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Tatiana B. Yanovskaya
Saint Petersburg State University
St. Petersburg, Russia

Andrei Kosterov
Saint Petersburg State University
St. Petersburg, Russia

Nikita Yu. Bobrov
Saint Petersburg State University
St. Petersburg, Russia

Andrey V. Divin
Saint Petersburg State University
St. Petersburg, Russia

Alexander K. Saraev
Saint Petersburg State University
St. Petersburg, Russia

Nadezhda V. Zolotova
Saint Petersburg State University
St. Petersburg, Russia

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Statistical Properties of the Geomagnetic Field Variations and Geomagnetically Induced Currents

A. V. Vorobev, V. A. Pilipenko, Ya. A. Sakharov and V. N. Selivanov

Abstract The relationships between variations of geomagnetic field and geomagnetically induced current (GIC) are studied using data from the station for registration of GIC in the electric transmission line and the IMAGE magnetic observatory. A highest correlation of GIC intensity ($R > 0.7$) is found with the field variability $|d\mathbf{B}/dt|$, whereas the correlations of GIC with the time derivatives of X and Y components are about the same. The diurnal variations of hourly values of geomagnetic field variability and GIC intensity have a wide night maximum associated with the substorm activity, and a wide morning maximum presumably caused by geomagnetic pulsations of the Pc5-Pi3 type. A regression linear model is constructed to estimate GIC magnitude from the local time derivative of geomagnetic field. The statistical distributions of the probability density of $|d\mathbf{B}/dt|$ and GIC correspond to the log-normal law. On the basis of the constructed distributions the probabilities of extreme values of GIC and $|d\mathbf{B}/dt|$ are estimated.

Keywords Geomagnetically induced currents · Geomagnetic field variations · Space weather

A. V. Vorobev (✉)
Ufa State Aviation Technical University, Ufa, Russia
e-mail: geomagnet@list.ru

V. A. Pilipenko
Institute of Physics of the Earth, Moscow, Russia

Geophysical Center of the Russian Academy of Sciences, Moscow, Russia

Ya. A. Sakharov
Polar Geophysical Institute, Apatity, Russia

V. N. Selivanov
Center for Physical and Technical Problems of Energy of the North, Apatity, Russia

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1 Introduction

Research on space weather is stimulated, on one hand, by the fundamental scientific interest in the Earth's environment comprising magnetosphere, ionosphere, atmosphere, and lithosphere. On the other hand, understanding and monitoring of space weather is vitally important to ensure the stable operation of technological systems. One of the most significant manifestations of space weather is the excitation of geomagnetically induced current (GIC) in conducting technological structures (power transmission lines, pipelines, transformers, cable networks) during magnetic storms and substorms [4]. With the development of technology, energy systems are becoming increasingly susceptible to space weather perturbations. Modern energy electric power networks with complex geometry in fact operate as a giant antenna which is electromagnetically coupled to the currents of the Earth's ionosphere. In grounded networks, GICs were recorded during magnetic storms up to 200–300 A [8], while currents with an intensity of only a few Amperes are capable to shift some types of transformers from the linear regime [15]. Although the most powerful disturbances of geomagnetic field, which lead to the excitation of intense GICs, occur in auroral latitudes, dangerous GICs can also be observed at middle and low latitudes [16].

Diagnostics and prediction of GIC levels during various types of geomagnetic disturbances, which can be used by network operators to take the necessary measures to mitigate the risk of catastrophic failures, is an extremely important task. At the same time, the solution of such a problem is not reduced simply to the "engineering" application of the space physics results for calculating GIC in a specific technological system, but also requires clarification of the physical nature of some magnetosphere and ionosphere phenomena. Greatest perturbations of magnetic field on the Earth's surface are caused by an extended auroral electrojet which creates magnetic perturbations oriented predominantly in the N–S direction [2]. However, small-scale ionospheric current structures can make a significant contribution to the rapid changes in the magnetic field, which are essential for the excitation of GIC [1, 12]. The nature of such structures has not yet been fully clarified.

Geophysical literature describes many individual events, when a close connection between geomagnetic field variations and GICs has been revealed during such space weather events as interplanetary shocks [7] and magnetic storms [3, 14]. At the same time, statistical studies of the relationship between geomagnetic field variations and GIC are lacking. Research of space weather effects on technological systems is limited by the lack of databases of GIC recording available for scientific analysis.

This paper is largely based on the data of unique Russian system of GIC registration in power transmission lines, deployed at the Kola Peninsula [10, 11]. The paper examines the statistical characteristics of geomagnetic disturbances, geomagnetic field variability $d\mathbf{B}/dt$, and GIC during 2015. In the case of a closed circuit with Ohmic resistance, the GIC magnitude would be completely determined by the electromagnetic induction, i.e. time derivative of geomagnetic field $d\mathbf{B}/dt$. In reality, even in the simplest case, GIC occurs in a spatially distributed system formed by the power lines, substations with poorly known characteristics, and underlying Earth surface with frequency-dependent anisotropic geoelectric properties. Thus, it is not a priori evident whether magnetic field variability $d\mathbf{B}/dt$ totally controls GIC intensity. For practical applications, it is important to estimate what GIC magnitude can be expected for various disturbances. Knowledge of such empirical relationship is necessary to build a diagnostic model for GIC based on parameters of geomagnetic field. A statistical distribution of the probability density of the geomagnetic field derivative and GIC may help to outline responsible mechanisms and to estimate probabilities of extreme values of GIC and $|d\mathbf{B}/dt|$ [9].

2 Data and Pre-processing

The GIC registration system measures with a time resolution of 1 min the quasi-DC current flowing in grounded neutral of transformer (http://eurisgic.org). For this study the "Vyhodnoi" (VKH) station with geographic coordinates 68.83° N, 33.08° E has been selected, in which the registration of the GIC is carried out on the 330 kV line. This station terminates the power line, so a measured current matches much better GIC in the line.

To characterize the local geomagnetic field activity, data of nearby magnetic stations from the IMAGE network (www.geo.fmi.fi/image) are considered. The 1-min data from closest to the GIC station observatories have been used: IVA (geographical coordinates 68.56° N, 27.29° E, separation 236 km), KEV (69.76° N, 27.01° E, separation 260 km) and SOD (67.37° N, 26.63° E, separation 313 km). Station IVA is at the same geomagnetic latitude with VKH, so global geomagnetic disturbances at those sites are expected to be similar. About 93.3% of the total data set is available for cross-station analysis (490,385 samples) [17].

The statistical relationships between GIC and planetary characteristics of space weather, such as AE (http://wdc.kugi.kyoto-u.ac.jp/aedir) and PC (http://www.geophys.aari.ru) indices have been examined in [16]. Apparently, planetary indices cannot reveal the conditions under which extreme values of currents occur at a selected station.

The perturbations of geomagnetic field horizontal component $\Delta\boldsymbol{B} = \{\Delta X, \Delta Y\}$ (X and Y are the N–S and E–W field components, correspondingly) and the time derivative $d\mathbf{B}/dt = \{dX/dt, dY/dt\}$ are calculated. Under horizontal homogeneity of geoelectric properties of underlying medium, the orientation of vector $d\mathbf{B}/dt$ is orthogonal to orientation of excited telluric field $\boldsymbol{E}$. The values of ΔB are calculated relative to the background level of B_0, which has been taken as the average value of $B(t)$ per day. To avoid difficulties with the changing sign of magnetic disturbance, the absolute values of disturbance components $|\Delta X|$, $|\Delta Y|$ are used. As a characteristic of field variability, absolute values of derivatives of horizontal components $|dX/dt|$ and $|dY/dt|$, and the full derivative $|d\boldsymbol{B}/dt| = \sqrt{(dX/dt)^2 + (dY/dt)^2}$ are used.

3 Diurnal Variation of Geomagnetic Disturbances and GIC

To examine diurnal variation of geomagnetic disturbances and GIC (dependence on local time LT) we construct histograms of yearly-averaged values of various characteristics of geomagnetic disturbance and GIC for 2015. Daily variation of disturbance $|\Delta X|$ at station IVA (Fig. 1a) show the presence of midnight (LT ~ 24) and late afternoon (LT ~ 15) maxima. These maxima are caused by the intensification of the western and eastern auroral electrojets above the station during the substorm activations. Though the difference between minimum and maximum values is not large, the dispersion of yearly-averaged estimates is significant.

Daily variation of hourly-averaged geomagnetic field variability $|d\mathbf{B}/dt|$ (Fig. 1b) has a different character: the wide night (LT ~ 24) and morning (LT ~ 5–6) maxima are observed. The night maximum is obviously associated with substorm activity. The increased field variability in the morning hours is presumably caused by intense geomagnetic pulsations of Pc5-Pi3 range, which are observed most often in the early morning hours [5]. The appearance of large values of geomagnetic field time derivative associated with Pi3 pulsations was noted in [18].

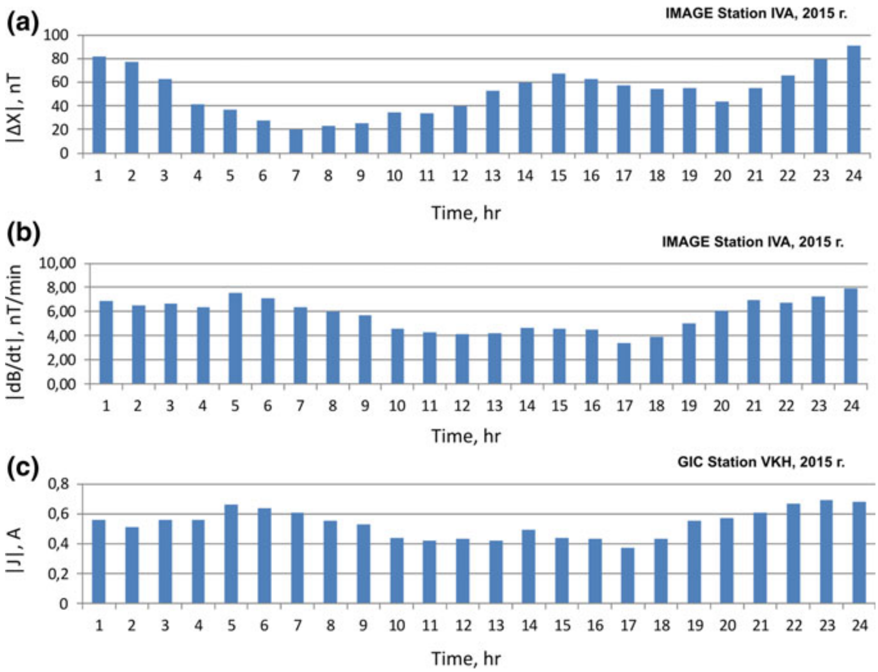

Fig. 1 Diurnal variations during 2015 of: **a** average magnetic perturbation $|\Delta X|$ at the IVA station; **b** average magnitude of geomagnetic field variability $|d\mathbf{B}/dt|$ at IVA, and **c** average GIC intensity $|J|$ at VKH station

The daily variation of the average intensity of the GIC at VKH station follows the variation of geomagnetic field variability $|d\mathbf{B}/dt|$ with the morning and midnight maxima (Fig. 1c). Our results confirm the conclusion made in [13] that the morning maximum in $|d\mathbf{B}/dt|$ does not have a counterpart in the distribution of geomagnetic disturbances intensity $|\Delta X|$, and in the region of maximum eastern electrojet there is no increase in the level of variability $|d\mathbf{B}/dt|$.

4 Correlations Between GIC and Magnetic Field Variability

Knowledge of statistical relationships is necessary as a first step to build diagnostic models of GIC based on the general characteristics of space weather. The problem how well the geomagnetic indices characterizing the substorm activity (AE, PCN) can predict the GIC magnitude was addressed in [16]. The maximum correlation between the absolute value of GIC $|J|$ recorded by VKH station was found for the indices AE ($R = 0.56$) and AL ($R = 0.55$), while the correlation with the PCN index was lower ($R = 0.44$).

Here we examine whether the magnitude of local geomagnetic disturbance and field variability are sufficient to predict the GIC magnitude. Table 1 shows the Pearson correlation coefficient R between the GIC absolute value $|J|$ and geomagnetic field perturbations $|\Delta X|$, $|\Delta Y|$, and the rate of change of field components $|dX/dt|$, $|dY/dt|$ at IVA, KEV and SOD stations for 2015.

Correlations of $|J|$ with the variability of horizontal components $|dX/dt|$ and $|dY/dt|$ are higher than with the field perturbation magnitude $|\Delta X|$, $|\Delta Y|$ by ~30%. Therefore, $|d\mathbf{B}/dt|$ is a more promising parameter to characterize a GIC. Nonetheless, though the correlation coefficient is rather high, $R \sim 0.7$, the determination coefficient $D = R^2 \sim 0.5$ indicates that $d\mathbf{B}/dt$ is responsible for ~50% of GIC variations only.

Correlations $|J|$ with variations of X- and Y-component derivatives are close (the difference in second digits). This result confirms that field derivative $d\mathbf{B}/dt$ fluctuates not only in magnitude but also in direction, which can indeed be caused by the presence of rapidly varying local vortex-like structures superimposed on the electrojet magnetic field [12].

Table 1 Correlation coefficients R between $|J|$ at VKH and geomagnetic variations at near-by magnetic stations

IVA				SOD				KEV			
$\|\Delta X\|$	$\|dX/dt\|$	$\|\Delta Y\|$	$\|dY/dt\|$	$\|\Delta X\|$	$\|dX/dt\|$	$\|\Delta Y\|$	$\|dY/dt\|$	$\|\Delta X\|$	$\|dX/dt\|$	$\|\Delta Y\|$	$\|dY/dt\|$
0.49	0.70	0.44	0.67	0.49	0.68	0.43	0.63	0.48	0.68	0.43	0.68

5 Regression Model of GIC

For applied assessments, it is important to know what magnitude of GIC can be expected under current level of geomagnetic field variability. To answer the question, a linear regression model has been synthesized, which in general has the form:

$$|J| = w_0 + w_1 \cdot |d\boldsymbol{B}/dt| \pm \Delta \quad (1)$$

where w_1, w_0 are weight coefficients, and Δ is the average simulation error. A model of the form (1) makes it possible to estimate statistically GIC value $|J|$ by the values of local magnetic field variability.

Linear regression model has been constructed for magnetic field variability $|d\mathbf{B}/dt|$ at IVA station for 2 months (from March 1 to April 30, 2015), as the largest interval for which there are no gaps in all analyzed parameters. The weights w_1, w_0 in (1) are calculated by the gradient descent method. The calculation with the model with restrictions (neglecting $|d\mathbf{B}/dt| \leq 1$ nT/min) gives the following coefficients: $w_0 = 0$, $w_1 = 0.074$ A min/nT. Figure 2 shows the result of comparing the simulation of GIC values with actual observations for the period of magnetic storm on March 17, 2015 with a series of substorm activations. A comparison of the predictions of models (2) with the measured values shows that the model based on $|d\mathbf{B}/dt|$ well predicts the moments of GIC intensifications and their magnitude in general, but underestimates extreme values. Model error $\Delta = \pm 0.9$ A proves that the regression model using the parameter $|d\mathbf{B}/dt|$ is adequate.

In general, the statistical model works well (small Δ) for intermediate values of $|d\mathbf{B}/dt|$ with the occurrence ~1% (which statistically corresponds to

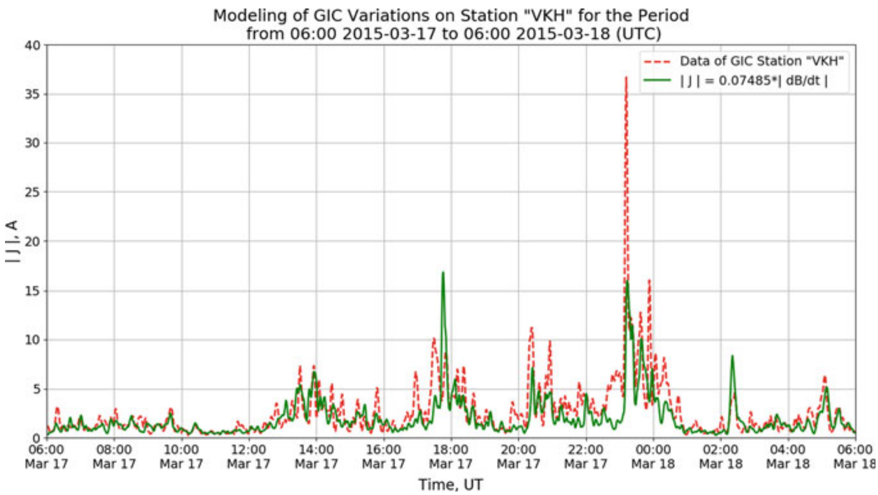

Fig. 2 Results of GIC modeling for the storm period from 00 UT to 24 UT on March 17, 2015

$|d\mathbf{B}/dt| < 40$ nT/min and the level $|J| < 3$ A). For large GIC values ($|J| > 20$ A), the regression model has $\Delta = \pm 2.3$ A, $w_0 = 11.677$ A, $w_1 = 0.11$ A min/nT.

6 Statistical Distributions of GIC and Geomagnetic Variations

The probability density function $F(x)$ of perturbation amplitude x is determined by a physical mechanism of the process. For example, under the action of random independent effects, a normal (Gaussian) distribution is formed; in a confined system, energy of its components is distributed according to the exponential Boltzmann/Laplace law; the power-law distribution (Pareto-type) is often attributed to self-organized criticality; a random multiplicative action of several factors results in a log-normal distribution, etc. The presence of heavy tails of distribution is important. With such power distributions, variance of a studied quantity is determined mainly by rarely intense deviations, rather than by frequent small deviations. In geophysical studies the following distributions are commonly encountered:

– the log-normal distribution

$$F(x,\sigma) = \frac{1}{\sigma x\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{\ln(x)}{\sigma}\right)^2\right);$$

– power-law distribution

$$F(x,\alpha) = F_0(x/x_0)^{-\alpha};$$

– the generalized Pareto power distribution

$$F(x,c) = (1+cx)^{-1-\frac{1}{c}}$$

We have calculated the normalized histogram $n(A)$ as a proxy of the probability density distribution, i.e. the probability of amplitude detection in the interval A, $A + dA$ as follows $n(A) = N(A)/Nt$, where Nt is the sample size. Also, we have calculated the amplitude distribution (survival function) $P(A)$ as follows

$$P(>A) = \int_A^\infty n(A)dA$$

This function is a probability to observe a magnitude $>A$. Often many natural processes are described by the power-law distribution $P(>A) \propto A^{-\alpha}$. This dependence in the log-log scale looks as a straight line.

Figure 3 shows normalized histograms of X-component disturbances at IVA station for 2015. According to Table 2, the probability density distribution of $|\Delta X|$ values most consistent with the generalized Pareto distribution with $c = 0.47$. The tail ($|\Delta X| > 400$ nT) of the amplitude distribution is well approximated by the power-law function.

Histograms of distribution of values $|d\mathbf{B}/dt|$ and $|J|$ are given in Figs. 4 and 5. The probability density distributions of $|d\mathbf{B}/dt|$ and $|J|$ are best approximated by the log-normal distribution with $\sigma = 1.15$ and $\sigma = 1.19$, correspondingly. The tails of

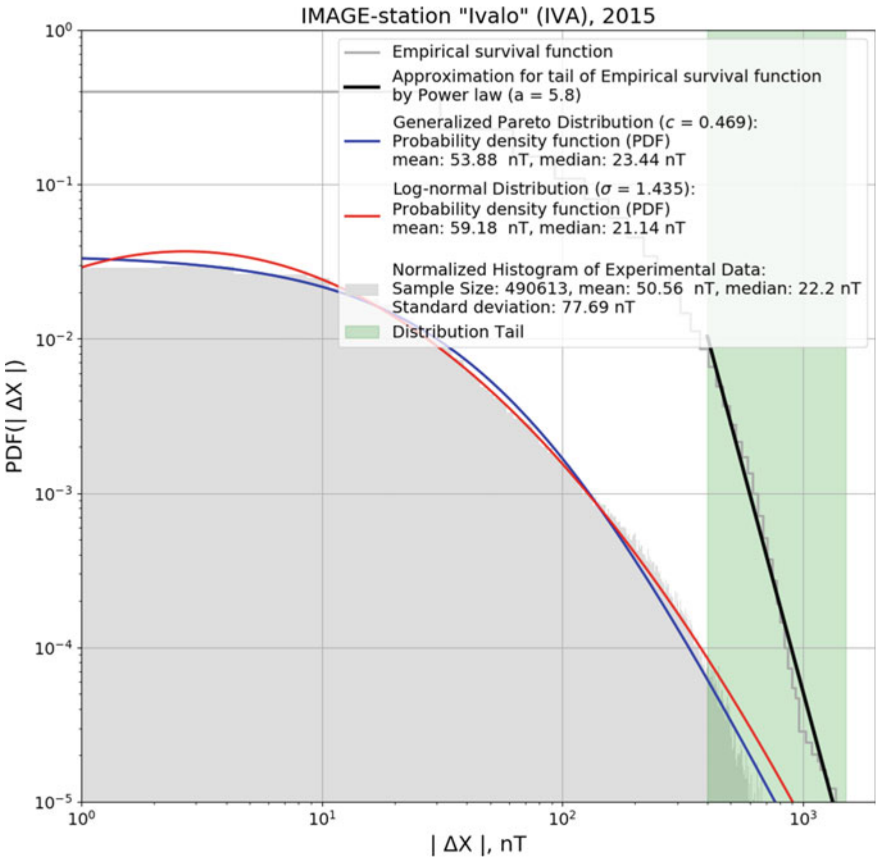

Fig. 3 Statistical distributions of magnetic field perturbation $|\Delta X|$ at IVA

Table 2 Kolmogorov criterion for the distribution of magnetic variations and GIC

Distribution	Time series		
	$\|X\|$	$\|d\mathbf{B}/dt\|$	$\|J\|$
Log-normal	0.0286	0.0331	0.0185
Generalized Pareto	0.0196	0.0763	0.0649

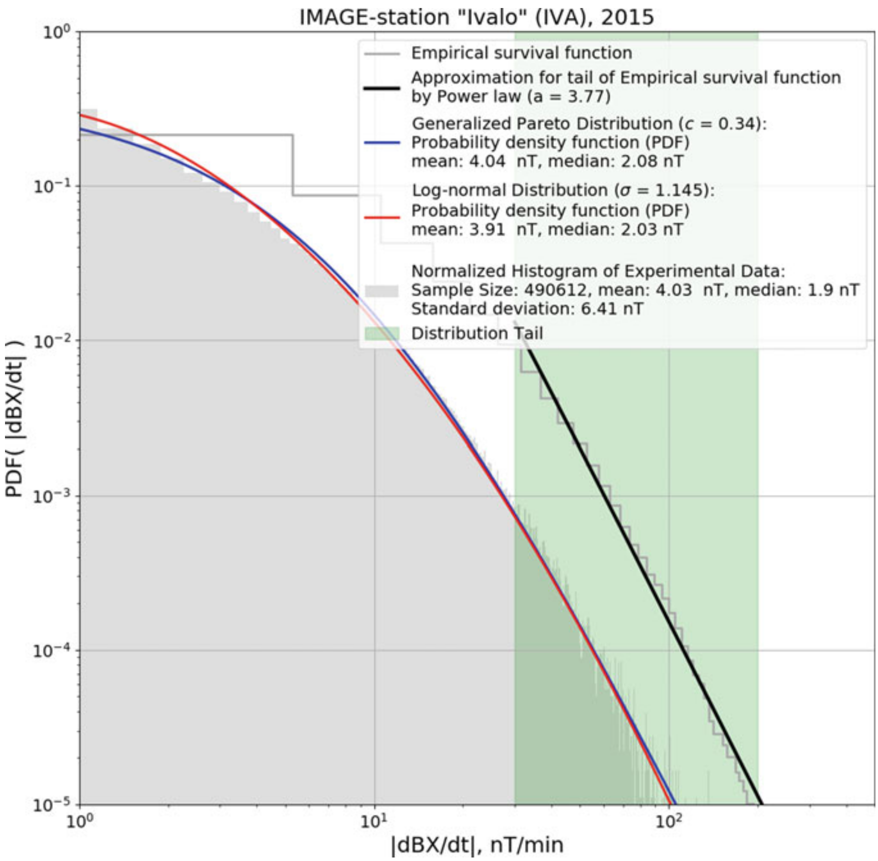

Fig. 4 Statistical distributions of the field variability $|d\mathbf{B}/dt|$ at IVA

the amplitude distributions of the field variability ($|dX/dt| > 30$ nT/min) and of the GIC ($|J| > 2$ A) are also well approximated by the power-law functions.

The obtained non-Gaussian distributions allow us to correctly determine the median, expected value and the probability of observing the analyzed parameters in a given range, as well as to evaluate the association of recorded values with anomalous events. Knowledge of such statistical distribution makes it possible to estimate probability of an extreme event, which during the observation period may not even be observed (assuming that it obeys the same law) [9]. From the probability curve (Figs. 3, 4 and 5), it is possible to estimate statistically which maximum perturbation of $d\mathbf{B}/dt$ and J is possible for a given observation period. In 2015 $|J| > 10$ A is observed ~0.03% of the time, and $|d\mathbf{B}/dt| > 60$ nT/min is observed ~0.2% of the time. With a probability of ~0.01% (approximately 50 times a year), regional perturbations of GIC and magnetic field may exceed $|J| > 13$ A, $|d\mathbf{B}/dt| > 113$ nT/min, and $|\Delta X|$

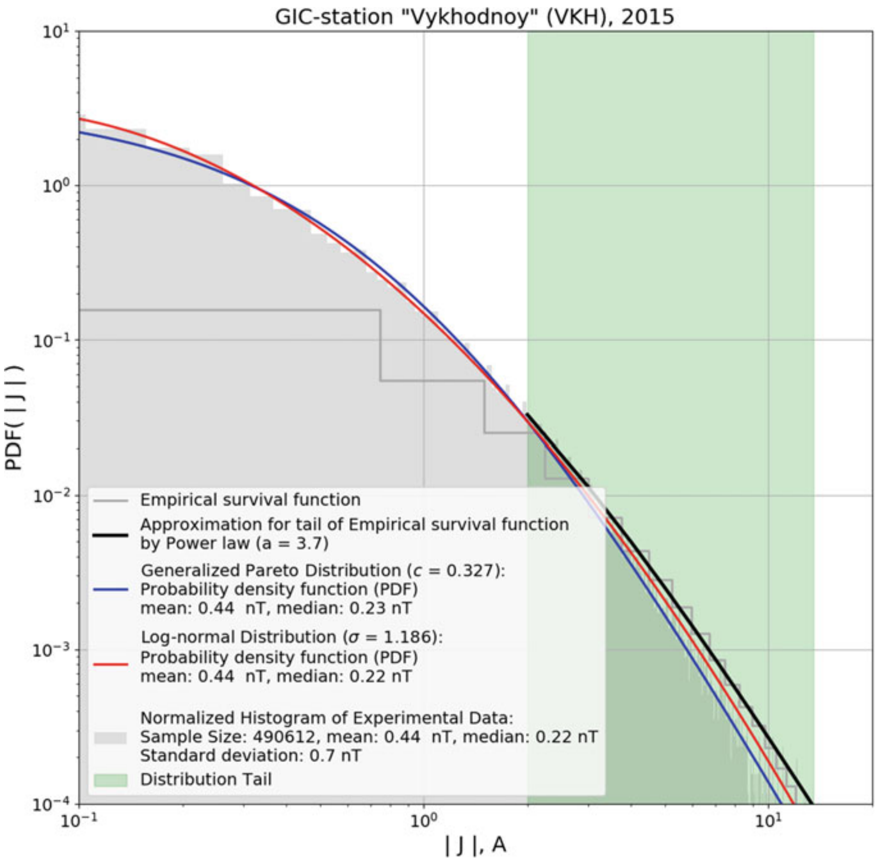

Fig. 5 Statistical distributions of GIC at VKH station

> 880 nT. Significant GIC variations ($|J| > 1$ A) are observed with a probability of ~9.7%.

After evaluating and analyzing the statistical characteristics of the time series, one can speculate about the similarity of their physical mechanisms. To test the hypothesis that the analyzed sample belongs to a particular known distribution, the Kolmogorov criterion is used, which characterizes the absolute maximum discrepancy between the experimental curves and the expected known distribution. A distribution with the minimum value of this criterion describes best the statistics of the experimental sample (Table 2).

According to Table 2, one may conclude that the statistics of $|\Delta X|$ values distribution is somewhat better described by the generalized Pareto distribution, whereas field variability and GIC correspond match better the log-normal distribution. The proposed hypotheses can be rejected with a significance level not exceeding 0.01%.

The fact that the probability distribution of both F (|J|) and F (|$d\mathbf{B}/dt$|) are described by heavy-tailed log-normal distribution indicate that this distribution is formed as a result of a multiplicative stochastic effect. It is interesting, that according to many observations, turbulence of near-Earth plasma often has a log-normal form [6]. Thus, such a coincidence may indicate that the turbulence of the near-Earth plasma is largely responsible for the variability of geomagnetic field and, therefore, for the appearance of GIC.

7 Conclusions

The yearly-averaged correlation between GIC and variability of geomagnetic field components $|dX/dt|$ and $|dY/dt|$ was found to be rather high, $R \sim 0.7$, higher than that between GIC and magnetic perturbations $|\Delta X|$, $|\Delta Y|$, $0.5 < R < 0.7$. The correlations $|J|$ with variations of the derivatives of X- and Y-components are close, which confirms the quasi-isotropy of rapid variations of geomagnetic field derivative $d\mathbf{B}/dt$ [1, 12].

Daily variations of average values of geomagnetic field variability $|d\mathbf{B}/dt|$ and GIC intensities have a wide night maximum associated with the electrojet, and a wide morning maximum, presumably caused by intense geomagnetic pulsations of the Pc5-Pi3 type.

Regression linear diagnostic model with input parameter $|d\mathbf{B}/dt|$ predicts a GIC of moderate magnitude with an error ±0.9 A. Large GICs (20 A < $|J|$ < 45 A) can be predicted based on the parameter $|d\mathbf{B}/dt|$ with an accuracy of ±2.3 A.

The statistical probability density distributions of values $|d\mathbf{B}/dt|$ and $|J|$ are most consistent with the log-normal distribution, whereas the probability density of the values $|\Delta X|$ somewhat better corresponds to the generalized Pareto distribution. On the basis of the constructed distributions the probabilities of extreme values of GIC and $|d\mathbf{B}/dt|$ can be estimated.

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