



Original paper

Natural Factors of Accidents at Power Transmission Lines

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Abstract Power lines are energy infrastructure facilities that are most severely affected by the impacts of various natural hazards, especially those of hydrometeorological genesis. Accidents and emergency situations with power outages triggered by natural hazards and adverse phenomena account for more than a half in the total number of natural-technological accidents registered in Russia. The exposure and vulnerability of overhead power transmission networks to natural impacts is caused by their large length and the harsh environment. The paper considers regional differences in the occurrences of accidents triggered by hazardous natural impacts on power transmission lines, identifies natural factors of these accidents, and reveals regions most at risk. The methods used are the geographic and statistical analysis of the information collected by the author in an electronic database of technological and natural-technological accidents and emergency situations. The majority of natural-technological accidents with power disruptions are caused by wind loads, which are especially dangerous in combination with other hydrometeorological factors such as rain, snow, ice and rime deposit, thunderstorm, and hail.

Keywords: Electric power industry, power transmission line, natural hazard, natural-technological accident, emergency situation, database, hydrometeorological hazard and phenomenon

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1. INTRODUCTION

The electric power industry is one of the sectors of the economy most affected by natural factors of various origins (Chang *et al.* 2007; Petrova 2011; Lu *et al.* 2017; Bian *et al.* 2021; Tervo *et al.* 2021; Dobson 2021). This is due to a large number of power infrastructure facilities including the long-distance overhead power transmission lines, transformer substations, and other elements of the energy systems that often fall into the zone of natural risk.

In its turn, the disruption of power supply due to hazardous natural impacts entails a number of negative synergistic consequences. Particularly dangerous are long-term power outages that disrupt the normal living conditions of the population and the normal operation of various economic objects, thereby creating numerous emergency situations (Eidsvig *et al.* 2017; Huitu *et al.* 2020; Mitsova *et al.* 2018; Ulak *et al.* 2018). The greatest damage as a result of interruptions in power supply is reported in industrial, construction and transport types of economic activity (Kattsov 2017). Long-term interruptions in the operation of industrial and transport facilities not only cause economic losses and social problems, but can lead to a chain of further cascading accidents.

The most disastrous consequences had the severe energy crisis that occurred in February 2021 in the state of Texas (USA) as a result of three severe winter storms that swept the United States and led to a significant drop in temperature. It was accompanied by massive failures in power generation and, as a result, a shortage of water, food and heat supply. More than 4.5 million customers, both homes and businesses were left without power, some of them for days. The death of at least 151 people was directly or indirectly related to this disaster (Weber and Stengle 2021). Significant emissions of pollutants have been reported due to disruption of the infrastructure of chemical plants and fuel processing plants.

Due to the large spatial extent and severe environmental conditions of the power transmission lines, they are the equipment of the power system most affected by natural impacts (Bian *et al.* 2021). Among natural factors, the following are reported by the researchers to cause significant damage to power lines: strong wind and ice storm (Hosek *et al.* 2011; Kunz *et al.* 2013; Nateghi *et al.* 2014; Quiring *et al.* 2011), lightning, wildfire (Bian *et al.* 2021; Liu *et al.* 2021; Shield 2018), falling trees (Tervo *et al.* 2021), heavy snowfall, heavy rain, wet snow, and icing (Bonelli *et al.* 2011; Cigrè 2009; Farzaneh 2008; Llasat *et al.* 2014).

Strong winds are among the most significant natural hazards for overhead power lines (Gardiner *et al.* 2010; Kufeoglu and Lehtonen 2015). They can lead to the collapse of power transmission towers and breakage of wires, both directly and due to falling trees on power transmission lines. Windstorms pose a huge challenge for power distribution companies, especially in highly forested countries such as Finland, where falling trees cause power outages for hundreds of thousands of customers every year. Between the years 2010 and 2018,

on average 46 % of all transmission faults in Finland were caused by extra tropical storms (Tervo *et al.* 2021). In the United States, tropical cyclones cause massive damage to electricity supplies. Due to Hurricane Sandy in October 2012, more than 20 million people on the East Coast were affected by power outages that lasted several days to weeks in some regions (Kunz *et al.* 2013).

Icing formation on structures and power lines is another hazardous natural phenomenon that causes damage to electric power industry in many countries and regions with cold and temperate climate such as USA, Canada, Northern Europe, Mediterranean region, Kazakhstan, China, and Japan (Bonelli *et al.* 2011; Chang *et al.* 2007; Cigrè 2009; Dyusebayev *et al.* 2017; Fikke 2005; Fikke *et al.* 2007; Gutman *et al.* 2019; Hosek *et al.* 2011; Llasat *et al.* 2014). High humidity, sudden changes in air temperature from positive to negative contribute to the formation of ice on the wires of overhead lines. For example, wet snow icing accretion on power lines is a real problem in Italy, as well as in other Mediterranean countries, causing failures on high and medium voltage power supplies during the cold season (Bonelli *et al.* 2011). In Norway, ice events can lead to interruptions in the operation of overhead power lines for several days (Gutman *et al.* 2019). The northeast coast of North America is frequently hit by severe ice storms that can produce large ice accretions damaging power transmission and distribution infrastructure (Hosek *et al.* 2011).

In Russia, the energy system covers almost the entire economically developed territory of the country with a variety of weather and climatic conditions, exposing power transmission lines and other power facilities to a large number of different adverse and hazardous natural processes and phenomena. In order to prevent the negative consequences of accidents on power lines caused by natural factors, it is necessary to monitor such events, analyze their causes and identify the places of the greatest risk that need to be dealt with. These issues are especially relevant in the context of ongoing and future climate change. In recent decades, climate warming in Russia was happening faster and about 2.5 times more intense than the average globe. According to climatologists, these trends are expected to continue in the near future (Kattsov 2017).

The purposes of this study are to propose the possibilities of the database in monitoring and analyzing natural-technological accidents and emergency situations (ES) in power facilities; highlight regional features and differences in the manifestation of hazardous natural impacts on power transmission lines in Russia; reveal the main types of adverse and hazardous natural processes and phenomena that have the strongest impact on electrical networks; and identify areas most at risk for such accident occurrences. The lessons from the case study could be learned for regions with similar climatic conditions, since a wide variety of natural hazards and phenomena on the territory of the Russian Federation can be a kind of "testing ground" for studying their consequences for electrical networks.

2. STUDY REGION

The study region is the Russian Federation. The electric power industry is a key branch of the Russian economy, which provides production, transmission, distribution, and consumption of electrical energy, thereby creating the basic conditions for the functioning of the whole economy of the country and the life support of its population.

The energy system of the Russian Federation includes six interconnected energy systems (IES) that are part of the Unified energy system (UES) of Russia of the first synchronous zone: IES of Center, Middle Volga, Urals, North-West, South, and Siberia, as well as seven territorially isolated energy systems in the Far East of the country (Chukotka Autonomous Okrug, Kamchatka Territory, Sakhalin and Magadan Regions, and Nikolayevsk power district in Khabarovsk Territory) and in the Eastern Siberia (Republic of Sakha (Yakutia) and Norilsk-Taimyr power system in Krasnoyarsk Territory) (Ministry of Energy 2021). The IES of the East of Russia including Amur Region, Primorsky and Khabarovsk Territories, Jewish Autonomous Region, as well as the Republic of Sakha (Yakutia) operates separately from the rest of the energy systems. The functioning of isolated power systems in remote and economically isolated areas is much more vulnerable to the impacts of hazardous natural phenomena.

All power systems are connected by intersystem high-voltage power lines with a voltage of 220-500 kV and above and operate in a synchronous mode (in parallel). The power grid of the UES of Russia has more than 13,000 power transmission lines of 110–1150 kV voltage class with a total length of more than 490 thousand km and more than 10,000 electrical substations of 110–750 kV (Unified Energy System of Russia 2021).

Such a large scale of the Russian energy system and the harsh environment determine its strong exposure to a variety of natural factors.

Meteorological and hydrological hazardous processes and phenomena such as strong winds, heavy rains and snowstorms, wet snow and icing, floods, thunderstorms, hailstorms, especially dangerous for overhead power transmission lines, are widespread in the country. The highest frequency of strong winds is observed in the Far East of Russia, as well as in the south and middle parts of the European Russia. The combination of heavy precipitation in liquid and solid form and strong wind is one of the most dangerous climate situations in the coastal regions of the Far East (Sakhalin Region; Kamchatka, Khabarovsk, and Primorsky Territories). The most intense rains are typical for Kamchatka, Krasnodar, and Primorsky Territories; the heaviest snowfalls happen in the North Caucasus, north and south-west of Siberia, as well as Far East (Sakhalin and Magadan Regions; Chukotka; Kamchatka, Khabarovsk, and Primorsky Territories). Regions of the Far East, such as Republic of Sakha (Yakutia), Khabarovsk and Primorsky Territories, Amur Region, as well as the south part of the European Russia (Republics of the North Caucasus; Krasnodar and Stavropol Territories) are mostly exposed to catastrophic floods (EMERCOM 2010).

The cumulative degree of natural hazard is increasing in Russia from the west to the east and south, with progress to the mountainous regions. The most affected by natural hazards are the North Caucasus, Ural and Altai Mountains, Irkutsk Region and Trans-Baikal Territory, the Pacific coast of the Khabarovsk Territory and Magadan Region, and especially Sakhalin, the Kuril Islands, and Kamchatka (Malkhazova and Chalov 2004).

3. MATERIALS AND METHODS

The study is based on the results of the geographic and statistical analysis of the information collected by the author in an electronic database of technological and natural-technological accidents and emergency situations occurring in the Russian Federation. An emergency situation is considered as a situation that has developed in a certain area as a result of an accident, a dangerous natural phenomenon, a catastrophe, the spread of a disease, a natural or other disaster that may or did entail human casualties, damage to human health or the environment, significant material loss and disruption of the living conditions of people (Federal Law 1994). Natural-technological events include accidents and emergencies in technological systems and infrastructure triggered by the impact of any natural hazard.

The database analyzed in this study was created by the author using Microsoft Access. The relational structure of the database and the procedure of its development and operation were described in Petrova (2009) and Petrova (2020). When creating the database, the following research task was set: to collect data about accidents and emergency situations in a structured form with the possibility of their future processing and analysis. All the pieces of information are accumulated in the main database table that has the following columns / database fields: sequence number (assigned automatically); the date of accident; country; region; location; type of accident; its short description including time of occurrence, main characteristics of the event, its probable causes and triggers, consequences and taken measures; the extent of the emergency situation (from local and regional to national and cross-border); the number of fatalities and injuries, if any; material damage; source of information. Each accident / ES is recorded in a separate line of the table. The types of natural-technological accidents are distinguished by the author according to the types of affected infrastructure and the influencing natural factor.

Currently, the database contains more than 25 thousand pieces of information about accidents and emergencies at various technological systems and infrastructure facilities, including those of power grid, which have occurred in Russia since 1991. The database is constantly updated with new relevant information. It should be emphasized that only open data sources are used to fill the database. The main data are obtained from daily operational reports by the Ministry for Civil Defense, Emergencies, and Elimination of Consequences of Natural Disasters of the Russian Federation (EMERCOM 2022) and media news reports. Daily reports by the Ministry for Emergencies are publicly available on the Ministry website:

<https://en.mchs.gov.ru/for-mass-media/operativnaya-informaciya>. The information on the website is a brief list of incidents of natural or technological character and situations under EMERCOM control for the corresponding day. When they are selected for inclusion in the author's database, they are systematized and classified. Of course, not all accidents occurring in Russia fall into the operational reports of the Ministry of Emergency Situations. Each type of accident has specific criteria to be included. The criterion for information by EMERCOM about emergency situations at electric power facilities is a disruption of the living conditions of 50 people or more for one day or more (EMERCOM 2021). Only those accidents that meet these criteria are reported. Since the early 1990s, EMERCOM changed criteria, so the input data is not uniform.

The database format allows an automated search for the information among the accumulated data array, depending on the goals and objectives of the study. For this, such general database tools are used as search queries by keywords and selected parameters and sorting of data. Search results are displayed in tabular form as query tables. These search results may be subjected to further computer processing.

For the purposes of this study, a search of information about accidents and ESs on power transmission lines caused by the impact of adverse and hazardous natural processes and phenomena of various origins was carried out in the author's database. The found information was then sorted by the type of natural hazard and region of their occurrence (constituent entity of the Russian Federation).

The geographic and statistical analysis of the results obtained from the search queries made it possible to trace the spatial and temporal distribution of natural-technological ESs on power lines at the regional level. The proportion of natural-technological events in the total number of accidents and ESs in power grids, as well as their share among all natural-technological events in Russia was evaluated; the main types of natural factors affecting power lines were identified, regions most at risk were revealed.

4. RESULTS AND DISCUSSION

As the statistical analysis of the database has shown, power supply disruptions due to various adverse and hazardous natural influences on electrical networks account for the largest share (more than a half) in the total number of natural-technological accidents and ESs in Russia. Overhead power transmission lines are especially vulnerable to dangerous natural impacts, since they stretch over large distances and inevitably find themselves in the area of activation of natural hazards of various nature and genesis. The greatest damage is caused by hydrometeorological phenomena.

Through search queries in the database, 1470 natural-technological ESs with power outages due to accidents on power lines triggered by natural hazards and phenomena in the

period 1991-2020 have been identified. They account for about 30% of the total number of accidents on power lines. Other accident factors include: deterioration of aged infrastructure, shortcomings in operation and repair, mechanical damages, errors and defects in design and installation, *etc.* All the 1470 ESs were examined. Their triggers and consequences, geospatial distribution, long-term and seasonal variations were considered.

Table 1. Hazardous natural processes and phenomena causing accidents at power lines

Type of hazardous natural process and phenomenon	Intensity of the process leading to losses	Season of the greatest danger
Strong wind	wind speed over 15 m / s	May – August
Ice-rime deposit	more than 10 mm	October – November, February – March
Thunderstorm / lightning	direct lightning strike	June – August
Hail	more than 1 mm	June – August
Precipitation	heavy rain, heavy snowfall, mixed precipitation – of 10 mm or more over an interval of 12 hours or less	May – November; December – February; September – April
Temperature effect	heat, frost – depending on the region	June-August, November – March
Hydrological phenomena	ice jam, rain flood, flood, <i>etc.</i>	April-October
Exogenous slope process	debris flow, snow avalanche	depending on the region
Compound events:	• strong wind and ice-rime deposits; • strong wind, hail, and rainfall; • hail and rainfall; • strong wind and rainfall; • strong wind and snowfall (blizzard) – duration of 12 hours or more at a wind speed of 15 m/s or more	October – November, February – March; June -August; June -August; May – November; December – February

The following natural processes and adverse phenomena were found as triggers of ESs at power lines (Table 1). The intensity of each natural event leading to damages in power

networks and losses in energy sector was evaluated using information from the author's database analysis and results by previous investigations (Analytical report 2010; Vlasova and Rakitina 2009). The second column of the table shows the actually registered minimum intensity of the processes during which breakouts in electrical networks were observed in 1991-2020. The seasons of the greatest danger of manifestation of each natural factor (the third column of the table) were found out using the dates of the events recorded in the database. The previous analytical studies cited above came up with similar results. In case of discrepancies, the minimum value was used.

Wind loads prevail among the main factors of accidents at power lines. They account for more than 80% of all the events recorded in the database. In 63% of these events, the impact of strong wind is accompanied by manifestations of other adverse and hazardous meteorological processes and phenomena. The following compound events triggering ESs with power failures and outages combine wind loads with other weather and climatic factors: joint impact of strong wind with rainfall - in 350 ESs (24%), with snowfall (blizzard) -266 ES (18%), with hail and rainfall -135 ES (10%), with ice-rime deposits -76 ES (5% of events) (Figure 1).

Additionally, accidents at power lines were caused by heavy rains - 94 ES, thunderstorm / lightning strikes - 66 ES, snow loads - 65 ES, debris flows - 21 ES, landslides - 17 ES, floods - 11 ES, earthquakes - 7 ES, snow avalanches - 5 ES, and wildfires - 4 ES.

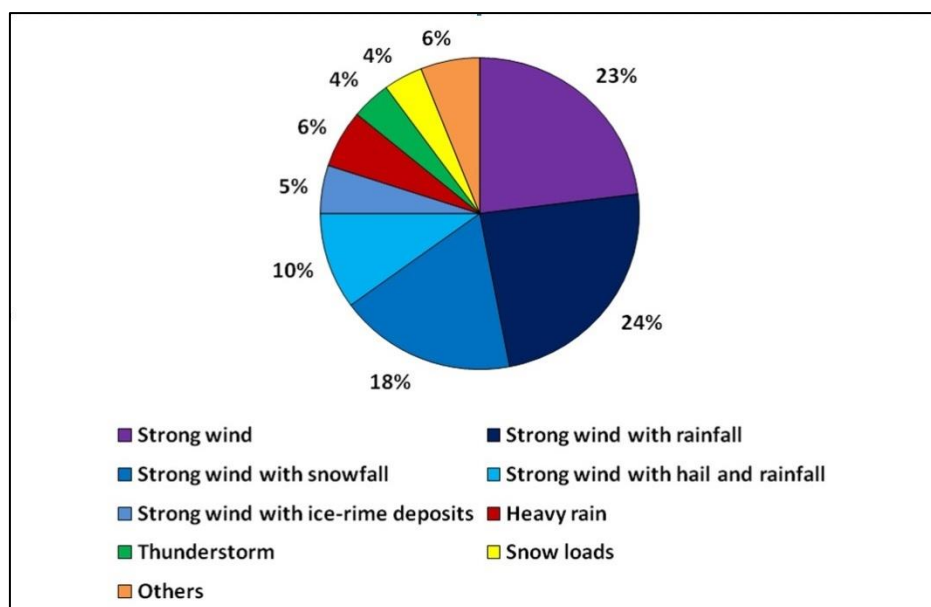


Figure 1. Natural factors of emergencies at power lines registered in Russia in 1991-2020

These results on the identification of the main natural factors of accidents in electrical networks are generally consistent with the findings of other researchers obtained for other

countries and regions (see Section 1), although the proportions of the identified factors may have regional differences. Regional features for Russia are discussed below.

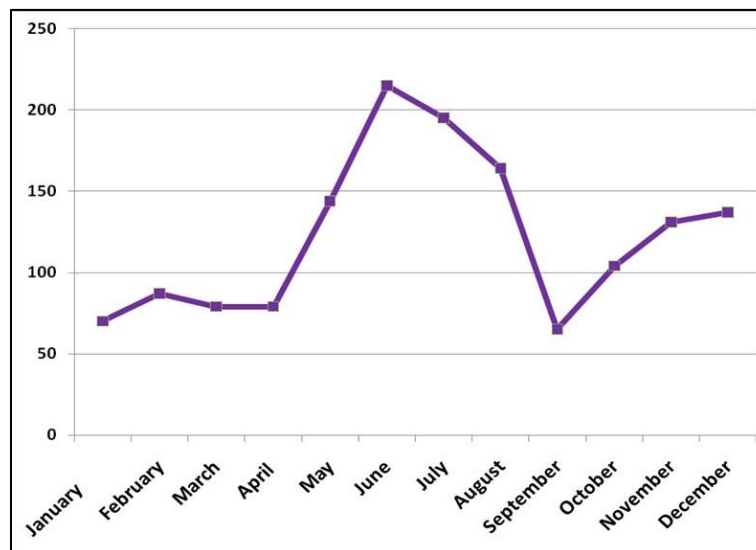


Figure 2. Seasonal cumulative variability in the number of emergencies on power lines caused by natural factors in 1991-2020

The greatest numbers of ESs happen in Russia during the warm months, from May to August, with the maximum in June, as well as during the cold season with the maximum in November and December (Figure 2). Such a seasonal distribution is quite expected, based on the found main accident factors: the summer maximum of emergencies is caused by strong winds, heavy rains and thunderstorms; the winter maximum is mainly due to heavy snowfalls, blizzards and ice-rime deposits.

Geographic distribution of ESs with power outages triggered by compound hydrometeorological events since the early 1990s was examined at the regional level. The results of this analysis are shown in Figure 3. Circles of different colors mark the type of natural hazard combination. The combination of strong winds with rain and snow is widespread throughout the country, while compound events with ice-rime deposits are more characteristic for the middle and south parts of the European Russia and the North Caucasus, as well as the Far East (Sakhalin Region, Primorsky Territory, *etc.*). The distribution of large areas with rather high thicknesses of ice-rime deposits and the most frequent occurrence of their formation on electrical wires in the southern part of Russia including the North Caucasus is mainly due to the unstable weather regime in winter, which is characterized by a frequent change of warm and humid air masses to cold intrusions from the north. In the Far East region, the conditions for the frequent formation of thick ice-rime deposits are favorable due to the intrusion of warm and humid air masses from the Sea of Japan into this area in winter. The largest number of accidents due to rainfall with hail was registered in the south of

Russia and the North Caucasus, which is determined by the geographical location of these regions and their orographic features. Complicated terrain conditions, the close proximity of the Black Sea basin determine the heightened temperature and moisture regimes, which contribute to the activation of atmospheric processes during the warm season in this area (EMERCOM 2010).

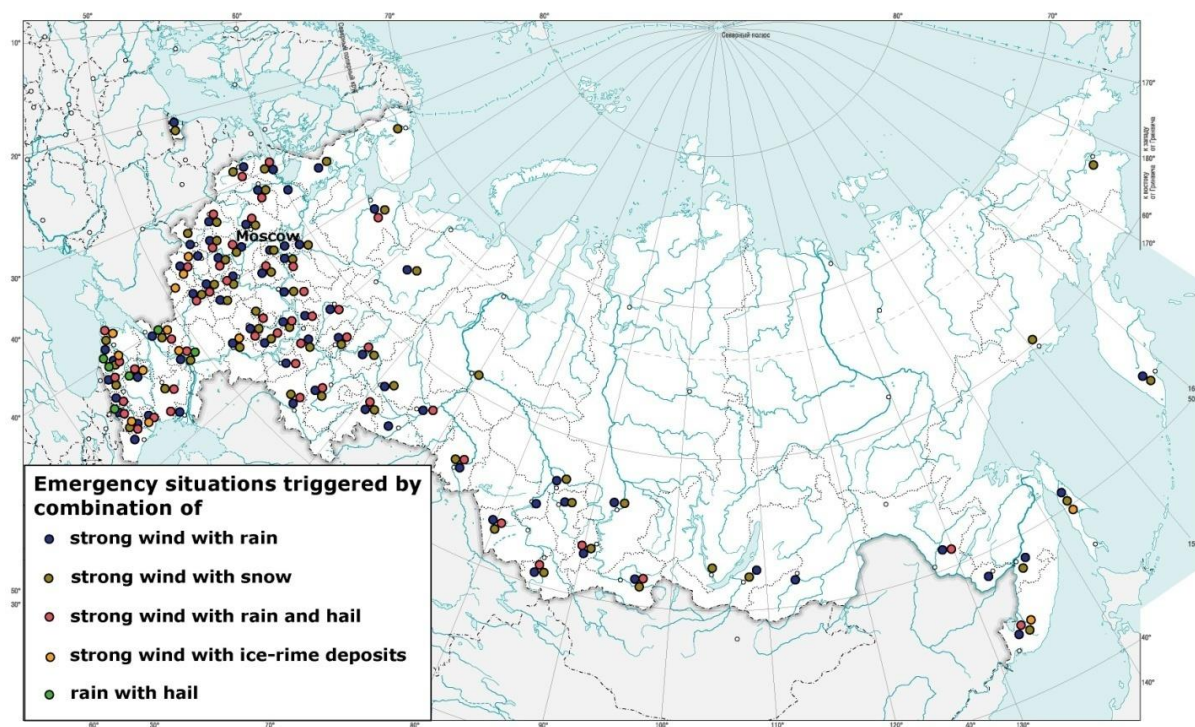


Figure 3. Emergencies at power lines triggered by compound hydrometeorological events in 1991-2020

An average annual frequency of occurrences of ESs at power lines due to all natural factors was calculated at the level of the constituent entities of the Russian Federation. All the 1470 events registered in the database were taken into account in these calculations. At first, a long-term average number of ESs was calculated for each constituent entity, and then the results obtained were compared with the average number for Russia. Based on the comparison, five groups were found according to the frequency (recurrence rate) of such events: 1) very high - more than 2 ESs on average per year; 2) high - 1.5-2 ESs; 3) average – 1-1.5 ESs; 4) low - 0.5-1 ESs and 5) very low - less than 0.5 ESs per year. All constituent entities of the Russian Federation were grouped according to the value of this indicator. The analysis results are shown in the cartogram (Figure 4).

The Sakhalin Region and Krasnodar Territory (with more than 4 ESs on average per year), as well as the Leningrad Region, Primorsky and Stavropol Territories (with more than 2 ESs on average per year) had the highest frequency of occurrences of ESs at power lines due to

natural factors in 1991 - 2020. Quite often, these events were also recorded in the Republic of Tatarstan, Khabarovsk Territory, Nizhny Novgorod, Novgorod, Pskov, Rostov, Tver, and Chelyabinsk Regions (1.5-1.8 ESs on average per year). These results reflect not only the manifestation of natural factors of accidents described in Section 2, but also the greatest exposure of power grids to their impacts in the most economically developed regions of the European part of Russia, where the length and density of power lines is much higher. In the north of the European Russia and in remote areas of Siberia, a smaller number of accidents may be explained by a significantly lower density of power lines, despite harsher environmental conditions.

The main triggers of these accidents were meteorological hazards and phenomena such as strong winds in combination with different kinds of liquid and solid precipitations including snowfall, rain and hail, as well as ice-rime deposits and thunderstorms. The ESs due to compound events of hydrometeorological nature listed above occurred most often and caused the greatest damage to power transmission lines and troubles to the economy and population.

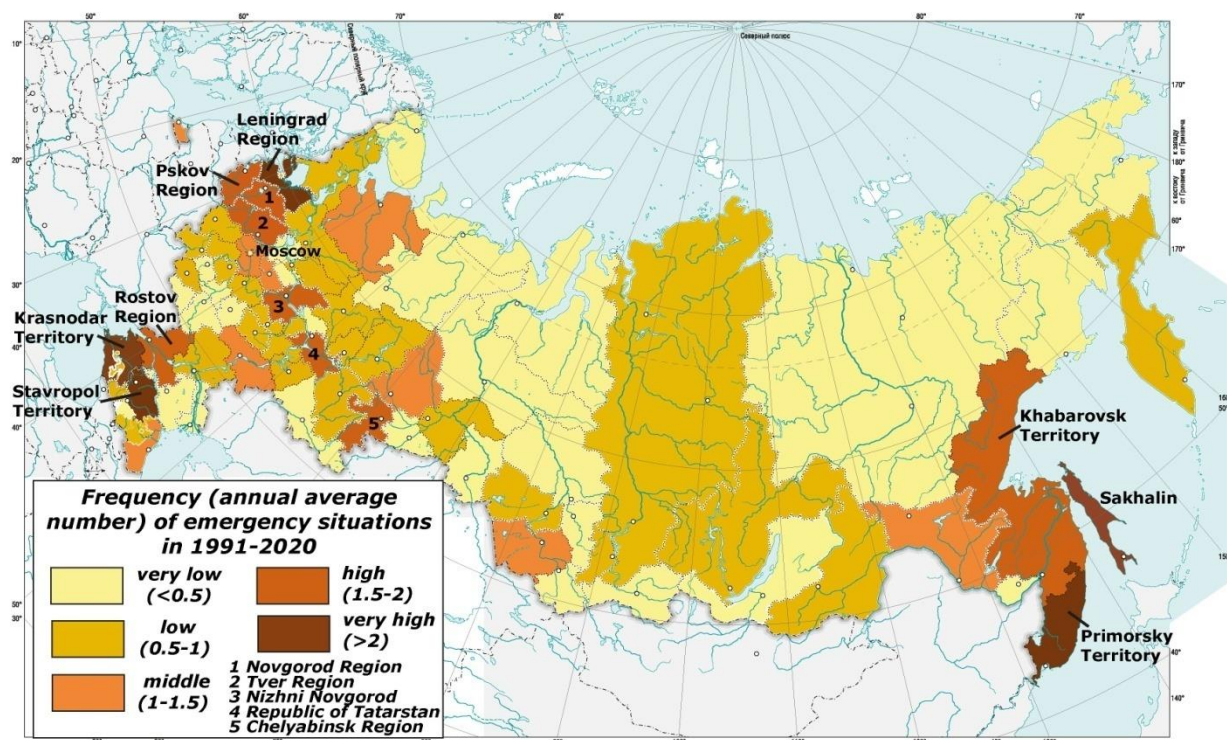


Figure 4. Frequency of occurrences of ESs with power failures caused by natural factors

The climate changes observed in recent decades on the territory of Russia may have significant consequences for the power industry. These climate changes are characterized by increasing in the air temperature during the cold season, increasing in evaporation against the background of a decreasing in precipitation during the warm season, and a more frequent

recurrence of hazardous hydrometeorological phenomena in the whole (Kislov et al. 2008; IPCC 2014). Geographic analysis shows the highest growth rate of the average annual temperature on the coast of the Arctic Ocean, especially in the Asian part of Russia (+0.9 °C/10 years) (Roshydromet 2017). Melting of permafrost is observed in the Arctic zone. In winter, the maximum warming occurs in the northwest, and in summer - in the south of the European part of Russia. On average per year, the least warming is registered in the south of Western Siberia. An increase in precipitation is expected throughout Russia in winter. The increasing in the amount of summer precipitation is observed mainly in the north and east of Russia. In the south of the European part, the number of droughts is increasing and drought conditions are expected to worsen (Kattsov 2017). In general, with warming, the proportion of liquid precipitation increases, which can lead to a change in the hydrological regime of rivers: to decreasing in flood volume and increasing in winter runoff. A further increasing in the intensity of precipitation is expected, which more often will have a stormy character (Kislov *et al.* 2008).

The listed climate changes can lead to increasing in the frequency of occurrences of various natural hazards of meteorological and hydrological origin and other related hazards such as landslides, debris flows, and snow avalanches, as well as to increasing in their intensity and destructive power (Malkhazova and Chalov 2004; Petrova 2019). Over the 21st century, an increase in the number of severe rain floods and high water, storm winds, and weather fluctuations in the form of a series of cold and warm periods are likely to increase within the territory of Russia. In most of the European Russia, an increase in the number of days with an anomalously high amount of precipitation is expected in winter, while in summer, on the contrary, their decrease (Kattsov 2017).

As result, this will entail an increase in the frequency and severity of the consequences of ESs created by them in the technological systems and infrastructure facilities, primarily on overhead power transmission lines, which are especially vulnerable to these natural impacts. In particular, the positive dynamics of precipitation during the cold season, the alternation of thaws and cold snaps, will increase in the risk of wire breakage and destruction of bearing towers of power lines due to snow loads and icing. The melting of permafrost strata creates danger of destruction of various objects of the power grid infrastructure, built on the basis of permanently frozen ground.

In addition, extremely high values of air temperature, leading to a decrease in the original transmitted power, also negatively affect the process of electricity transmission (Bobilev and Dygan 2020). High air temperatures lead to stretching of power lines. In this case, they may sag and contact with adjacent wires, causing a short circuit (Nefedova 2020).

The database does not track statistically significant trends related to climate change due to record inconsistencies and insufficient data collection time. However, we can state an increase in the number and severity of accidents caused by strong winds, heavy snowfalls, rains, ice-rime deposits, and thunderstorms, especially in recent years, which may be due to

climate change. Our findings are consistent with the results of studies in other countries. Thus, atmospheric icing has been analyzed from a climate point of view in Czech Republic, measuring ice-load deposition for a long time in the station of Studnice (Cigrè 2005). The analysis shows a positive trend that is explained as a probable effect of Global Warming. In Italy as well, the frequency of “warm and wet” snowfall events, observed by means of SYNOP data since 1951, shows a positive trend (Bonelli and Lacavalla 2010).

Significant climate change is taking place around the world. According to some data, 90% of the damage from natural disasters in the world is due to dangerous weather and climate events (AGCS 2013). Monitoring and investigation of such phenomena and their consequences is an extremely important and urgent task.

5. CONCLUSIONS

The paper reveals the main triggers of accidents and emergency situations on power transmission lines in the Russian Federation using the information of the author’s database. The majority of natural-technological accidents are caused by various hydrometeorological hazards and phenomena. Most of the events (more than 80%) are due to strong winds; in 63% of cases wind loads are accompanied by other adverse and dangerous meteorological processes and phenomena including precipitation in liquid and solid form such as rain, snow, hail, and ice-rime deposits. The proportion of these natural factors of accidents is assessed; their parameters leading to damages in power networks and losses in energy sector are evaluated. Seasonal variations in the ESs occurrences are examined and months of the greatest danger of manifestation of each natural factor are identified. The greatest number of ESs is observed from May to August, with maximum in June, as well as in November and December.

Regional differences in the accident occurrences on power transmission lines due to hazardous natural impacts are also considered. The highest frequency of ESs over 1991 to 2020 is recorded in Sakhalin Region and Krasnodar Territory, as well as in Leningrad Region, Primorsky and Stavropol Territories where hazardous hydrometeorological events most often occur.

The climate changes observed and expected in the near future can lead to increasing in the frequency and intensity of hazardous hydrometeorological phenomena, which, in turn, will increase in the number of accidents and emergencies on power lines.

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CONFLICT OF INTEREST

The author declares no conflicts of interest in this paper.

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