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PROBABILISTIC ASSESSMENT OF GEOMAGNETICALLY INDUCED CURRENT LEVEL BASED ON AURORAL LOCALIZATION AND STRUCTURE DATA

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Abstract. Development of new probabilistic and statistical models for operational assessment of technospheric risks caused by space weather impacts on high-latitude power systems is a relevant research task with significant practical applications. Such models are of the greatest practical importance in polar and subpolar regions with insufficient availability of reliable and accurate geomagnetic data sources.

This paper presents an original approach to hardware-free (without specialized equipment) assessment of geomagnetically induced current (GIC) levels in power systems of the Russian Arctic zone by interpreting visually observable auroral features as natural indicators of space weather conditions. Using the case study of the 330 kV Vykhodnoy substation in the Severny Transit main power grid, a stable statistical relationship is demonstrated between the auroral observation area, auroral structure, and GIC levels in high-latitude power systems. It is established that during periods of discrete auroras the probability of GIC exceeding 10 A is over 7.5 %, whereas for diffuse auroras this probability is only 0.31 %.

In the absence or scarcity of hardware measurement data, the developed models can be employed to estimate the likelihood of extreme GIC in Arctic power distribution systems and grids, relying solely on visual natural indicators. The practical application of the proposed models in certain scenarios may improve decision-making efficiency in situations with low situational awareness in the relevant field.

Keywords: geomagnetic variations, space weather, high-latitude power grids, statistical models.

INTRODUCTION

The greatest risks of reducing the level of technospheric safety posed by space weather are concentrated in the auroral oval — a belt of intense auroras that occurs when electrons from near-Earth space penetrate into the atmosphere. One of the most significant manifestations of space weather during magnetic storms and substorms is geomagnetically induced currents (GICs) that appear in extended conductive structures such as main pipelines, railways, power transmission lines, and other ground infrastructure facilities [Ptitsyna et al., 2008; Marshall et al., 2011; Pilipenko, 2021; Sokolova et al., 2019; Pilipenko et al., 2023].

In grounded power grids, GICs up to 200–300 A were recorded during magnetic storms [Pirjola et al., 2003], despite the fact that, according to [Vakhnina et al., 2012], even a few amperes of current is sufficient to shift the operating point in transformers of some types to the saturation region and provoke an emergency situation.

One of the most well-known examples of the impact of GIC on the technosphere is thermal damage to power transformers and PTL cascade blackout in the Province of Quebec (Canada) during the March 13, 1989 magnetic storm. As a result, the power grid was de-energized for more than 9 hours, knocking out power for nearly 6 million consumers [Kataoka, Ngwira, 2016]. Similar events happened in the unified energy system of northwestern Russia in November 2001: due to a strong magnetic storm (K_p=7), a single blackout of the overhead 330 kV Olenegorsk—Monchegorsk PTL occurred at the Olenegorsk substation, which led to blackout of a total capacity over 73 MW [Pulyaev, Usachev, 2015; Danilov et al., 2015].

In October 2003, geomagnetically induced currents caused 20–50 min blackouts in the power grid in Malmö (Sweden). At the same time during the magnetic storm initial phase, relay protection misoperation was recorded at the Olenegorsk substation [Radasky et al., 2019].

Economic after-effects of such events are also very significant. According to the Zurich Insurance Group report, 47 cases of power equipment failures were registered only in the United States in 2005–2015 due to increased geomagnetic activity. Insurance payouts were more than 1.9 billion dollars [Dobbins, Schriiver, 2015].

Besides malfunction of power grids located near the equatorial boundary of the auroral oval, extreme GICs have also an effect on the frequency of failures in automation systems of railway infrastructure in high-latitude regions (Figure 1). In [Zeleny, Petrukovich, 2015; Kanonidi et al., 2002], it is observed that during strong magnetic storms induced currents systematically cause synchronous anomalies (false alarms) of semaphore automation in sections of the Oktyabrskaya and Severnaya railways [Yagova et al., 2023].

During periods of extreme geomagnetic activity accompanied by expansion of the auroral oval, mid- and low-latitude energy systems face these risks [Marshall et al., 2011], hence the problem is global.

The relationships between geomagnetic variations and the GIC level established in [Vorobyov et al., 2018; Vorobev et al., 2022a] allow us to diagnose induced currents if there is a corresponding geomagnetic data set with accuracy depending on its quality and the number of sources. For example, according to [Vorobev et al., 2022a], the GIC level (with 15 min averaging) at the 330 kV Vykhodnoy substation (VKH) can be estimated with a root-mean-square (RMS) error ~0.122 A^2.

Despite the acceptable accuracy of the proposed models, the limits of their applicability, in which the dependences remain linear, are still uncertain. An equally serious problem is that the proposed approaches are practically inapplicable to the regions that do not have dense coverage with reliable sources of geomagnetic data (the Taimyr Peninsula, northern regions of the Republic of Sakha (Yakutia), the Gydan Peninsula). This situation significantly impedes the online monitoring of the response of high-latitude power grids to magnetospheric conditions and changes in the telluric electric field, so auroras remain the main publicly available indicator of space weather events.

Vorobev et al. [2024] have already discussed the use of natural space weather indicators for assessing its impact on high-latitude power grids. However, this study took into account only the location of auroras imported from all-sky camera plots (ASCP) [Yagodkina et al., 2019] and paid little attention to other significant features such as the auroral structure.

The purpose of this work is to develop previously proposed approaches to the interpretation of natural space weather indicators by analyzing additional features of upper ionosphere conditions. This will help to fill in the gaps in knowledge of the operation of high-latitude power distribution systems when they are within auroral oval boundaries.

1. PREPARATION OF INITIAL DATA

The Lovozero Observatory (LOZ), which is part of the Polar Geophysical Institute (PGI), is used as a source of data on auroras and their properties. It is practically the only station in the north-west of Russia that has been continuously observing and recording auroras, geomagnetic variations, and other geophysical effects at high latitudes for a long time. We analyze data on auroras in the vicinity of LOZ (Figure 2) for a 14-year period (from 2011 to 2024) providing the highest quality results of synchronous observations of the sky and GIC in the region from LOZ (67.97° N, 35.02° E) to VKH (68.83° N, 33.08° E).

Since 2009, the results of optical observations of auroras have been published by PGI in the form of quarterly ASCP available at [http://pgia.ru/lang/ru/archive_pgi]. With ad hoc algorithms [Vorobev et al., 2023], original all-sky camera plots were transformed into computer-processable spreadsheets. After synchronization with GICs recorded at VKH (see Figure 2), these spreadsheets can be considered as a training sample including 92208 episodes of 30-min synchronous observations of the sky and GIC (Table 1). The tabulated GIC values obtained at VKH were calculated using the formula from [Vorobev et al., 2024]:

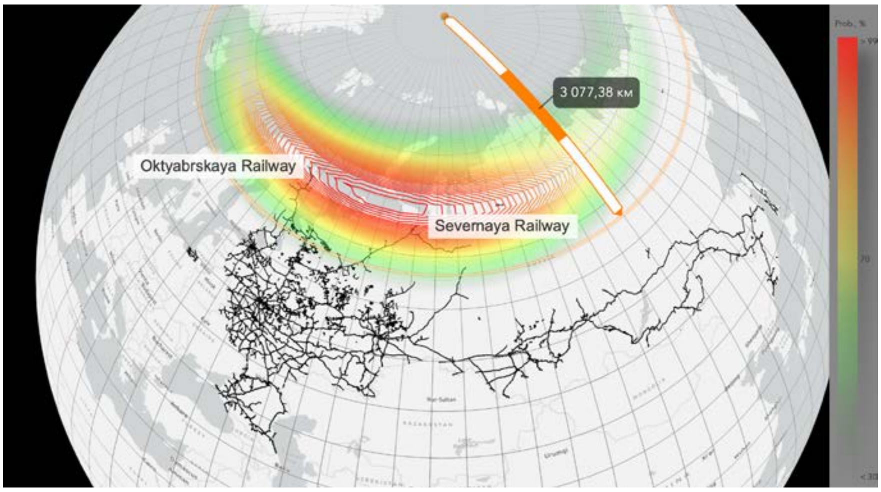

Figure 1. Comparison of the probability of auroras in the main railway lines of the Russian Federation during a magnetic storm with an auroral index *AE*=1450 nT. The forecast is given for February 17, 2022, 18:30 UT according to [Vorobev et al., 2022b; https://aurora-forecast.ru]

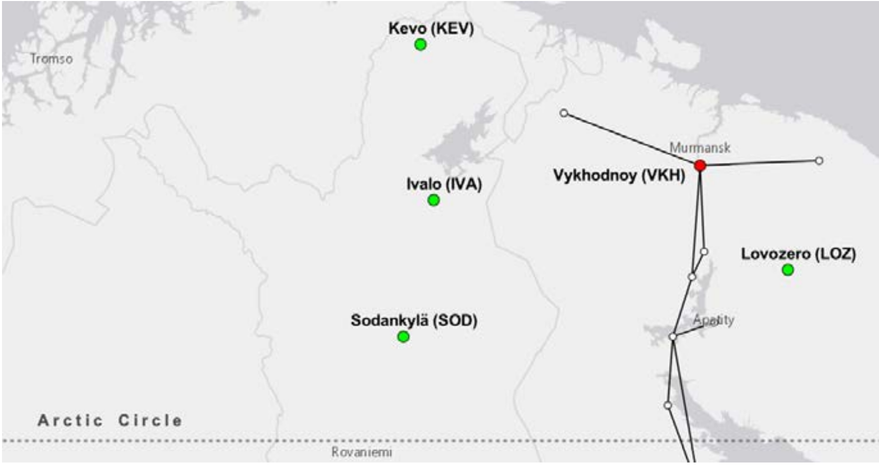

Figure 2. Geography of the main electric power grid Severny Transit (solid black line), which includes the VKH transformer substation (red circle). Green circles mark the surrounding magnetic stations, in particular those indistinguishable on this scale: the Lovozero magnetic station (LOZ), owned by the Murmansk Agency for Hydrometeorology and Environmental Monitoring, and the Lovozero Observatory (LOZ) being part of the Polar Geophysical Institute

Table 1

Chunk of synchronous observation data on auroras and GICs

№	UTC	J_{VKHn}, A	Auroras in the north	Auroras at the zenith	Auroras in the south
…	…	…	…	…	…
12191	Dec. 14, 2013, 18:00	1.415	1	1	2
12192	Dec. 14, 2013, 18:30	8.226	1	1	1
12193	Dec. 14, 2013, 19:00	8.179	1	1	2
12194	Dec. 14, 2013, 19:30	2.878	1	1	2
…	…	…	…	…	…

Note: J_{VKHn} is GIC calculated from Formula (1); 0 — no auroras; 1 — auroras are present; 2 — cloudiness [Vorobev et al., 2024]

$$J_{VKHn} = \frac{1}{N} \sum_{m=n}^{n+\Delta t_1/\Delta t_2} \left| J'_{VKH} \right|_{m'}, \quad (1)$$

where Δt_1=30 min is the sampling increment of chunks of optical observations of auroras (ASCP); Δt_2=0.5 s is the sampling increment of GIC data; J_{VKH} is GIC data published by PGI; $N=\Delta t_1/\Delta t_2$.

A significant amount of information on the impact of geomagnetic activity on the main electric grid over 800 km long was accumulated due to the regional monitoring system for currents in the neutral conductors of transformers, which was established in 2011. The Kola Science Center of the Russian Academy of Sciences (KSC RAS) together with PGI with the assistance of the Federal Grid Company of Unified Energy System [Barannik et al., 2012] in 2022 published a database of GIC measurements in neutrals of autotransformers at three substations (Vykodnoy, Loukhi, Kondopoga) of the 330 kV main electric power transmission line Severny Transit for 2011–2022 [RF Certificate of State Registration of Database No. 2022623220 "Geomagnerically Induced Currents in the Main Electric Power Transmission Line Severny Transit, http://gic.en51.ru; Selivanov et al., 2023].

Optical observation data set (since 2015), publicly available at [http://aurora.pgia.ru:8071/?p=2], comprises RGB images with a resolution 600×600 px and a sampling increment of 10 s. Taking into account both the amount of graphical information and the dynamics of the observed phenomena, we analyzed images with a sampling increment of 10 min. At the preprocessing stage, the images were scaled to 224×224 px, which reduced their volume and increased the speed of the digital assistant involved in labeling the observational data. Upon preprocessing, the sky photodata from December 04, 2015 to April 27, 2024 includes 163899 sequentially recorded non-repeatable images with a total volume of ~8 GB.

We have processed and classified 92987 sky images, using the classification presented below, for the period of interest. The ratio between the number of elements of each class is shown in Table 2.

1. Clear sky/no auroras — an image in which auroras are not definitely observed.

2. Discrete aurora — an image in which the aurora with discontinuous structure has the shape of a spiral or vortex with brightness exceeding that of background stars.

3. Auroral arc (arc) — an image in which there are one or two pronounced horizontal auroral arcs.

Table 2

Ratio between occurrence of images of different classes, taken by the LOZ Observatory camera

Occurrence	Class						
	Clear sky	Discrete aurora	Arc	Diffuse aurora	Aurora beyond the horizon	Aurora and cloudy	Defective images
N	51278	1201	3078	2806	5908	24560	4159
P, %	55.1	1.3	3.3	3.0	6.4	26.4	4.5

4. Diffuse aurora — an image showing large areas of auroras with blurred edges. The brightness of the auroras is comparable to or weaker than the brightness of background stars.

5. Aurora beyond the horizon — an image in which most of the aurora is located near or beyond the horizon, which makes it difficult to identify the structure of the aurora.

6. Aurora and cloudy — an image in which an aurora is observed under cloudy conditions, indicating the potential presence of an aurora, but it is impossible to place it unambiguously in one of the classes.

7. Defective image — an image with great noise and/or other artifacts.

If there were auroras of several types in one image, identification was carried out from the average brightness of the image: first discrete, then arc, and diffuse at the end. The exception was the images of auroras near the horizon, whose shape resembles an arc. In such cases, the event was classified as an aurora beyond the horizon. If the identification was impossible, the image was ignored.

2. CORRELATION AND STATISTICAL RELATIONSHIPS BETWEEN GIC AND REGION OF OBSERVATION OF AURORAS

As shown in [Vorobev et al., 2024], the distribution of J_{VKH} during simultaneous observations of auroras in different areas of the sky corresponds to the lognormal law [Eckhard et al., 2001; Wintoft et al., 2015]. This is confirmed by the Kolmogorov—Smirnov test [Dimitrova et al., 2020], is consistent with the previously obtained results [Vorobev et al., 2019; Vorobev, Pilipenko, 2021; Vorobev et al., 2022a], and also does not contradict the research conducted by PGI [Vorobyov et al., 2018], Schmidt Institute of Physics of the Earth (IPE RAS) [Pilipenko et al., 2024], and other organizations [Tanskanen, 2009].

It has previously been found that the most probable J_{VKH} level for auroras in the north, zenith, and south is 0.08, 0.23, and 0.68 A respectively (Figures 3, 4), which is attributed to the expansion of the auroral oval during periods of intense geomagnetic activity. This gives grounds to consider the probable level of currents, induced in high-latitude PTLs, as function of the region of manifestation of auroras in the optical range [Vorobev et al., 2024]. Vorobev et al. [2024] have indicated that the probability that the GIC level exceeds 2 A in a power grid (averaged over 30 min) for auroras in the north is 6 %; and for auroras at the zenith and in the south, 10 % and 15 % respectively (see Figure 4, *b*). The probability that J_{VKH} will exceed 10 A during auroras in the south is 0.15 % versus 0.06 % and 0.04 % for auroras at the zenith and in the north respectively.

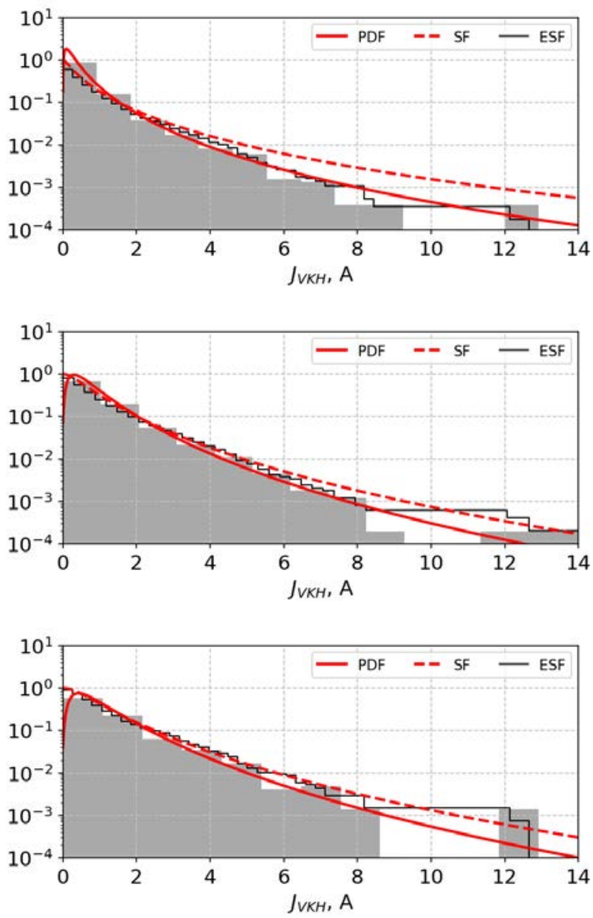

Figure 3. GIC statistics for auroras in the north (*a*), at the zenith (*b*), and in the south (*c*): red solid and dashed lines are respectively probability density function (PDF) and survival function (SF) of the lognormal distribution law; the black solid line is the empirical survival function (ESF) [Vorobev et al., 2024]

It has also been established that in the absence of auroras at high latitudes or with weak diffuse auroras the statistical characteristics of GIC demonstrate maximum asymmetry and excess (see Figures 3, 4). This suggests a predominant concentration of J_{VKH} in the lower range and a minimum level of uncertainty (see Figure 4, *a*). It can be assumed that extreme GICs almost always accompany auroras. At the same time, the presence of auroras is not a sufficient condition for the occurrence of extreme GICs, which indicates a complex relationship between these phenomena.

3. STATISTICAL RELATIONSHIP BETWEEN GIC AND AURORAL STRUCTURE

For comparative analysis of GIC levels with the auroral structure, we have used four best classified states of the sky: no auroras, diffuse, arc, and discrete auroras. The distribution pattern of J_{VKH} values averaged over 10-min intervals, corresponding to one of the states of the sky, is illustrated in Figure 5. All histograms, as before, are closest to the lognormal distribution. The thickness of the distribution tail increases monotonously from Figure 5, *a* to Figure 5, *c*, and at statistical grouping of J_{VKH} values it may be indicative of the structure of observed auroras.

Table 3 presents some statistical characteristics of GIC observed synchronously with one of the states of the sky considered. It follows from Table 3 that during discrete auroras the GIC level exceeds 2.58 A with 50 % probability. With the same probability, during auroral arcs GICs exceed the threshold of 0.98 A. During diffuse auroras or in the absence of auroras as such, the GIC level with 50 % probability does not exceed 0.72 and 0.41 A respectively.

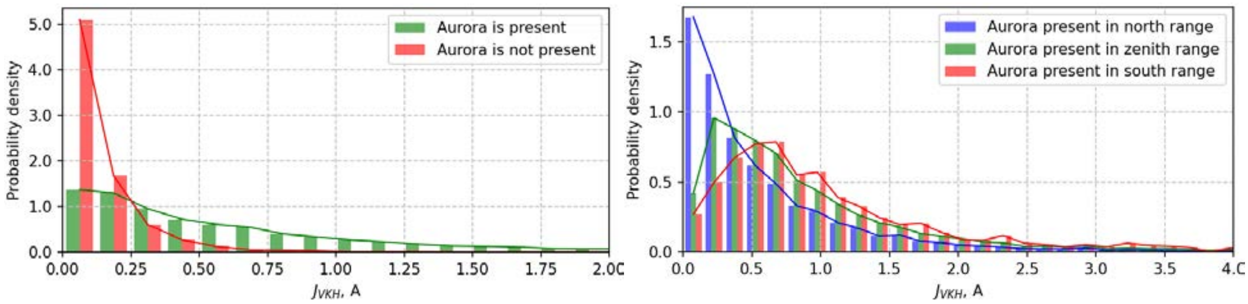

Figure 4. Histograms of probability density distributions of GIC values in the presence/absence of auroras (*a*) and their differentiation by areas of the sky (*b*). In this case, the width of the histogram intervals is determined according to the rule h_n=3.49$sn^{-1/3}$, where n is the sample size and s is the standard deviation [Scott, 1979], and corresponds to ~0.15 A [Vorobev et al., 2024]

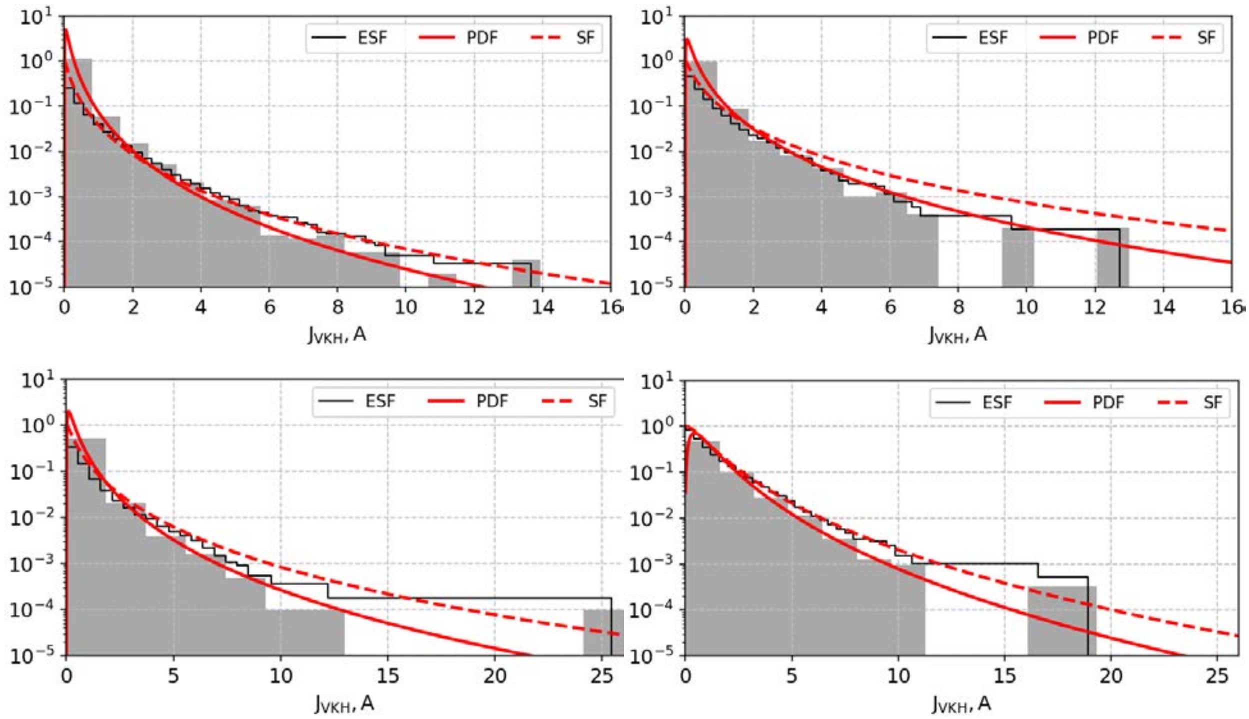

Figure 5. Distributions of J_{VKH} values (averaged over 10 min) during periods of absence of auroras (*a*) and during diffuse (*b*), arc (*c*), and discrete (*d*) auroras. Designations are the same as in Figure 3

Table 3

Estimated GIC values for different conditions of the upper ionosphere

Condition \ Characteristic	Mean value, A	Mean maximum in pulse, A	Threshold exceeded with 50 % probability, A	Probability of exceeding the 10 A threshold, %
No auroras	0.28	0.84	0.41	0.17
Diffuse aurora	0.45	1.30	0.72	0.31
Auroral arc	0.59	1.79	0.98	1.70
Discrete aurora	1.29	4.05	2.58	7.56

Table 4

Statistical characteristics of GIC samples for auroras of different types

Condition \ Characteristic	Standard deviation, A	Interquartile range, A
Diffuse aurora	1.93	1.17
Auroral arc	2.91	1.55
Discrete aurora	4.57	3.35

Note that diffuse auroras have a minimum standard deviation of J_{VKH} and the highest interquartile range IQR (Table 4), which indicates a shift in the distribution maximum to the region of weak GICs. In other words, during observation of diffuse auroras, the probability of extreme GICs that can trigger serious consequences is extremely low.

The situation with the absence of auroras is less clear because during labeling of all-sky camera data [Sigernes et al., 2014] auroras simply may not get into the lens of the photorecorder. This problem can be solved by increasing the density of coverage of the sky with photorecorders. Note that this problem is not relevant to the practical application of the approach we put forward, i.e. in visual assessment of the sky.

4. DISCUSSION

Using the region in question as an example, we have shown the statistical relationship between the region of observation of auroras, their structure and GICs in high-latitude power grids. This relationship can be employed to estimate the GIC probability level in polar power distribution systems and grids. We have found that during observations of discrete auroras the GIC level exceeds 10 A with 7.5 % probability; whereas during diffuse auroras, the probability of reaching a similar level is 24 times lower.

Further research should be aimed at integrating the distributions of GIC values depending on the structure and location of auroras into a single correlation and statistical model. The relationship between GIC and auroral structure should also be investigated further. In addition, it is deemed advisable to expand the classification system of auroras in the context of the subject area under study.

Since statistical methods were mainly adopted, some of the numerical values obtained in the work are estimated and may vary in the case of other initial data; it can, however, be expected that the qualitative relationships between them will remain unchanged.

Our approach is undoubtedly inferior in accuracy to classical methods based on satellite and ground-based instrumental data on conditions of Earth's magnetosphere, but its advantage is independent from hardware and communication systems.

Note also that achieving a qualitatively new level of technospheric safety of the high-latitude infrastructure facilities considered requires the development of proper observation networks.

CONCLUSION

Due to the high probability of extreme disturbances of auroral oval boundaries, there is a real threat of a decrease in the level of technospheric safety. The decision support and monitoring systems designed to promptly diagnose and predict the reaction of technological facilities to space weather impacts are not always effective so far. For example, in Russia, in fact, the only GIC measurement system belongs to the Polar Geophysical Institute and the North Energy Center, which have been monitoring GIC in Kolenergo power grids since 2010, providing specialists with the opportunity to investigate this phenomenon on the Kola Peninsula [Gvozdarev et al., 2024].

In the rest of the Russian Arctic, the auroras remain the only universally available indicator of space weather conditions. A scientifically based interpretation of auroras can help in assessing the probability of failures in high-latitude navigation and power distribution systems, communication systems, as well as at railway infrastructure facilities, since the diurnal variation in the occurrence of failures in automation systems correlates with the diurnal variation in the probability of auroral observations.

Figure 6 illustrates the distribution of anomalies in automation systems of the Severnaya Railway (*a*) and the probability of observing auroras in the vicinity of the LOZ station (*b*) depending on local time. Both distributions

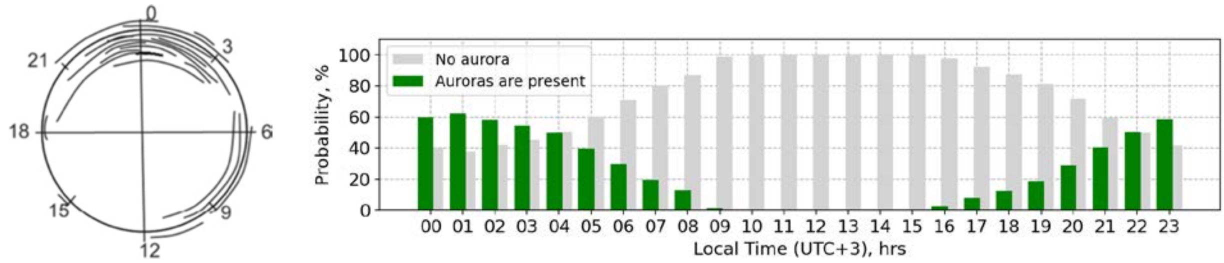

Figure 6. Possibility of diagnosing the probability of failures in automation systems of high-latitude railways based on natural indicators of space weather conditions: distribution of alarm anomalies on the Severnaya Railway relative to local time during severe magnetic storms in 1989 and 2000–2005 [Eroshenko et al., 2010] (*a*); daily variations in the probability of observing auroras in the vicinity of the LOZ station (*b*)

reveal a well-defined maximum near midnight, which is consistent with the known daily pattern of geomagnetic activity and the frequency of substorms. Note that the coincidence of the maxima is not a direct evidence for the cause-effect relationship. Both processes must have been caused by a common factor — large-scale variations in the magnetic field during substorms, which trigger intense auroras and generate GICs.

Furthermore, as follows from Figure 6, *a*, the distribution of failures has a secondary maximum in the morning, probably associated with intense Pc5 pulsations rather than with auroral activity as auroras are observed less frequently during this period (see Figure 6, *b*). This effect calls for further research.

Vorobev et al. [2024] have shown that GIC depends on the area of manifestation of auroras, and a posteriori probability of them exceeding a certain value can be approximated by Expression (2):

$$P\left(A|B\right) \approx P\left(J_0\right) = a\exp\left(bJ_0\right) + c, \qquad (2)$$

where $P(A|B)$ is the probability that when observing auroras in a given area $J_{\text{VKH}} \geq J_0$, where J_0=const is a certain preset value of GIC; a=102.87 for cases of absence of auroras, a=102.68, 104.69, 103.60 for cases of observation of auroras in the north, at the zenith, and in the south respectively; similarly, b=–4.34, –1.69, –1.21, –0.95 and c=0.04, 0.68, 0.53, 0.62 for cases of absence of auroras and their observations in the north, at the zenith, and in the south respectively. At the same time, the limits of applicability of Formula (2) in the given form have yet to be clarified, primarily in the range of large current values (J_0>10 A), which were not considered in [Vorobev et al., 2024].

The development of this line of research has also allowed us to identify statistical relationships between GIC and auroral structure. We have shown that during diffuse auroras and in the absence of auroras GICs with 50 % probability do not exceed 0.72 and 0.41 A respectively. During auroral arcs, J_{VKH} with 50 % probability exceeds the 0.98 A threshold. During discrete auroras with the same probability J_{VKH}>2.58 A.

The assumption has been formulated and justified that during diffuse auroras and in the absence of auroras the probability of occurrence of extreme GICs capable of triggering serious consequences is extremely low. It has been hypothesized that GICs are linked to the location (north, zenith, or south) and structure (diffuse, discrete, or arc) of auroras observed in the vicinity of high-latitude PTL.

This approach can be used to assess both the probability of failures in automation systems of high-latitude railways and the additional error in satellite navigation systems and magnetic inclinometers applied in controlled directional drilling of oil-and-gas wells in the Russian Arctic [Gvishiani, Lukyanova, 2017; Soloviev et al., 2022]. A natural limitation to the applicability of this approach is that observing auroras in the night sky at high latitudes is possible only seven months a year under favorable meteorological conditions.

We are grateful to the Polar Geophysical Institute (PGI) for the data on auroras provided by the Lovozero Observatory, as well as to PGI and the KSC RAS Center for Physical and Technical Problems of the Energy of the North for the GIC data from the VKH station. We would also like to thank the reviewers for their comments and suggestions, which made it possible to significantly improve the paper.

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