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APPROACH TO HARDWARELESS ASSESSMENT OF THE GEOINDUCED CURRENTS LEVEL IN HIGH-LATITUDE POWER ELECTRIC SYSTEMS

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Abstract: The development and implementation of new correlation-statistical models for the operational assessment of technospheric risks arising from the impact of space weather on power electric systems operating within the boundaries of the auroral oval is currently an urgent research problem with a pronounced applied nature. Such models demonstrate the highest practical significance in polar subregions with a low density of coverage by reliable and credible sources of geomagnetic data (Taimyr Peninsula, Gydan Peninsula, northern regions of Yakutia, etc.), i.e., in fact, the overwhelming territory of the Arctic zone of the Russian Federation (AZRF). Thus, the paper is concerned with a new approach, which is proposed to the non-hardware assessment of the level of geoinduced currents (GIC) in the power electric systems of the AZRF, which is based on correlation-statistical modeling of the GIC level according to the observation of auroras as an accessible natural indicator of space weather state. Using the example of the Vykhodnoy substation of the Northern Transit main power grid, it is shown that when registering auroras in the north, at the zenith, and in the south, the probable (averaged over 30 min) GIC levels are ~0.08 A, ~0.23 A, and ~0.68 A, respectively. At the same time, the probability of exceeding the average half-hour GIC levels of 2 a (in the case of auroras in the north, at the zenith, and in the south) are ~6%, ~10%, and ~15%, respectively.

Keywords: geoinduced currents, auroras, geomagnetic variations, space weather, high-latitude power electric systems, statistical models.

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1. Introduction

It is known that the highest risks of reducing the level of technosphere safety associated with the space weather effects on technical systems and networks are determined within the auroral oval, which is a belt of intense luminosity created by the invasion of electrons from near-Earth space into the atmosphere. One of the most significant responses of ground infrastructure objects to space weather variations during magnetic storms and substorms are geoinduced currents (GIC) excited in conductive spatially distributed structures: trunk pipelines, railways, power transmission lines (PTL), etc. [*Marshall et al.*, 2011; *Pilipenko et al.*, 2023; *Ptitsyna et al.*, 2008; *Vorobev et al.*, 2019; *Vorobev and Vorobeva*, 2017].

For example, the magnetic storm of March 13, 1989 caused the failure of power transformers and a cascade blackout of power transmission lines (PTL) for more than 9 hours in the province of Quebec (Canada) [*Kataoka and Ngwira*, 2016]. In November 2001, in the unified power electric system of northwestern Russia, due to geomagnetic activity (GMA), there were two unilateral shutdowns of the overhead power line (330 kV) "Olenegorsk-Monchegorsk" from the side of the "Olenegorsk" substation, as a result of which consumers with a total capacity of more than 70 MW were disconnected [*Danilov*, 2015; *Pulyaev and Usachev*, 2002]. In October 2003, a similar case caused a 20–50-minute power outage in the Malmö power grid in southern Sweden, as well as a false tripping of

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a relay at the Olenegorsk substation at the very beginning of a magnetic storm [*Radasky et al.*, 2019]. According to a report by Zurich Insurance Group, in the United States, insurance payments exceeded $1.9 billion as a result of electrical equipment failures during magnetic storms from 2005 to 2015 alone [*Dobbins and Schriiver*, 2015]. In the works [*Pilipenko*, 2021; *Pilipenko et al.*, 2023; *Zeleny and Petrukovich*, 2015] note that current interference after almost every strong magnetic storm is the cause of synchronous anomalies (false alarms) in the operation of the signaling automation of the northern branches of the October and Northern Railways [*Kanonidi et al.*, 2002; *Yagova et al.*, 2023], located beyond the Arctic Circle, near the equatorial boundary of the auroral oval.

The global scale of the problem is given by the fact that during periods of extreme geomagnetic activity (GMA), due to the shift (northern and southern) of the auroral oval in the equatorial direction, the named risks are projected onto power electric systems operating at middle and even low latitudes.

The relationships between geomagnetic variations (GMV) and the GIC level established in [*Blake et al.*, 2018; *Marshall et al.*, 2011; *Vorobev et al.*, 2024, 2019, 2022] partially provide the possibility for current interference diagnostics in the presence of appropriate sources of geomagnetic data with an accuracy depending on their number and quality. For example, according to [*Vorobev et al.*, 2022], the GIC level at the Vykhodnoy station (VKH) averaged over 15 min can be estimated from expression (1) with a root-mean-square error of ~ 0.122 A^2.

$$|J_{\mathrm{VKH}}| = \beta_0 + \beta_1 \left|\frac{dY_{\mathrm{LOZ}}}{dt}\right| + \beta_2 \left|\frac{dY_{\mathrm{IVA}}}{dt}\right| + \beta_3 \left|\frac{dY_{\mathrm{KEV}}}{dt}\right| + \beta_4 \mathrm{IE}, \tag{1}$$

where $dY_{\mathrm{LOZ}}/dt, dY_{\mathrm{IVA}}/dt, dY_{\mathrm{KEV}}/dt$ are variability of the eastern component of the GMV recorded by the stations Lovozero (LOZ), Ivalo (IVA) and Kevo (KEV) respectively; IE is a value of IE-index [*Tanskanen*, 2009], $\beta_0, \beta_1, \ldots, \beta_4$ are coefficients.

Despite the good accuracy of the method, the limits of its applicability, within which the specified dependence keeps its linear nature, remain unclear. However, a more significant problem with the proposed approach is that it is practically inapplicable to regions that do not have dense coverage by reliable [*Vorobev and Pilipenko*, 2021] sources of geomagnetic data, such as the Taimyr Peninsula, the Gydan Peninsula, the northern regions of the Sakha Republic (Yakutia), etc.

This situation is typical for most of the Arctic zone of the Russian Federation (AZRF) and practically excludes the possibility of prompt diagnostics of high-latitude power electric systems response to changes in the state of the upper ionosphere. Here, the auroras remain practically the only publicly available indicator of space weather state. Thus, the aim of the research is to study the statistical and correlational relationships between polar auroras and GIC. It can provide the possibility of operational non-instrumental assessment of the GIC in conditions of data deficiency, which is typical for the Asian part of the Arctic region.

2. Experimental data

The Lovozero Observatory (LOZ), which is part of the Polar Geophysical Institute (PGI) and is practically the only station in the Russian Federation that continuously and for a long time conducts observations and records of polar lights, variations in the magnetic field and other geophysical effects of high latitudes caused by processes in the magnetosphere, ionosphere and atmosphere of the Earth, is used as the main source of data on the presence of polar lights. The data on auroras in the vicinity of the LOZ observatory (Figure 1) were analyzed for a period of more than 10 years (from October 10, 2011 to December 31, 2021), corresponding to the highest quality results of synchronous observations of the sky and the GIC level in the subregion limited by 67.97° N, 35.02° E (Lovozero village, Murmansk region, Russia) and 68.83° N, 33.08° E (Vykhodnoy transformer substation (VKH), Murmansk region, Russia).

Since 2009, the results of optical observations of auroras have been published by PGI in the form of quarterly sets of ascaplots (Figure 2) [*Yagodkina et al.*, 2019], available at: http://pgia.ru/lang/ru/archive_pgi. The format of information presentation, unchanged since the 1970s, is outdated and is practically unacceptable for the tasks of intellectual analysis of large volumes of this kind of data [*Vorobev et al.*, 2023b]. In this regard, based on specially developed algorithms [*Vorobev et al.*, 2023a], the original ascaplots were converted into corresponding electronic tables, which, in turn, were synchronized with the GIC values recorded at the VKH station (Figure 1). This became possible in many ways due to the fact that in 2011 the Kola Science Center of the Russian Academy of Sciences (KSC RAS), together with PGI and with the assistance of the Federal Grid Company of the Unified Energy System (FGC UES), created a regional system for monitoring currents in transformer neutrals, which accumulated a significant amount of information on the impact of GMA on the main electrical network with a length of over 800 km [*Barannik et al.*, 2012]. As a result, in 2022, a database of GIC measurements in the neutrals of autotransformers at three substations (Vykhodnoy, Louhi, Kondopoga) of 330 kV of the Northern Transit main electrical network for the period 2011–2022 was published (Certificate of the Russian Federation on state registration of the database No. 2022623220 "Geoinduced currents in the Northern Transit main electrical network", http://gic.en51.ru) [*Selivanov et al.*, 2023].

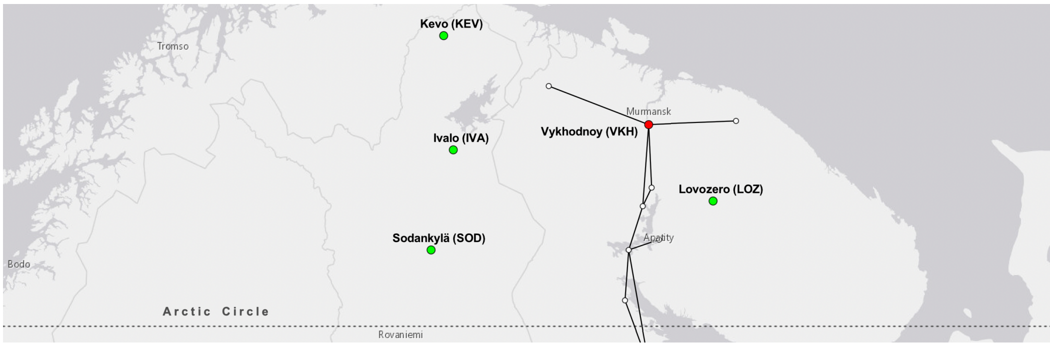
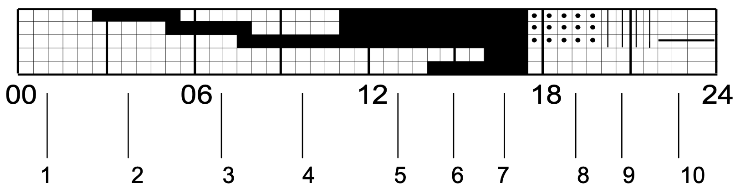
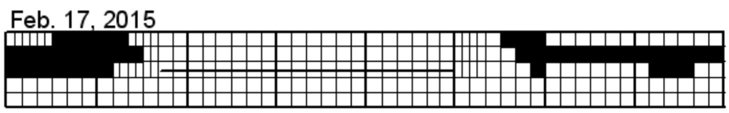


Figure 1. Geography of the Northern Transit main power grid (solid black line), including the Vykhodnoy transformer substation (red marker). Green markers correspond to nearby magnetic stations, including the spatially indistinguishable Lovozero (LOZ) magnetic station, which belongs to the Murmansk Department for Hydrometeorology and Environmental Monitoring and the observatory, which is part of the Polar Geophysical Institute.



(a)



(b)

Figure 2. Data presentation format as an ascaplot: 1 – no aurora observed; 2 – aurora in the northern region; 3 – aurora at zenith; 4 – aurora in the south; 5 – aurora at zenith, northern and southern regions; 6 – moderate aurora at zenith, in addition, aurora is present in the northern and southern regions; 7 – strong aurora at zenith, in addition, aurora is present in the northern and southern regions; 8 – partial cloudiness; 9 – solid cloudiness; 10 – no registration was carried out (a); an example of an ascaplot of the LOZ observatory for 14.12.2013 [*PGI Geophysical data*, 2013] (b).

Thus, as a result of digitizing 1921 ascaplots for 2011–2021, 92,208 episodes of 30-minute synchronous observations of the sky in the vicinity of the LOZ observatory and the GIC level at the VKH station were obtained (Table 1).

Table 1: Fragment of data from synchronous observation of polar auroras and GIC.

No.	UTC	J_{VKHn}, A	Auroras in the north	Auroras at the zenith	Auroras at the south
…	…	…	…	…	…
12191	2013-12-14 18:00	1.415	1	1	2
12192	2013-12-14 18:30	8.226	1	1	1
12193	2013-12-14 19:00	8.179	1	1	2
12194	2013-12-14 19:30	2.878	1	1	2
…	…	…	…	…	…

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

where Δt_1 is a discretization step of optical observations of auroras (ascaplots) $\Delta t_1 = 30$ min, Δt_2 is a discretization step for GIC $\Delta t_2 = 0.5$ s, J_{VKHn} are data on GIC published by PGI.

As an example, Figure 3 shows a time diagram of synchronous registration of the GIC at the VKH substation and auroras by the LOZ observatory as of December 14, 2013. As follows from the figure, the periods of auroras presence correspond to the time intervals of the occurrence of significant variations in the GIC. At the same time, the existence of auroras in the southern part of the sky correlates with the occurrence of extreme values of the GIC.

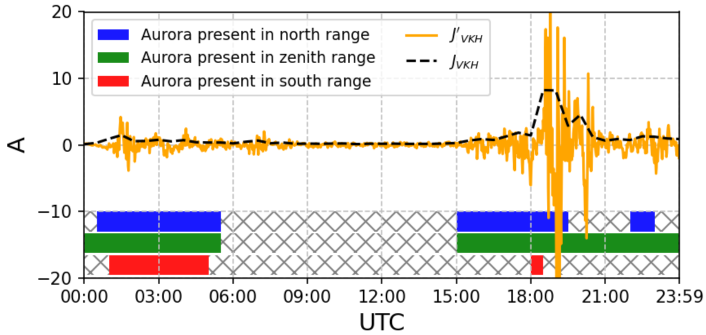


Figure 3. Comparison of the GIC level at the VKH station and the aurora observation area in the vicinity of the LOZ observatory (for December 14, 2013).

3. Correlation-statistical relationships between GIC and auroras observation area

Let us consider the basic approach to diagnosing the level of GIC according to the observations of auroras based on Bayes' theorem. Thus, in the context of the problem being solved, we have:

$$P(A \mid B) = \frac{P(B \mid A)P(A)}{P(B \mid A)P(A) + P(B \mid \sim A)P(\sim A)}, \tag{2}$$

where $P(A \mid B)$ is the probability that when observing auroras in a given region $J_{\mathrm{VKH}} \geq J_0$, where $J_0 = \mathrm{const}$ is some given value of the GIC; $P(B \mid A)$ is the probability of observing auroras in a given region when $J_{\mathrm{VKH}} \geq J_0$; $P(A)$ and $P \sim A$ are the probabilities that $J_{\mathrm{VKH}} \geq J_0$ and $J_{\mathrm{VKH}} < J_0$, respectively; $P(B \mid\sim A)$ is the probability of observing auroras in a given region when $J_{\mathrm{VKH}} < J_0$.

Thus, the posterior probability that the GIC level at the VKH station will exceed 2 A when observing auroras in the north is 5.78%, while the probability of exceeding this value in the presence of auroras at the zenith and in the south is 10.04% and 14.93%, respectively (Figure 4). In the absence of auroras, the probability of J_{VKH} reaching a similar level does not exceed 0.26%, and the probability of exceeding 3 A is already practically zero [*Vorobev et al.*, 2024].

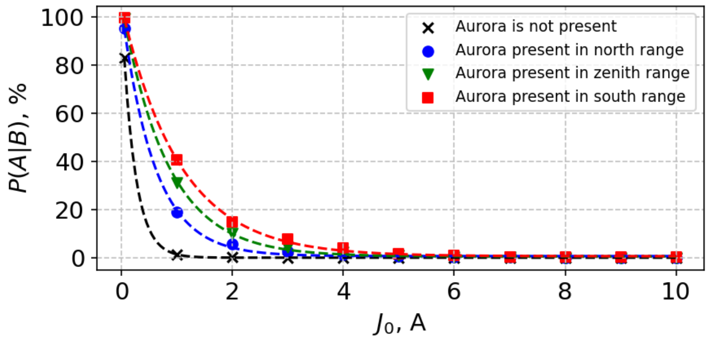


Figure 4. A posteriori probability of exceeding the GIC level J_0 at the VKH station with simultaneous observation of auroras in different areas of the sky. Markers indicate empirical values; dotted lines indicate approximation of empirical values by expression (2).

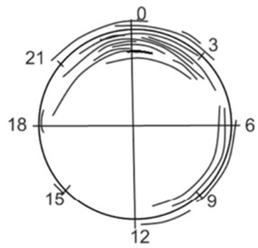
As follows from the location of similar markers (for example, ■) on Figure 4, the dependence of the probability of exceeding the GIC level J_0 has an exponential character, depends on the region of manifestation (relative to the object of influence) of auroras, and can be approximated quite well by an expression of the form:

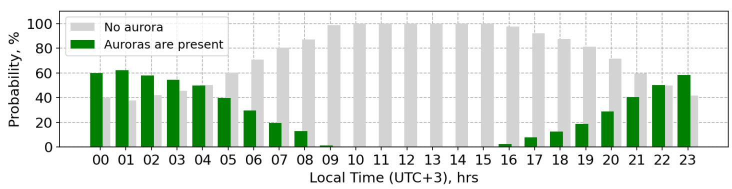
$$P(A \mid B) \approx P(J_0) = a \cdot \exp(b \cdot J_0) + c,$$

where $a = 102.87$ for cases of absence of auroras, $a = 102.68, 104.69, 103.60$ for cases of aurora observation 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 observation in the north, at the zenith and in the south, respectively.

4. Conclusion

Practically the only accessible indicator of space weather statetoday remains the auroras, the scientifically based interpretation of which can reduce the level of situational unawareness and determining the probability of failure in polar navigation and power distribution systems, communication systems, as well as at high-latitude railway infrastructure facilities (Figure 5).





(a) **(b)**

Figure 5. On the possibility of diagnostics of automation systems failures probability on high-latitude railways based on natural indicators of space weather state: a – Distribution of anomalies in the operation of signaling on the Northern Railway relative to local time during periods of strong magnetic storms in 1989 and 2000–2005 [*Eroshenko et al.*, 2010]; b – Diurnal variations in the probability of observing auroras in the vicinity of the LOZ station.

Having processed about 2000 ascaplots for more than 10-year period, including 92,208 episodes of 30-minute sky observations in the vicinity of LOZ station, it was shown that the most probable GIC level at VKH station when registering auroras in the north, at the zenith and in the south is 0.08 A, 0.23 A, and 0.68 A, respectively. At the same time, the a posteriori probability that during auroras in the north J_{VKH} will exceed 2 A is 5.78%, while the probability of exceeding this value during auroras at the zenith and in the south is 10.04% and 14.93%, respectively. In the absence of auroras, the probability of reaching J_{VKH} a similar level does not exceed 0.26%, and the probability of exceeding 3 A is practically equal to zero.

It has been established that the probability of exceeding the GIC of a certain level decreases exponentially with an increase in this level, clearly depends on the region of manifestation of auroras, and can be approximated by an expression $P(A \mid B) \approx P(J_0) = a \cdot \exp(b \cdot J_0) + c$, where $P(A \mid B)$ is a probability of exceeding the GIC level J_0 when observing auroras in the area; a, b, and c are coefficients determined empirically.

In addition to diagnostics and prediction of the GIC level in Arctic power transmission lines, the proposed approach has practical significance in assessing the probability of failures of automation systems of high-latitude railways, as well as the possible additional error of magnetic inclinometers, widely used in the processes of directional drilling of deep wells in the Arctic Zone of the Russian Federation [*Gvishiani and Lukyanova*, 2017]. A natural limitation of the applicability of the proposed approach is that ground-based registration of auroras in the night sky at high latitudes is possible only up to 7 months a year, provided that the meteorological conditions are favorable.

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