"Physics of Auroral Phenomena", Proc. XL Annual Seminar, Apatity, pp. 34-37, 2017

Polar
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THE MAGNETIC FIELD VARIABILITY AND GEOMAGNETICALLY INDUCED CURRENTS IN ELECTRIC POWER LINES DURING MAGNETIC STORM MARCH 17, 2003

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Abstract. The data of registration system of geomagnetically induced current (GIC) of the Polar Geophysical Institute and Kola Scientific Center in power lines of Kola Peninsula and Karelia, data of IMAGE magnetometers was used for the investigation the characteristics of the geomagnetic field variability. The technique of the vector representation of the geomagnetic field variations shows the great variability of the dB/dt according to ΔB for the magnetic storm 17 March 2013. The quantity estimation with using the so named RB parameter confirm that the geomagnetic field variation occur as in value as in direction. These results can't be explained the simple model of the prolonged ionosphere current and show the importance of the accounting of the small-scale currents structures for the GIC calculation. The ionosphere currents fluctuate not only in E-W direction but also in N-S direction. So the GIC are dangerous also for the technological systems extended in N-S direction.

1. Introduction. One of the most significant factors of space weather for terrestrial technological systems are electric geomagnetically induced currents (GIC) in the surface layers of the Earth caused by abrupt changes of the geomagnetic field. GIC are dangerous for extended high-voltage power lines, railway equipment, marine and ground communications cables, telephone and telegraph lines [*Pirjola et al.*, 2005]. The most intense currents (up to hundreds of amperes) and fields (more 10 V/m) are excited at auroral latitudes during magnetic storms and substorms [*Lanzerotti*, 2001]. Induced currents cause saturation, overheating and even damage of the high-voltage transformers. Geomagnetic variations with dB/dt>1 nT/s were found to be sufficient to induce GIC in Finnish power lines about several A and higher, and variations with dB/dt>40 nT/s caused failures in the operation of Scandinavian power lines [*Viljanen*, 1997].

In this paper we examine the contribution of geomagnetic disturbances during two moderate geomagnetic storms into enhancements of GIC recorded by the GIC-recording system and IMAGE array of magnetometers. Predominantly geomagnetic field disturbances are supposed to be oriented in the N-S direction, and produced by the E-W ionospheric currents. Thus, such disturbances seemingly would not induce any significant GIC in a latitudinally-oriented system. However, during magnetic storms GIC in power systems were quite significant.

2. GIC and magnetic field recording systems. The system to monitor the impact of GIC on power lines has been deployed in 2010 at Kola Peninsula and Karelia by the Polar Geophysical Institute and Center for Physical and Technical Problems of North's Energetic [*Sakharov et al.*, 2009]. The system consists of 4 stations at "Kolenergo" company power line 330 kV and a station at power line 110 kV. Each station records a quasi-DC current in dead-grounded neutral of autotransformer in power line. Information about GIC is important not from practical point of view only, but from a fundamental scientific view, revealing a fine structure of fast geomagnetic variations during storms and substorms. To characterize the geomagnetic field variations we use data from IMAGE magnetometers located in the vicinity of GIC recording stations.

3. Characteristics of the geomagnetic field variability. To characterize the geomagnetic field variability in magnitude and direction the following characteristics have been applied.

Vector diagram. The vector diagram technique presents in a concise form a time evolution of the meridional profile of horizontal magnetic disturbances vector. For that, vectors of geomagnetic disturbances $\Delta\mathbf{B}=\{\Delta X,\Delta Y\}$ for each station are plotted on the same plot as time sequence of vectors. This technique was used in [*Fries-Christensen et al.*, 1988] for the analysis of travelling convection vortices. The same diagram can be constructed for the equivalent ionospheric current $\mathbf{J}$ and vector derivatives $d\mathbf{B}/dt=\{\partial_t X,\partial_t Y\}$. The current J is related to $\Delta\mathbf{B}$ as follows $\Delta\mathbf{B}=(2\pi/c)[\mathbf{J}\mathrm{x}\mathbf{n}]$, where $\mathbf{n}$ is the normal to the ground surface.

RB parameter. This parameter shows does a vector field experience fluctuations in magnitude or in direction? For the 2D case $\mathbf{B}(t)=\{\Delta X,\Delta Y\}$ the parameter *RB* for a time series of *N* samples is determined as follows [*Du et al.*, 2005]:

$$RB = 1 - \frac{1}{N}\sqrt{\left(\sum_{i=1}^{N}\cos_x \alpha\right)^2 + \left(\sum_{i=1}^{N}\cos_y \alpha\right)^2}$$

Here the vector orientation cosines are: $cos_x\alpha = \Delta X/|\Delta B|$; $cos_y\alpha = \Delta Y/|\Delta B|$and modulus of geomagnetic disturbance: $\Delta B = \sqrt{\Delta X^2 + \Delta Y^2}$. The parameter RB does not depend on magnitude of geomagnetic disturbance. If $RB\to 1$ a vector field experiences chaotic variations in all directions, while $RB\to 0$ denotes that a field varies in magnitude only, but not in direction.

4. Event on March 17, 2013. The magnetic storm on March 17, 2013 started with arrival of interplanetary shock on 06 UT. During the shock solar wind velocity jumped from ~400 km/s to ~650-700 km/s. IMF Bz turned southward providing a permanent energy supply into the magnetosphere. SYM-H index gradually dropped till -100 nT and remained on this level. The AE index shows several activations at auroral latitudes: just after SC till ~1100 nT at 08 UT, after ~12 UT with maximum ~1000 nT, and most intense increase up to ~2500 nT at ~17 UT. Geomagnetic field variations at IMAGE stations during this storm (Fig. 1) in X component are more intense than in Y component, that is |X|>>|Y|. This fact seemingly supports the notion about a dominant role of the westward electrojet fluctuations for GIC generation.

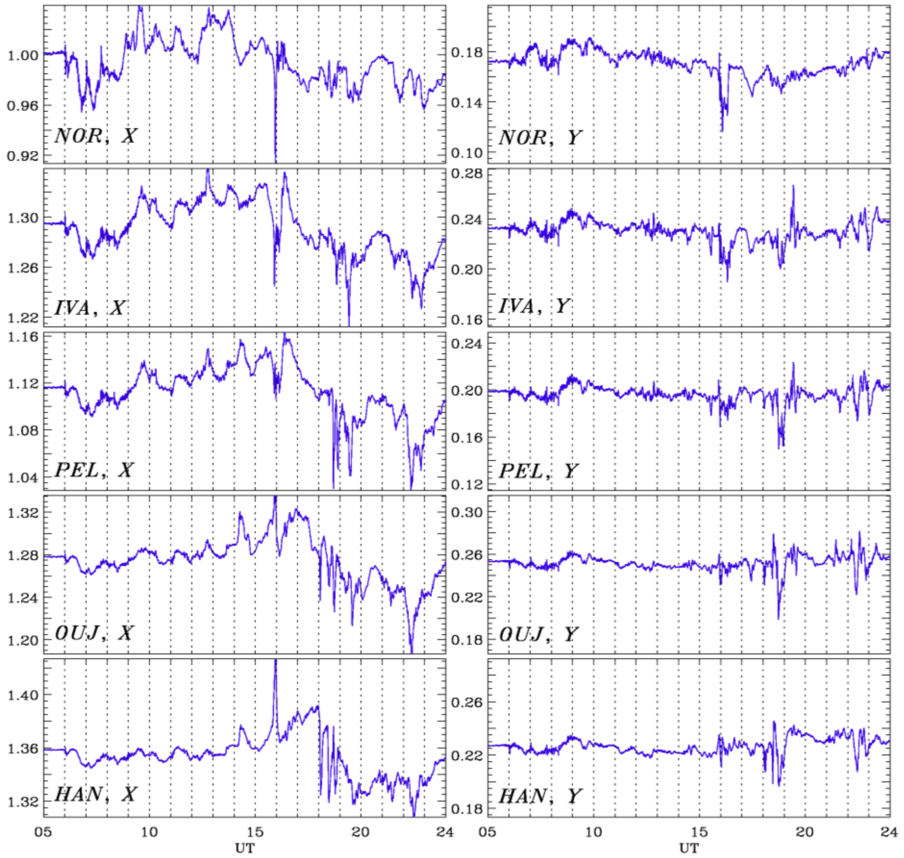

Figure 1. Geomagnetic field variations [in 10^4 nT] at latitudinal array of stations NOR, IVA, PEL, OUJ, HAN from IMAGE array during magnetic storm on March 17, 2013, 05-24 UT: left-hand panel shows X component, right-hand panel shows Y component. The vertical scale is the same for all stations and components.

The GIC recording stations recorded several significant bursts of GIC intensity (Fig. 2) reaching ~70 A at VKH. A growth of AE index during each activation generally corresponds to bursts of |dB/dt| (up to 250 nT/min) and GIC intensity (at ~06-08 UT, ~16 UT, and ~18 UT) (Fig. 4). However, there are non one-to-one correspondence between the substorm intensity characterized by AE index and GIC magnitude. For example, AE index during the activation on ~13 UT is comparable to the index during the activation on ~08 UT, but the GIC intensity during the latter activation is much weaker. At the same time, intense GIC bursts occurred at ~19-20 UT and at ~2130-2330 UT, when AE index was somewhat decreased.

We have applied the vector diagram method to the available mid-latitude IMAGE magnetometer data (Fig. 3.). The diagram shows that during the storm not only the magnitude of magnetic disturbance varied, but its orientation as well. These variations are caused by rapid changes of regional ionospheric current direction. The observed pivot of equivalent ionospheric currents on ~08 UT, ~16 UT, and ~19 UT correspond to localized vortex-like current structures moving across the magnetometer array.

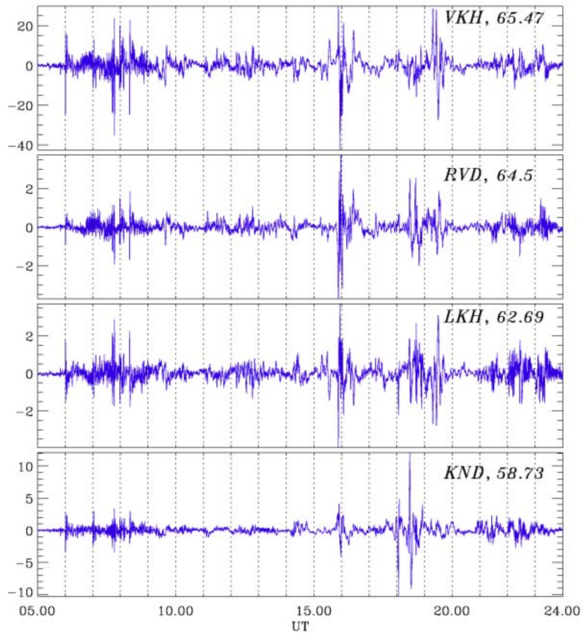

Figure 2. GIC [A] recorded at stations VHD, RVD, LKH, and KND during magnetic storm Mar. 17, 2013, 05-24 UT. Near station's codes the geomagnetic latitudes are indicated.

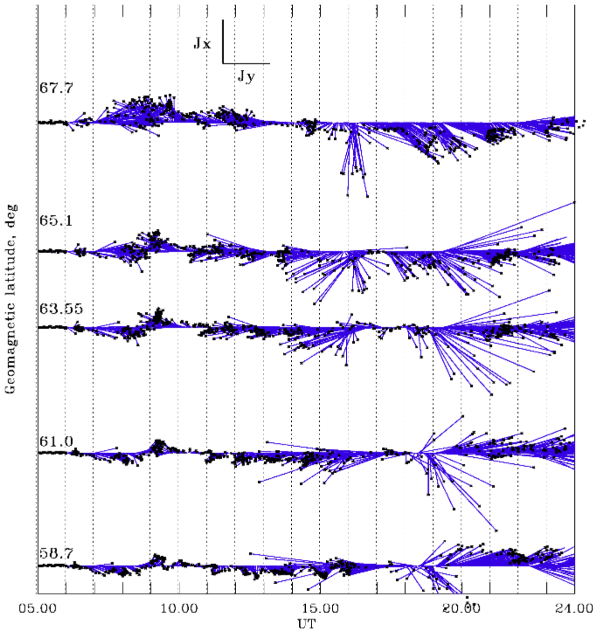

Figure 3. Vector diagram of ionospheric equivalent currents **J** along the meridional magnetometer profile in Fig. 1 for the period from 05 UT-to 24 UT, Mar. 17, 2013 (time step 2 min).

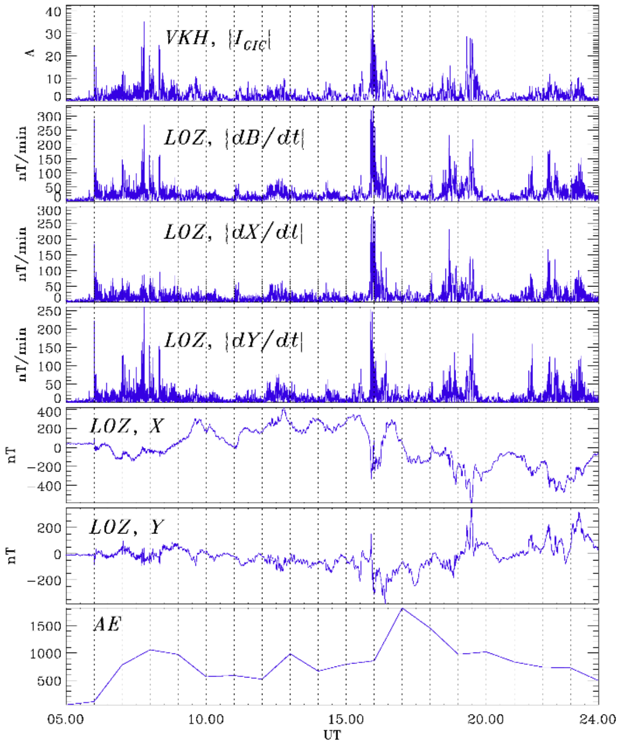

Figure 4. Comparison between GIC amplitudes [A], derivatives |dX/dt| and |dY/dt| [nT/s], and geomagnetic disturbances ΔX and ΔY [10^4 nT] at near-by stations VKH and LOZ.

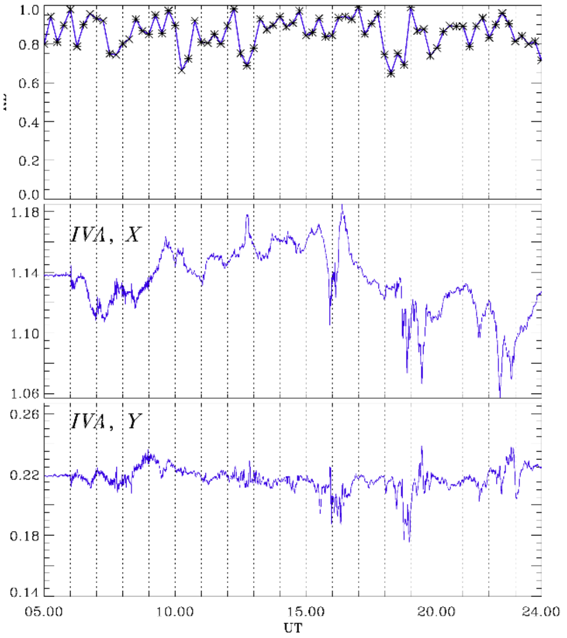

Figure 5. Time variations of the *RB* parameter estimated from geomagnetic variations (bottom panels) at station IVA during the period 05 - 24 UT (time cadence 15 min).

Comparison of magnitude of magnetic disturbances X and Y with amplitudes of time derivatives |dX/dt|, |dY/dt| and magnitude of derivative |dB/dt| (Fig. 4) shows that though the magnetic disturbance is much large in X-component than in Y-component, |X|>>|Y|, but their derivatives |dX/dt| and |dY/dt| are comparable. Therefore, small *Y* does not mean small d*Y*/dt, and variations of both components provide a similar contribution into increase of |dB/dt|.

The estimates of the correlation coefficients *R* between the GIC intensity and magnitudes of the geomagnetic field derivatives during the time intervals 07-10 UT gives the following results: *R*($|dX/dt|$-$|I_{GIC}|$)=0.45, *R*($|dY/dt|$-$|I_{GIC}|$)=0.61, and *R*($|dB/dt|$-$|I_{GIC}|$)=0.63. Hence, the magnitude of total derivative $|dB/dt|$ correlates best with GIC variations, whereas the derivative of *Y*-component even better correlates with GIC variations than the derivative of *X*-component. The same regularities are observed for other time intervals.

The application of the *RB* parameter (Fig. 5) to the data from IVA station evidences that during this geomagnetic storm geomagnetic field varies not only in magnitude, but in direction, too. Indeed, at this station, as well as at other IMAGE stations, *RB* rapidly increases from ~0.6 to ~1.0 during the periods of vortex-like ionospheric structures occurrence. Thus, such geomagnetic variations cannot be attributed to variations of the east-west auroral elecrojet intensity only.

5. Discussion. The GIC occurrence is often interpreted as a result of fluctuations of auroral electrojet, flowing mainly in the westward direction. Accordingly, for GIC modeling the model of extended east-west electric current has been used [*Viljanen*, 1997]. In accord with these models the conclusions have been stated that predominantly power systems elongated in longitudinal E-W direction are vulnerable to impact of geomagnetic storms and substorms. The vector technique used here has demonstrated a much larger variability of d**B**/dt in magnitude and direction as compared with just magnetic variations Δ**B**. The applied quantitative estimate of vector field variability *RB* confirmed that geomagnetic field variations occur in a comparable rate both in magnitude and direction. These results indicate an importance of account of small-scale current structures embedded into global auroral electrojet for GIC estimates. The observed patterns of d**B**/dt distribution cannot be interpreted by a simple model of elongated electrojet and demands an account of magnetic field from nonstationary vortex-like structures, produced by localized field-aligned currents flowing in/out the ionosphere [*Belakhovsky et al.*, 2017]. Though amplitudes of currents in such structures are not large, so they cannot modify essentially Δ**B** distribution, but their temporal variations are fast, so they influence substantially distribution of d**B**/dt. The physics and morphology of these small-scale fast-varying current filaments have not been established yet. Thus, though largest magnetic disturbances are produced by the auroral electrojet and directed in north-south direction, rapid variations of geomagnetic field essential for the GIC excitation are considerably determined by small-scale current systems, which disturbed both horizontal components of geomagnetic field. An evident confirmation of this fact is a noticeable vulnerability of Kola power lines extended in the north-south direction to GIC occurrence.

6. Conclusion. The large-scale structure of the ionosphere currents at auroral latitudes are determined by the east–west electrojet. So, the X-component of the geomagnetic field is prevalence here. However, on small scales these equivalent currents and induced geomagnetic disturbances undergo strong variations not only in value but also in direction. So, the GIC are oriented as in east-west as in north-south direction. The vector technique of the geomagnetic field and its derivate representation shows the greater variability of the dB/dt in comparison with ΔB. These results cannot be explained by the simple model of auroral electrojet and shows the importance of the accounting of small-scale currents for the GIC calculations.

Acknowledgements. This study is supported by the Russian Foundation for Basic Research № 16-35-60049 mol_a_dk (VB), № 15-45-05108 r_vostok_a (VAP). Data from PGI system are available at *http://eurisgic.org*. We acknowledge Finish Meteorological Institute for IMAGE magnetometer data (*http://www.geo.fmi.fi/image/).*

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