics are not accompanied by the necessary technical calculations. The IPCC: 6AR [17] indicates that a further increase in the number of technological disruptions caused by the impact of natural factors is expected in the future. The trend towards an increase in the share of outages due to the influence of climatic factors is observed, including in Russia. Underestimating the impact of meteorological loads during the design and/or reconstruction of power lines can lead to emergency situations, and, as a result, to a break in the power supply to consumers and economic losses due to under-supply of electricity.

The electric grid complex is one of the critical infrastructure facilities that must meet the high requirements of stability, reliability and survivability. In the conditions of climate change, accompanied by an increase in the number of unfavorable events for the power system, one of the main threats to reliability is the influence of climatic factors.

In Russia, all the main recommended requirements for the structural integrity and strength of electric grid facilities and the criteria for their calculation are presented in the rules of electrical installations. Thus, a comprehensive analysis of the design requirements for power lines includes:

- analysis of the normative and calculated wind load on wires and cables;
- analysis of normative and calculated icy load on wires;
- analysis of additional loads at higher, average annual and lower temperatures;
- checking the cross section of the selected lightning rod for thermal resistance when assessing the impact of thunderstorms.

It should be emphasized that various research organizations, institutes and individual teams of scientists identify wind speed as a significant factor affecting the stability and operability of elements of the electric grid, and the data of the IPCC reports [17] confirm the assumptions that the intensity and frequency of this meteorological phenomenon in the future may increase with an increase in global temperatures, which subsequently, it will lead to an increase in the number of technological violations on power lines.

Climatic factors affecting the objects of the power grid complex have a significant impact on the reliability of each individual element of the power system, and the greatest interest in this context is the assessment of reliability indicators of system elements. These include quantitative characteristics of one or more properties that determine the reliability of an object.

They are divided into single, characterizing one property, and complex, characterizing several properties of an object. Individual indicators of the reliability of elements are divided into indicators of reliability, recoverability and durability. The complete classification of reliability indicators in accordance with [18] is shown in Fig. 1. All existing reliability indicators are calculated based on a statistical data set and information about the network element itself. The main disadvantage of this approach is the fact that this tool does not make it possible to consider the impact of individual reasons on the decrease in reliability and to identify priority areas of modernization.

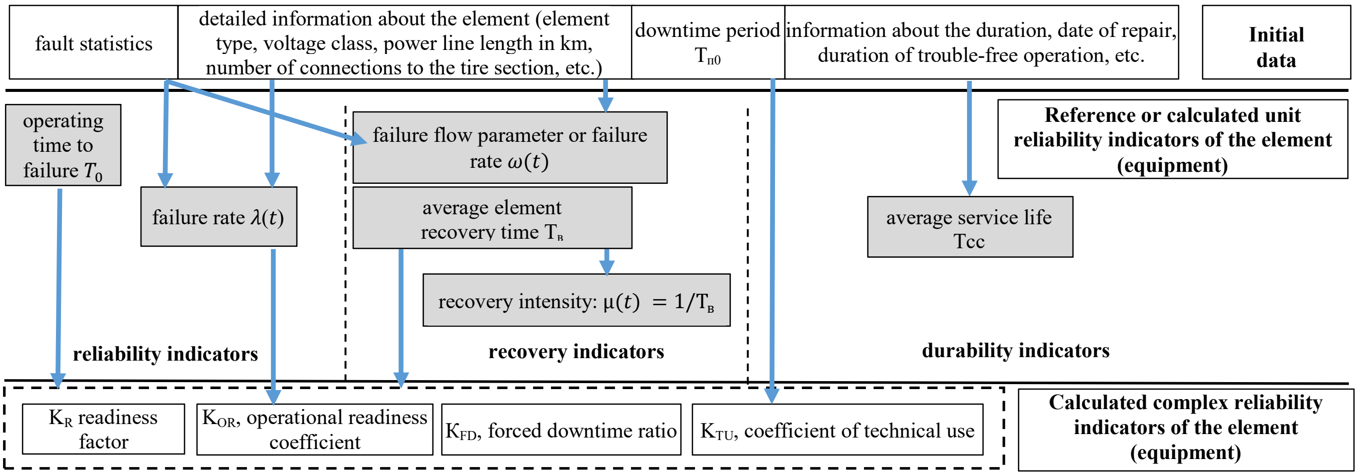

Fig. 1. The relationship between the initial data and the calculated single and complex indicators of equipment reliability

To ensure the integrity and strength of structures of power grid facilities, domestic and foreign power engineering uses a number of documents in the field of construction climatology. Each of them takes into account the wind impact as the most significant factor [19].

In Russia, the impact of thunderstorm overvoltages, ice-frost and extreme temperature loads are additionally taken into account. Despite the extensive work carried out in the field of meteorological and climatological support at the design and operation stages of the network infrastructure, the estimates of the observed and, moreover, expected changes in applied climatic characteristics do not correspond to real conditions. In turn, underestimating the influence of climatic factors on the reliability of network equipment can lead to technological disruptions, a decrease in the quality of electricity, a change in the structure of the system, disconnections of consumers, which will entail economic losses.

II. Methods and Materials

As part of the research, it was carried out the analysis of statistical data on emergency outages in power grid complexes with different territorial location and climatic conditions, namely: Russian (PJSC "Rosseti") [20], U.S. (NERC) [21], Nordic-Baltic Eight countries (ENTSO-E) [22] and Chinese (China Southern Power Grid) [23]. To simplify the analysis, all the reasons for the outages were brought to the reporting form provided by ENTSO-E, in accordance with the order presented in Table I.

TABLE I. Classification of Failures at Power Grid Facilities as Result of Climatic Factors

ENTSO-E [18]	NERC [17]	CSPG [19]
Lightning	Lightning	Lightning
Other environment causes	Weather, excluding lightning	Wind Damage
		Ice damage
External influences	Contamination	Wild fire
	Fire	Polution flashover
	Vegetation	External damage
		Foreign object
Operation and maintenance	Foreign Interference	Maloperation
	Misoperation	
	Human Error	
Technical equipment	Failed AC Substation Equipment	Line fault
	Power System Condition	Equipment failure
	Failed AC Circuit Equipment	
Other	Other	Unknown Fault

As initial data for a comparative analysis of standards for the design of overhead power transmission lines., at least during the service life of the equipment were used normative documents of Russia [24], EC [25], Canada [26], USA [27, 28], Australia-New Zealand [29], Japan [30], which establish quantitative values of climatic parameters with probabilities of non-exceeding.

Therefore, foreign studies [31-36] were analyzed to assess the impact of climatic factors on the reliability of power grid infrastructure facilities, which allow solving two main tasks. One of them is connected with the problem of forecasting adverse weather conditions, and the other with the assessment of the reliability of electric grid facilities based on probabilistic models. Conceptually, the methods differ in the nature of the causes of accidents under consideration, but most of them focus on wind exposure, sometimes in combination with rain or icy load.

III. Results and Discussion

A. *Distribution of accidents causes at power grid facilities in various countries*

The main results with the percentage distribution of accidents in the power grid complexes in different countries are shown in Fig. 1. It was found that as a result of climatic factors impact, 43% of outages occur on average in the US power system, 42% in the Nordic-Baltic Eight countries, 43% in Russia, 63% in China. Also, the structure of accidents for climatic reasons was estimated for the USA in the context of 8 large NERC Regional Reliability Councils (Fig.2), and for individual Nordic-Baltic Eight countries – Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Norway, Sweden (Fig. 3).

It was found that in the United States, the causes of technological disruptions as a result of the climatic factors impact vary from 22% for Florida (FRCC) to 61% for the Southwest (SPP). In the context of the Nordic-Baltic Eight countries, the distribution of a similar parameter ranges from 20% for Lithuania to 56% for Latvia.

The analysis results of the requirements for the structural reliability of power grid facilities, which are presented in Table II showed that most of the standards take into account wind impact and icy-frost deposits. And only some of them also allow taking into account the loads associated with extreme temperature phenomena and thunderstorm activity. In the context of developing climatic changes, it should be noted that none of the standards takes into account changes in wind and ice loads when calculating the strength of structures.

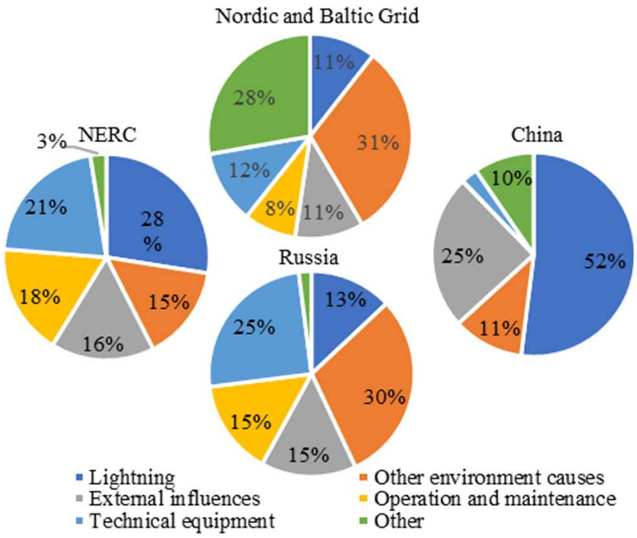

Fig. 2. Percentage distribution of accidents and causes of technological disruptions in the electric grid complex in USA, Nordic-Baltic Eight countries, Russia and China

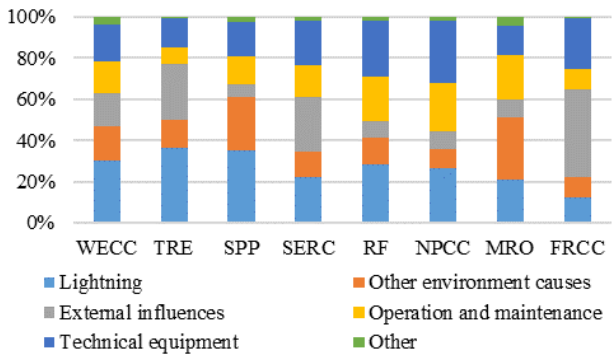

Fig. 3. Detailed structure of the technological violations causes in the USA, according to NERC data

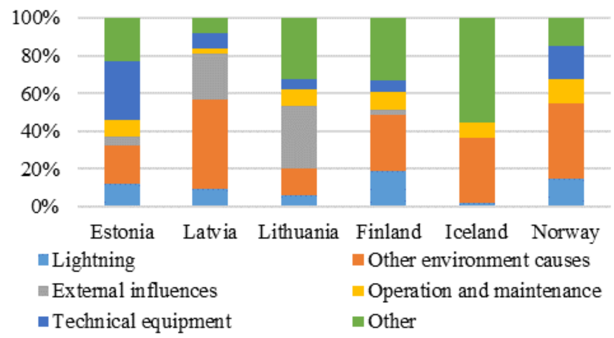

Fig. 4. Detailed structure of the technological violations causes in Nordic-Baltic Eight countries, according to ENTSO-E data

TABLE II. REQUIREMENTS FOR THE STRUCTURAL INTEGRITY OF POWER GRID FACILITIES FROM THE CLIMATIC FACTORS IMPACT IN RUSSIAN FEDERATION AND ABROAD

Document	Win d	Ice	Extreme temperatures	Light-ning
PUE [24]	+	+	+	+
IEC 60826 [25]	+	+	+	-
CAN/CSA-C22.3 [26]	+	+	-	-
ASCE Manual No.74 [27]	+	+	-	+
NESC [28]	+	-	-	-
AS/NZ 1170-2-2011 [29]	+	-	-	-
JEC -127 1979 [30]	+	+	-	-

As a consequence, when designing facilities under current conditions, errors may occur, which will subsequently lead to a reduction in the service life or unforeseen failures of system elements and a decrease in the reliability of both the facilities of the power grid complex and the system as a whole.

It should be noted that the single reliability indicators recorded in domestic standards do not allow to identify the influence of individual (in particular, climatic) factors on the reliability of the infrastructure of the electric grid complex, which complicates the assessment and, as a consequence, decision-making in the field of reliability management. To solve this problem abroad, a number of methods are used to assess the reliability of electric grid facilities from the effects of wind in various combinations with other climatic factors (rain, thunderstorms, icy-frost deposits).

B. Methods for assessing the infrastructure reliability of the power grid facilities from the climatic factors impact

The study [31] includes an analysis of the reliability of the network stages of modeling the reaction of individual objects to external disturbances. To assess the reliability of the transmission line, it is divided into segments with a length of 1 km, and the wind load on each segment of the line is estimated. In this case, the total power loss on the load is selected as the reliability indicator. The calculation of the fragility model of components is also provided by combining information about calculated and actual wind loads.

Integral risk analysis and calculation of the quantitative assessment of the impact of climatic factors on the probability of failure of individual segments of the overhead lines and the system as a whole [32] takes into account the influence of structural flexibility, interconnection of segments, geometric nonlinearities and uncertainty on the transmission line capacity. The probability of failure of each line segment is estimated as the ratio of the number of events for which demand exceeds throughput to the total number of generated simulations according to pre-designed scenarios.

The study of the sensitivity of overhead lines [33] provides the information necessary to increase throughput and reduce long-term risks associated with the effects of climate change. Within the framework of this approach, the authors propose to evaluate reliability indicators based on calculating the variation of the mean value and standard deviation of climatic variables, such as extreme wind speed and ice thickness.

The approach to assessing the combined impact of rain and wind load on the reliability of electric grid facilities [34] is based on the use of the Clayton bundle and the use of probability distributions of wind speed and rain intensity. As initial data, the intensity of precipitation with different time resolution recorded at more than 1300 weather stations over a 60-year period of time and the marginal probability distributions of the annual extreme wind speed are used.

The study [35] suggests using a system solution for determining geometric defects of power transmission poles in real time, which allows to estimate the throughput and the probability of failures of supports. Based on the results of the assessment of the probability of failure of each component of the line, technical measures for wind protection are proposed, taking into account wind load and aerodynamic parameters. In the process of uncertainty analysis, only the probability of failure of a single support is mainly taken into account, and not the relationship between their number and the span length. For a more detailed modeling of the reliability of power lines under the influence of wind pressure, the methodology proposes to comprehensively evaluate separately each component of the line, the wind environment and its aerodynamic parameters.

TABLE III. ANALYSIS OF FOREIGN STUDIES ON ASSESSING THE RELIABILITY OF THE POWER GRID FACILITIES INFRASTRUCTURE FROM THE CLIMATIC FACTORS INFLUENCE

№	Country, methodology		Influencing natural factors	Initial data	Description of the quantitative assessment of the impact factor consideration
1	Germany, Norway [31]	Assessment of the power grid reliability exposed to wind impacts: methodology and application to the northern regions	Wind loads	Power loss on load	System reliability expressed in binary representation $p_S = 1 - \Pr(F_S)$
2	Canada [32]	Analysis of the climate change impact on the reliability of overhead lines (methodology for assessing the reliability of transmission lines)	Wind loads, icy loads	The number and design of the supports of the considered overhead line	Error in forecasting the selected model $R(\omega) = R_{emp}(\omega) / /(1 - \sqrt{p - p \cdot \ln(p) + \frac{\ln(n)}{2n}})$
3	Canada [33]	Analysis of poles and overhead lines reliability under spatiotemporal variations of wind and seismic load	Wind loads, icy loads	The average and maximum value of wind speed at a height of 10 m; the number of overhead poles and the distance between them	Probability of failure of the overhead pole $P_{fsys}(m) = = Prob[\delta_{TC} - \max(\delta_{T1}, \delta_{T2} ... \delta_{Tm}) \le 0]$
4	China [34]	Analysis of overhead lines failures taking into account the joint probability distribution of wind speed and rain intensity	Wind loads, rain (icy) loads	Weather station data on wind speed and rain intensity	The probability of overhead lines failure under the combined effects of wind and rain $p_f = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_{V,R}(V,R) P_{V,R}(V,R) dVd$ $= \int_0^{\infty} \int_0^{\infty} f_{V,R}(V,R) P_{V,R}(V,R) dVdR$
5	China [35]	Evaluation of wind fragility and sensitivity analysis for a system of overhead lines poles	Wind loads	Number of poles, span length, design of poles	Model of the fragility of overhead lines under wind influence $P[D \ge C \mid IM] = \Phi[\frac{\ln m_{D\|IM} - \ln m_c}{\sqrt{\beta^2_{D\|IM} + \beta^2_C}}]$
6	China [36]	Predicting the failure of overhead lines pole based on a model for monitoring and predicting deformation using a fiber Bragg grid	Wind loads, subsidence of the soil, seismic phenomena	No initial meteorological data is required; sensors and software are required	Average absolute error $MAE = \frac{1}{n} \sum_{t=1}^{n} \left\| y_t - \hat{y}_t \right\|$
7	China [37]	Analysis of wind-induced power grid failures using long-term measurement data and orientation effect	Wind loads	Data on wind directions and speeds from meteorological stations; limit of static stability of overhead lines	The actual probability of overhead lines failure, calculated taking into account the wind direction $P_{ik} = \int P_f(EDP > LS_k \mid v, \gamma_i) f(v, \theta) dv$

The model for predicting the deformation of power lines in the medium and short term from the work [36] is aimed at providing early warning of the failure of the support. The authors propose to introduce an online tower deformation monitoring system based on the monitoring of fiber Bragg lattice deformation based on sensors sensitive to the slightest fluctuations caused by external climatic influences.

The study [37] proposed a comprehensive system for assessing the reliability of the transmission line system both from the point of view of design safety and from the point of view of normal operation. The combined influence of wind speed and direction is considered as an influencing factor. The methodology makes it possible to estimate the probability of failure (structural reliability) and takes into account the overall fragility of the system together with taking into account various wind loads on power lines.

Based on the results of the analysis, it should be noted that in all the studies considered, the main emphasis is placed on taking into account wind loads and the degree of their influence on the occurrence of accidents at power lines. But it should also be emphasized that the estimated estimates of hurricane winds are based on annual synoptic reports, according to which 50-year maps of wind speed and pressure are compiled. Most of them do not take into account the lateral wind direction, which is why they may not meet modern climate changes. Many of the methods considered also use information from annual weather reports as input data, which is unrepresentative from the point of view of objectivity and accuracy of information. Nevertheless, the forecasting models proposed by the researchers are formed in such a flexible way that, if necessary, they can be rebuilt to match the initial data of the CMIP 6 global climate models, and in this case generate really correct results at the output.

IV. CONCLUSION

The failures' structure research of the world's largest power systems has shown that from 40 to 63% of outages occur due to the effects of natural and climatic phenomena. Against the background of unprecedented climate changes being recorded around the world and, especially, in Russia, an increase in the proportion and severity of failures caused by the influence of climatic factors, and above all wind, is expected. The main advantage of the reliability assessment methods considered is flexibility in relation to the loaded information as input data, which allows, if necessary, to rebuild the model to the data of the CMIP6 global climate models, and to obtain a result with a high degree of actualization. However, most of them don't take into account the complex influence of climatic factors, as well as the lateral direction of the wind, which may not meet modern conditions. In addition, data from annual weather reports are used as input data in most methods, as a result, the results obtained have a low degree of representativeness. Thus, the results of the study show the need to update the existing requirements for the structural integrity and strength of electric grid facilities, taking into account current and projected changes in climatic loads, as well as the relevance of preparing standards regulating the calculation of reliability indicators, allowing to identify the influence of individual factors on the reliability of the system and its elements.

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REFERENCES

[1] S. Lee and Y. Ham, "Probabilistic framework for assessing the vulnerability of power distribution infrastructures under extreme wind conditions," Sustainable Cities and Society, vol. 65, 2021, pp. 1-11.

[2] V. V. Klimenko and E. V. Fedotova, "Long-term prospects for the development of wind energy in russia in the context of expected climate change," Thermal Engineering, vol. 67 (6), 2020, pp. 331-342.

[3] CIGRE No. 485: Overhead Line Design Guidelines for Mitigation of Severe Wind Storm Damage (2012).

[4] CIGRE No. 598: Guidelines for the Management of Risk Associated with Severe Climatic Events and Climate Change on OHL (2014).

[5] CIGRE No. B2-10974: Design of Overhead Lines in a Changing Climate (2022).

[6] IEA "Power systems in transition - Challenges and opportunities ahead for electricity security," 2020, 70 p.

[7] O. E. Kondrateva, E. M. Myasnikova and O. A. Loktionov, "Analysis of the effect of climate change on the reliability of overhead transmission lines," Environmental and Climate Technologies, vol. 24 (3), 2020, pp. 201-214.

[8] S. Pineda, J.M. Morales, Y. Ding and J. Østergaard, "Impact of equipment failures and wind correlation on generation expansion planning, " Electric Power Systems Research, vol.116, 2014, pp. 451-458.

[9] R. Rocchetta, E. Zio and E. Patelli, "A power-flow emulator approach for resilience assessment of repairable power grids subject to weather-induced failures and data deficiency," Applied Energy, vol. 210, 2018, pp. 339-350.

[10] D. Zhang, X. Song, H. Deng, X. Hu and X. Ma, "Experimental and numerical study on the aerodynamic characteristics of steel tubular transmission tower bodies under skew winds," Journal of Wind Engineering and Industrial Aerodynamics, vol.214, 2021, pp. 1-14.

[11] C. Fant, B. Boehlert, K. Strzepek, P. Larsen, A. White, S. Gulati, Y. Li and J. Martinich, "Climate change impacts and costs to U.S. electricity transmission and distribution infrastructure," Energy, vol.195, 2020, pp. 1-10.

[12] F.H. Jufry, V. Widiputra and J. Jung, "State-of-the-art review on power grid resilience to extreme weather events: Definitions, frameworks, quantitative assessment methodologies, and enhancement strategies," Appl Energy, vol. 239, 2019, pp. 1049 -1065.

[13] C. D. Zamuda, P. H. Larsen, M. T. Collins, S. Bieler, J. Schellenberg and S. Hees, "Monetization methods for evaluating investments in electricity system resilience to extreme weather and climate change," The Electricity Journal, vol.32, 2019, pp. 1-9.

[14] V. V. Klimenko, O. E. Kondratyeva, A. G. Tereshin, E. V. Fedotova, O. A. Loktionov and E. M. Voronkova, "Wind regime change over the russian territory and the accident rate of overhead power lines," Doklady Physics, vol. 66(3), pp. 80-87. doi:10.1134/S1028335821030034.

[15] K. V. Mankov, D. A. Akimov, I. P. Voltov, and A. D. Ruchkina, "Forecasting of emergency power line outages based on weather data and past emergency outages," Conference of Russian Young Researchers in Electrical and Electronic Engineering, ElConRus 2022, pp. 765-767. doi:10.1109/ElConRus54750.2022.9755779.

[16] O. A. Loktionov, O. E. Kondrateva, E. V. Fedotova, A. I. Makeev, and E. M. Myasnikova, "Analysis of dangerous wind loads influence on 110-220 kV power grid reliability in yamalo-nenets autonomous district of Russian Federation," 2nd 2020 International Youth Conference on Radio Electronics, Electrical and Power Engineering, REEPE 2020, doi:10.1109/REEPE49198.2020.9059204.

[17] IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

[18] Volkov N. G. Reliability of power supply. Textbook / Vol. polytech. un-T. – Tomsk, 2003, pp. 14-26 (in Russian).

[19] O. A. Loktionov, O. E. Kondrateva and E. V. Fedotova, "Analysis of prerequisites for changing wind load standards for electric grid facilities," 4th International Youth Conference on Radio Electronics, Electrical and Power Engineering, REEPE 2022, doi:10.1109/REEPE53907.2022.

[20] Annual report of PJSC Rosseti for 2021. https://www.rosseti.ru/investors/common/results/doc/Pril1_2022.pdf (in Russian).

[21] NERC, State of Reliability, May 2016. https://www.nerc.com/pa/RAPA/PA/Pages/default.aspx.

[22] ENTSO-E, Nordic and Baltic Grid Disturbance Statistics 2020, 10.12.2021. https://eepublicdownloads.azureedge.net/clean-documents/SOC%20documents/Nordic/Nordic_and_Baltic_Grid_Disturbance_Statistics_2020.pdf.

[23] B. Chen, "Fault Statistics and Analysis of 220-kV and Above Transmission Lines in a Southern. Coastal Provincial Power Grid of China," Power and Energy, vol. 7, 2020, pp. 1-2.

[24] Rules for the installation of electrical installations. 7th edition revised and expanded (in Russian).

[25] IEC 60826: Design Criteria for Overhead Transmission Lines – 2003.

[26] CAN/CSA-C22.3 No.608626-06: Design criteria for overhead power transmission lines.

[27] ASCE Manual No. 74: Guidelines for Electrical Transmission Line Structural Loading – 2009.

[28] NESC – National Code of Rules for the safety of electrical Installations – 2012

[29] AS/NZ 1170-2-2002: Structural design activities.

[30] JEC-127 1979. Standards for the design of structures for power transmission lines.

[31] A. Scherb, L. Garrè and D. Straub, "Evaluating component importance and reliability of power transmission networks subject to windstorms: methodology and application to the nordic grid," Reliability Engineering & System Safety, vol. 119, 2019, pp. 1-11.

[32] S. N. Rezaei, L. Chouinard, S. Langlois and F. Légeron, "Analysis of the effect of climate change on the reliability of overhead transmission lines," Sustainable Cities and Society, vol. 27, 2016, pp. 137-144.

[33] S. C. Yang, T. J. Liu and H. P. Hong, "Reliability of Tower and Tower-Line Systems under Spatiotemporally Varying Wind or Earthquake Loads," American Society of Civil Engineers, vol. 143, 2019, pp. 1-13.

[34] X. Fu, H.-N. Li, G. Li, Z.-Q. Dong and M. Zhao, "Failure analysis of a transmission line considering the joint probability distribution of wind speed and rain intensity," Engineering Structures, vol. 233, 2021, pp. 1-13.

[35] J. Wang, H.N. Li, X. Fu, Z.Q. Dong and Z.G. Sun, "Wind fragility assessment and sensitivity analysis for a transmission tower-line system," Journal of Wind Engineering & Industrial Aerodynamics, vol. 231, 2022, pp. 1-10.

[36] Z. Li, R. Jiangjun, D. Zhiye, H. Daochun and D. Yongqing, "Transmission line tower failure warning based on FBG strain monitoring and prediction model," Electric Power Systems Research, vol. 214, 2022, pp. 1-8.

[37] B. Wenzhe, T. Li, L. Chao, M. Zhen and P. Haiyang, "Wind-induced failure analysis of a transmission tower-line system with long-term measured data and orientation effect," Reliability Engineering and System Safety, vol. 229, 2022, pp. 1-14.