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# DATABASE OF GEOMAGNETICALLY INDUCED CURRENTS IN THE MAIN TRANSMISSION LINE "NORTHERN TRANSIT"

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**Abstract.** Database containing the results of measurements of geomagnetically induced currents (GIC) for the period of 2011 to 2022 in transformer neutrals at three 330 kV substations of the main power transmission lines "Northern Transit" passing through the territory of the Republic of Karelia, Murmansk and Leningrad regions has been created and is publicly available. The GIC value depends on the geoelectric field magnitude in the Earth surface, on the relative position of the substations to which the power transmission lines are connected, and on the resistance of electrical network elements. Important factors are the electrical network branching, which determines paths of induced current spreading, and the network topology at the time of monitoring data acquisition. We describe the structure and principles of functioning of the Russian unique regional monitoring system of geomagnetically induced currents in the electrical network. We demonstrate the features of the data contained in the GIC database, which must be taken into account when processing and analyzing the data. Examples of using the GIC database for energy and geophysical studies are given. The work performed on the organization of continuous monitoring of GIC at substations of the main power transmission line in the Arctic zone has no analogues in the Russian Federation and provides extensive original material that allows us to study geomagnetic disturbances and their impact on electrical networks. The database is available at [http://gic.en51.ru].

**Keywords:** space weather, geomagnetically induced currents, transmission lines, transformer, database.

## INTRODUCTION

The Sun is a source not only of visible light, but also of electromagnetic and corpuscular radiation of other types; these radiations form Earth's space weather. Ionized particle fluxes (solar wind), reaching Earth, interact with its magnetosphere and trigger geomagnetic disturbances such as magnetic storms and substorms [Akasofu, Chapman, 1975; Coster et al., 2021]. Magnetospheric disturbances generate geomagnetically induced currents (GICs) flowing along the Earth surface and in extended conductors connected to the ground — overhead transmission lines (OHL), communication links, oil and gas pipelines, railway rails [Pilipenko, 2021; Pulkkinen et al., 2017]. The GIC value depends on the geoelectric field magnitude in the Earth surface and on the resistance of a closed current circuit formed by an extended conductor [Zheng et al., 2014]. During extreme geomagnetic disturbances, the geoelectric field can be as strong as 15 V/km. In OHL with a characteristic length of 100 km and a ~5 ohm total DC resistance of wires, transformer windings, and grounding of terminal substations, GIC can be 300 A and higher [Kappenman, 2005].

GICs do not pose a serious danger to OHLs themselves. GIC amplitudes are an order of magnitude lower than the overhead line wire ampacity, and the duration of the effect to currents capable of causing noticeable heating of wires is negligible. The GIC effect on OHL electrocorrosion is probably also insignificant. GICs pose the biggest danger to measuring transformers, as well as to power transformers and autotransformers with grounded neutral, installed at electrical substations [Gershengorn, 1993; Abda et al., 2020].

In terms of the power system frequency (50 or 60 Hz), GICs with a characteristic frequency from 0.001 to 0.1 Hz can be considered constant. The flow of direct currents in the windings of electrical machines (power and measuring transformers, reactors and generators) gives rise to constant magnetic fields in their magnetic cores. Core magnetization by a constant field causes its half-cycle saturation, which leads to additional heating of the equipment, distortion of the waveform of voltages and currents in an electrical grid, etc. They can result in performance degradation and service life decrease, as well as sudden equipment failure.

During intense geomagnetic disturbances, serious accidents may occur which are similar to those that happened at the end of the last century during the peak of geomagnetic activity in the northern regions of the USA and Canada, as well as in Sweden and Finland. Equipment failures in wired transport and information systems caused multibillion dollar economic losses [Bolduc, 2002].

In Russia, there is no provision for fixing technological disturbances triggered by GICs, hence there is no reliable information about the degree of impact of space weather on the power system equipment. In 1987, the accidents, whose causes had not been identified, were analyzed in three power systems: Kolenergo, Karelenergo, and Arkhenergo for the four-year period from 1980 to1984. As a result, a correlation was found between the K-index, which characterizes the level of geomagnetic disturbance in a three-hour interval, and power outages for unknown reasons.

The devices for measuring currents and voltages used in electrical grids are transformer converters; therefore, they cannot record signals of almost constant current. To measure quasi-constant GICs in transformer neutrals, either resistive current shunts or Hall effect current sensors are traditionally employed [Watari et al., 2021]. Direct measurements of GICs in OHLs are difficult to make since they involve working at high voltage. Different magnetic field sensors are used for such measurements: quartz, fluxgate, quantum or magnetoresistive [Hübert et al., 2020].

The Kola Science Centre of the Russian Academy of Sciences, together with the Polar Geophysical Institute, has been conducting research on the effect of geomagnetic storms on electrical grids and transformer substations on the Kola Peninsula and in Karelia since 1986. In 2011, with the assistance of the Federal Grid Company of the Unified Energy System (FGC UES), a regional monitoring system for currents in transformer neutrals was developed. This system has collected an extensive array of information concerning the impact of geomagnetic disturbances on the main electrical grid over 800 km long [Barannik et al., 2012]. The system includes GIC recorders installed in neutrals of autotransformers at the Vykhodnoy (Murmansk region), Loukhi, and Kondopoga (Republic of Karelia) 330 kV substations, a data collection, storage, and processing server, a web server [http://eu r isgic.ru ], the Lovozero magnetovariation station (LOZ). In 2022, a database containing results of GIC measurements in neutrals of autotransformers at three 330 kV substations of the main electric power transmission line “Northern Transit” for the period 2011–2022 was created and made publicly available. Certificate of the Russian Federation of the state registration of the database No. 2022623220 “Geomagnetically inducted currents in the main electric power transmission line “Northern Transit” was acquired.

This paper describes the design concept of the monitoring system and the database structure.

## 1. GEOMAGNETICALLY INDUCED CURRENTS IN ELECTRICAL GRIDS

GICs occur in extended ground and underground conducting communications having a galvanic coupling with the ground at least at two spaced points. With a characteristic frequency from 0.001 to 0.1 Hz, the GIC amplitude can be as high as 300 A. If an almost constant current flows in an extended electrical grid with transformers or autotransformers with dead-grounded neutral, the magnetization curve of the transformers may shift, thereby leading to a half-cycle saturation of the magnetic core. This causes breaking of the symmetry of energy transfer in phases, the appearance of higher harmonics, overheating of steel cores and structural elements, a sharp increase in vibrations, and, as the final result, leads to accelerated aging of the insulation of power transformers. Furthermore, repeated exposure to the insulation produces a cumulative effect, which can cause the transformer to get damaged by the impacts unrelated in time to geomagnetic disturbances.

Other elements of the power system that are directly affected by GICs are current transformers (CTs) whose cores can also be saturated with direct currents [Pulyaev, Usachev, 2002]. This brings about an increase in the CT error, and also a strong disruption of secondary current, which can lead to false alarms of the relay protection as well as to a decrease in its sensitivity and a response delay in emergency situations. CTs in transformer neutrals and shunt reactors are particularly strongly affected since GICs in them can reach three times the magnitude of the currents in phase wires. The GIC effect on CTs and relay protection has been examined for substations in North America, where during the superstrong geomagnetic storm in 1989 GICs were as strong as 200 A and led to saturation of CT cores during the half-period of the power system current [Boteler, 2019; Bozoki et al., 1996].

GICs also affect shunt reactors of the parallel system of reactive power compensation. Their cores can be saturated during GIC flow, which can cause local overheating of structural elements of the reactor due to an increase in the leakage flux. Shutdown of reactors during geomagnetic disturbances poses a hazard to service personnel because of the probability of arcover at the break place and release of energy accumulated in the reactor inductance during GIC flow.

GIC in electrical grid elements depends on the geoelectric field in the Earth surface, the relative location of the substations to which OHLs are connected, the resistances of OHL wires, transformer windings, and neutral grounding. An important factor is the electrical grid branching that determines the paths of spreading of the currents induced in the grids and their magnitude in specific elements. Figure 1 exemplifies a single-line diagram of a branched three-phase electrical grid and shows possible paths of GIC spreading in it. The following are the main points that need to be taken into account when analyzing the GIC impact on an electrical grid.

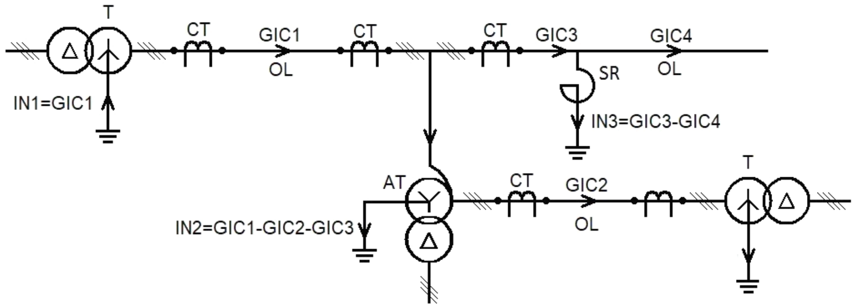


*Figure 1.* Geomagnetically induced currents in a branched electrical grid: T — transformer, AT — autotransformer, CT — current transformer, SR — shunt reactor, OL — overhead transmission line, GIC — geomagnetically induced current, IN — current in a grounded neutral

1. Industrial electrical grids are three-phase, currents pass through three parallel circuits (phases), each with identical elements — OHL wires, power and measuring transformers, shunt reactors. GIC in neutral transformers is the sum of phase currents, but it is the current flowing in one phase that affects the elements. To assess the impact on the equipment, it is necessary to measure GIC in each phase, but technically it is difficult to do because of the high phase voltage.

2. One or several power transformers can be connected to substation busbars. GIC flowing from OHL is distributed to all transformers connected to substation busbars. Most often there are two transformers in substations (in Northern Transit, for example, these are Serebryanskaya HPS, Vykhodnoy, Olenegorsk, Titan, Loukhi 330 kV substations, but there are substations with one transformer (Murmansk, Knyazhegubskaya, Kondopoga), with four (Monchegorsk), and eight transformers (Kola APP). When measuring GICs in the neutral of one of the transformers, the resulting value should be multiplied by the number of transformers currently connected to the substation busbars. It should be considered that transformers are periodically disconnected from the grid for repairs and maintenance; currents in this case are redistributed between the transformers that keep working.

3. GIC can circulate only in closed circuits connected to the ground at least at two spaced points. The grounded points are neutrals of the transformers with star-connected windings. In grids with an isolated neutral, GICs cannot flow. In Russia, 6–35 kV grids generally operate in an isolated neutral mode and hence are not affected by GICs. In addition, neutrals of some transformers with a voltage of 110 and 150 kV are also not grounded to limit the triggering currents in the grid. These transformers can be excluded from the GIC impact analysis.

4. In ordinary transformers, windings of different voltage classes are not galvanically connected to each other, so current in the neutral is equal to the superposition of phase currents in the transformer windings. In autotransformers, windings have branches that are connected to electrical grids of different voltage classes. GIC in the autotransformer neutral is a sum of currents inflowing from overhead lines, connected to both primary and secondary windings.

5. It is necessary to take into account the method of connecting a substation to a grid with a grounded neutral. If a substation is terminal, the current inflowing from OHL does not branch, but flows into the ground through transformer neutrals. Several OHLs are connected to busbars of through substations, each with its own GIC. Depending on the GIC magnitude and direction in these overhead transmission lines, current in transformer phase windings can be either summed or subtracted. For example, if a through substation is connected to OHLs having the same direction and GICs in them are approximately equal, in accordance with Kirchhoff's first law the inflowing and outflowing currents will compensate each other, and the current in windings of the transformer and in its neutral will be zero. In this case, GICs in the lines will affect only current transformers, with no effect on power transformers. For example, the through Loukhi and Kondopoga substations that are connected to the main line directed from south to north. In normal operation, GICs in the neutrals of these substations have low magnitude. However, if one of the connected lines is disconnected for repairs during a geomagnetic storm, GIC in neutral increases sharply, reaching several tens of amperes.

An example of a through substation with a complex electrical grid is the Vykhodnoy 330 kV substation (Figure 2). At the substation, there are two 330/150 kV autotransformers, and a total of 12 overhead lines of various lengths and orientations are connected to it. During geomagnetic disturbances, Vykhodnoy always records strong GICs in the AT-2 neutral because there is no compensation of currents induced by orthogonal components of the geoelectric field in mutually perpendicular lines.

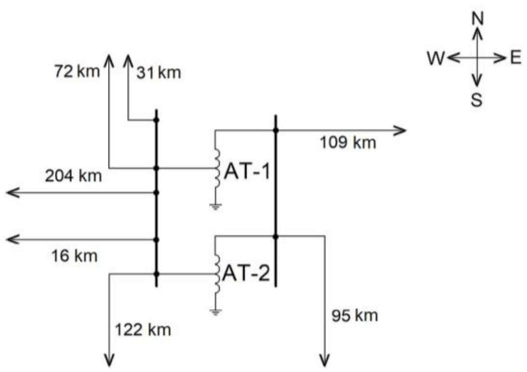


*Figure 2.* System diagram of the Vykhodnoy 330 kV substation

## 2. METHODS AND DEVICES FOR RECORDING GEOMAGNETICALLY INDUCED CURRENTS IN ELECTRICAL GRIDS

Geomagnetically induced currents in electrical grids are measured by direct and indirect methods. In transformer neutrals, current can be directly measured by a contact method, using a current shunt, or by a contactless method, using primary Hall effect transducers. In OHLs, these methods are difficult to adopt because of the high voltage in wires; therefore, the current-induced magnetic field is measured.

The contact method using a current shunt allows us to measure currents in a wide frequency range, does not need external power supply, does not introduce bias voltage, and is the most common and inexpensive. Nonetheless, its implementation requires breaking the current circuit, while the recorded current flows through the shunt, which causes power absorption and hence heating of the shunt. There is no galvanic isolation between the current circuit and the signal-conditioning circuit. The temperature coefficient of resistance of the current shunt, when externally mounted in the transformer neutral at an open substation, also introduces an appreciable error in GIC measurements.

In one of the first GIC recorders, adopted in 1986 at a 110 kV substation in Umba village, a 0.6 ohm ballast resistor for electrified trains was utilized as a shunt; it was installed in the discontinuity in the dead-grounded transformer neutral. The voltage drop from the current flowing in the shunt became steeper and transformed into direct current. A slowly varying signal was recorded by a 20 mm/hr DC strip chart recorder.

In February 1986, there was a strong geomagnetic storm (the planetary index $K_p$ was as high as 9), the storm peaked on February 8–9, 1986 [Garcia, Dryer, 1987]. GICs in the transformer neutral in Umba were as strong as 40 A. Figure 3 presents time coincident oscillograms of neutral GICs and geomagnetic magnetograms from the Kiruna Geophysical Observatory (KGO). Obviously, neutral GIC variations reliably correlate with geomagnetic variations.

To measure GICs in transformer neutrals, the best solution is to employ a clamp-type current sensor using Hall element. These sensors are designed for non-contact measurement of direct, alternating, and pulse currents in a wide range of frequencies and amplitudes. The clamps close around a busbar with current without breaking the circuit, providing galvanic isolation between the neutral busbar and the electrical circuits of measuring unit.

Figure 4 gives a schematic diagram of the neutral current measuring devices used to develop the GIC monitoring system in the main electric power transmission line "Northern Transit". The monitoring system can record quasi-constant currents in transformer neutrals, as well as to monitor the harmonic content in the grid. Current clamps have an analog output, the voltage at which is directly proportional to the magnitude of the current passing through the conductor. To convert an analog signal into a digital form and for further data processing, an 8-bit microcontroller unit with an analog-to-digital converter is used. The microcontroller unit converts a signal as follows:

- it selects an input signal ten times per second $i(t)$ and samples it with a frequency $f_d$=14400 Hz. Duration of the samples is 100 ms;
- each set of 1440 discrete samples $i_k$ is used to obtain averaged amplitudes of the constant component, the first, second, and third harmonics of the grid $f$=50 Hz by integrating over a time interval of 0.1 s.

The digital signal is transmitted via a cable line to the data processing, storage, and transmission unit. The continuous stream of data from the microcontroller unit is recorded in binary files containing 1-hour current components. The following components of the total neutral current, which are obtained by Fourier expansion with integration over a time interval of 0.1 s, are recorded:

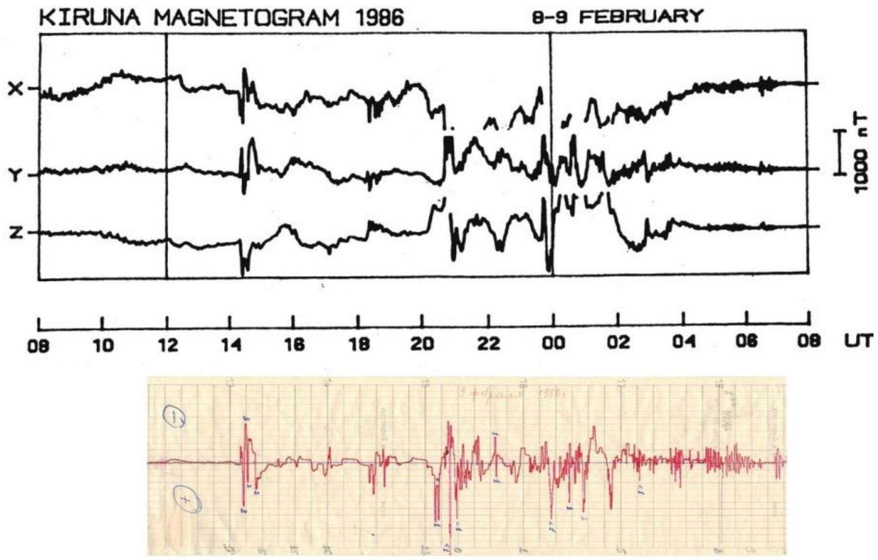


*Figure 3.* Time coincident oscillograms of GIC in a transformer neutral and magnetograms of geomagnetic variations

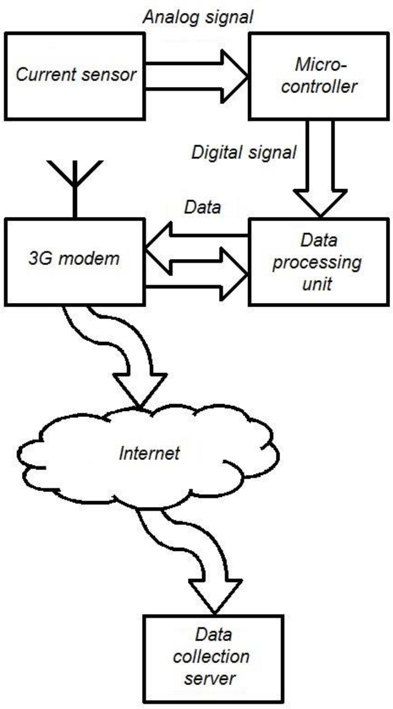


*Figure 4.* Schematic diagram of a GIC recorder

- A constant component that carries direct information on GICs. This component also contains a zero offset signal of current probe driven by residual induction of current clamps in the magnetic core and by temperature drift of parameters of electronic components.
- Amplitudes of currents of the first, second, and third harmonics, which allow us to estimate the change in the neutral total current harmonic content during the flow of high-amplitude GICs. In normal mode, the second and third harmonic currents are negligible, so we can assume that their increase is caused only by distortion due to core magnetization of the transformer by geomagnetically induced currents. The first harmonic current can reach significant magnitudes in the operating mode as well due to various asymmetries in the power system and transformer.

Besides, instantaneous currents flowing in neutrals during transient processes of various types, such as switching, short circuits, or thunderstorms, are recorded. The current curve contains 256 points at a sampling frequency of 14400 Hz, i.e. we can receive an 18 ms signal (almost the period of the power system frequency). The instantaneous current recording unit starts operating when a certain threshold value of the derivative of the neutral current is exceeded at a given time.

Every hour, a set of files containing neutral current components is zipped and transmitted via mobile communications to the server of data collection, storage, and further processing.

## 3. DESCRIPTION OF GIC DATABASE

The data server is a software and hardware complex for receiving, storing, processing, and presenting GIC measurement data. The complex includes a file server, a database management system (DBMS), and web servers.

At the first stage, archives with data in binary format, received every hour via the FTP protocol from GIC recorders, are unpacked into the database (DB) without preprocessing. Original archive files are also stored in DB. At the second stage, hourly files are combined into daily ones. The data is converted from binary format to text format and is processed, which involves correcting the signal baseline and reducing the sampling rate of the signal through its decimation. The database stores data samples with different sampling periods: 0.1 s (initial signal with a sampling frequency of 10 Hz), 0.5 s (used in DB "Geomagnetically inducted currents in the main electric power transmission line "Northern Transit"), 10 s (this sampling period usually has data from magnetovariation stations), and 60 s (used to create image files).

At the final stage, the data is converted into a graphical format necessary for the visual presentation of the results on the Internet. To this end, a website has been developed as part of the European Risk from Geomagnetically Induced Currents (EURISGIS) project [Viljanen, 2011] [http://eurisgic.ru ], which provides access to current and archived GIC measurement data obtained from the Vykhodnoy, Revda, Titan, Loukhi, and Kondopoga transformer substations, as well as to information about the rate of change in the magnetic field obtained from the Lovozero Observatory (LOZ).

The database stores GIC measurement results for a long period of time: data from the Revda 110 kV substation are available since May 2011; at the Titan 330 kV substation, recording was made from June 2010 to December 2014; at the Loukhi and Kondopoga330 kV substations, recorders were installed in September 2011; and at the Vykhodnoy330 kV substation, in October 2011. The data stream was not continuous because there were rather large gaps in the database. The main reasons for the data losses were equipment failure (four hard disk drives got out of order during the recording period); power outage of recorders due to outside interference; damage to cable lines when personnel performed works at substations; problems with data transmission (the Loukhi and Kondopoga substations are located in marginal reception areas). The number of days for which data is available in the database can be seen in Table 1.

On the website eurisgic.ru, only data plots are available. In order for monitoring data to be widely available, a database of machine-readable data has been developed as a network resource [http://gic.en51.ru]. This database contains the results of GIC measurements in neutrals of autotransformers at three 330 kV substations of the main electric power transmission line

"Northern Transit" (Vykhodnoy, Loukhi, and Kondopoga) for the period 2011–2022. According to a request generated in html, data for the selected day can be taken from the database as a text file containing the results of GIC measurements with a sampling period of 0.5 s or as an image file with a curve of GIC amplitude. The database contains over 20000 text and image files grouped by type and substations in six folders with a total volume over 50 GB.

Table 1

Number of days in the database by years and substations

| Year | Vykhodnoy | Revda | Titan | Loukhi | Kondopoga |
|---|---|---|---|---|---|
| 2010 | 0 | 0 | 183 | 0 | 0 |
| 2011 | 38 | 114 | 301 | 168 | 178 |
| 2012 | 366 | 325 | 286 | 253 | 366 |
| 2013 | 365 | 365 | 358 | 365 | 365 |
| 2014 | 365 | 365 | 286 | 365 | 365 |
| 2015 | 365 | 279 | 0 | 365 | 340 |
| 2016 | 366 | 366 | 0 | 366 | 337 |
| 2017 | 365 | 116 | 0 | 365 | 365 |
| 2018 | 343 | 365 | 0 | 106 | 365 |
| 2019 | 365 | 365 | 0 | 71 | 365 |
| 2020 | 366 | 304 | 0 | 366 | 366 |
| 2021 | 365 | 283 | 0 | 365 | 365 |
| 2022 | 365 | 262 | 0 | 365 | 365 |
| Total | 4034 | 3509 | 1414 | 3520 | 4142 |

If necessary, a text file can be saved at an on-device media as SSSYYYYMMDD.txt , where SSS is the substation identifier (vkh — Vykhodnoy, lkh — Loukhi, knd — Kondopoga), YYYY — year, MM — month, DD — day. For example, the file vkh20140325.txt contains data recorded by a GIC recorder on April 25, 2014 at the Vykhodnoy substation.

The data in a text file is presented as YYYY MM DD hh mm ss.s II.II, where YYYY is the year, MM is the month, DD is the day, hh is the hour, mm is the minute, ss is the second, II is the current in amperes. The daily file holds 172800 lines, its size is 4921138 b. For example, below is a fragment of a text file with the first, intermediate, and last records:

2021 03 01 00 00 00.0 0.07;
2021 03 01 19 41 17.0 25.01;
2021 03 01 23 59 59.5 –0.32.

Image files can also be downloaded as a 556×228 px bitmap image in png. Masks of the image and text file names are the same.

Below are examples of image files demonstrating some features of the data obtained by the GIC monitoring system, which should be taken into account when processing and analyzing the data.

Hall effect current sensors can have open-loop (direct detection) and closed-loop (force-balance) configurations. The advantage of force-balance sensors is the absence of output signal offset voltage and the low temperature drift. For the GIC monitoring system in transformer neutrals at the Vykhodnoy and Loukhi substations, we have chosen an inexpensive adapter clamp-type current sensor using open Hall element. To reduce the temperature drift, a heating element is installed in the measuring unit to maintain a constant temperature of 30 °C. The heating element is controlled according to the integral regulation law, which is characterized by fluctuations of the controlled quantity near a given value. Figure 5 illustrates a characteristic signal from a GIC sensor, which is generated during operation of the temperature control assembly. The signal amplitude is ~0.1 A, the period is ~1 hr. At Kondopoga substation, a Hall force-balance sensor is installed; therefore, there is no such an effect.

Another feature of open Hall sensors is the zero line offset caused by the residual induction in the measuring magnetic core of current clamps. This is a systematic error that is eliminated at software signal processing (baseline correction). However, transients regularly occur in electrical grids, which are accompanied by passage of strong currents in transformer neutral: emergency and scheduled switching of overhead lines, power transformers and loads, short circuits, and open-phase modes in the grid. A sharp change in neutral current leads to reverse of core magnetization of current clamps and to a zero line offset. Figure 6 shows how a signal looks like after baseline correction.

Note also that current sensors have a limited measuring range: at the Loukhi and Kondopoga substations, it is set at ±62.5 A; at Vykhodnoy, ±125 A. With currents exceeding these values, operational amplifiers are overloaded by the level of the input signal limited by supply voltage, and the operational amplifier enters

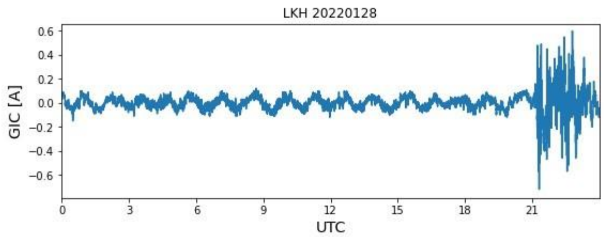


*Figure 5.* Signal temperature variations

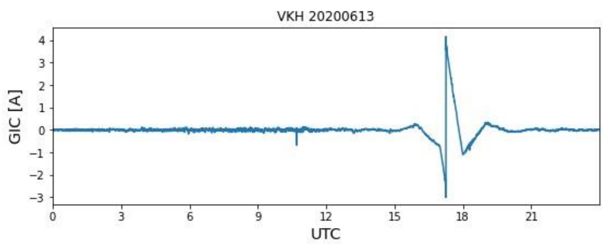


*Figure 6.* Zero line offset

the mode of amplitude limitation of a signal (clipping). Figure 7 exemplifies June 29, 2013 when during a powerful geomagnetic storm in the recovery phase [Apatenkov et al., 2020] the current in transformer neutral at the Vykhodnoy substation exceeded the 125 A amplitude range of measuring clamps. Such an excess of the predicted current became possible due to the fact that on that day one of the two transformers in the substation was taken out for repair, and all current flowed in windings of the transformer in neutral of which a GIC sensor was installed.

There are two power transformers installed at the Vykhodnoy and Loukhi substations, and one at Kondopoga. The transformers and overhead lines at the substations are periodically disconnected for repairs and maintenance. If a transformer, in the neutral of which a GIC sensor (the first one) is installed, is disconnected, the signal from this sensor will contain only noise and interference, induced in the transformer windings, from neighboring equipment since there is no current in the neutral of this transformer. An example of such a record is given in Figure 8.

If the second transformer is switched off or on, the current in the neutral of the first transformer abruptly changes its value (see Figure 9). A similar abrupt change in the signal can be observed when overhead power transmission lines are connected to or disconnected from substation busbars. 13 overhead lines are connected to the substation busbars of the Vykhodnoy substation; 6 at Loukhi; 4 at Kondopoga. Any change in the topology of a complex electrical grid leads to a redistribution of currents in its branches and nodes, which should be taken into account when analyzing GIC DB.

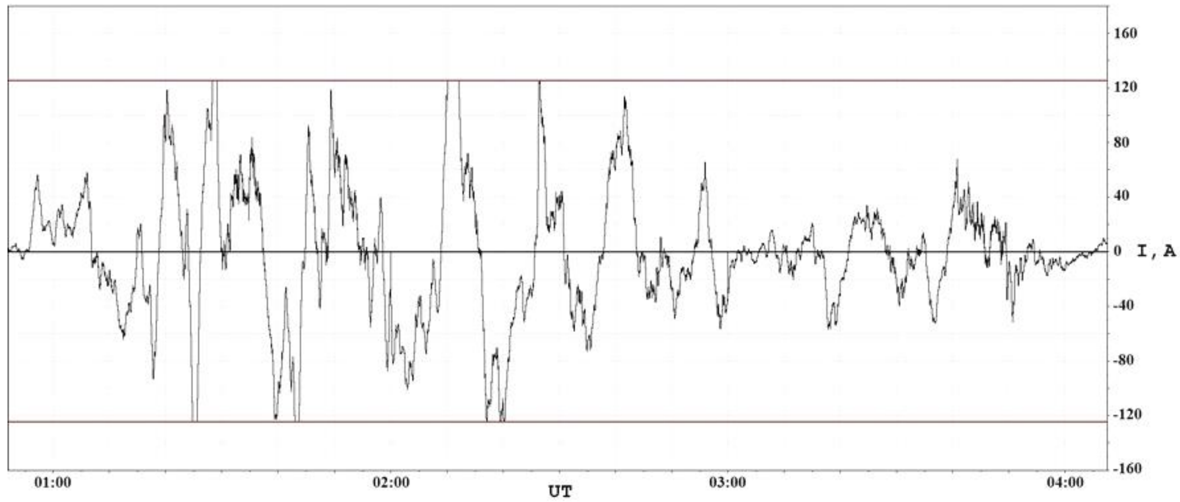


*Figure 7.* Signal clipping (June 29, 2013)

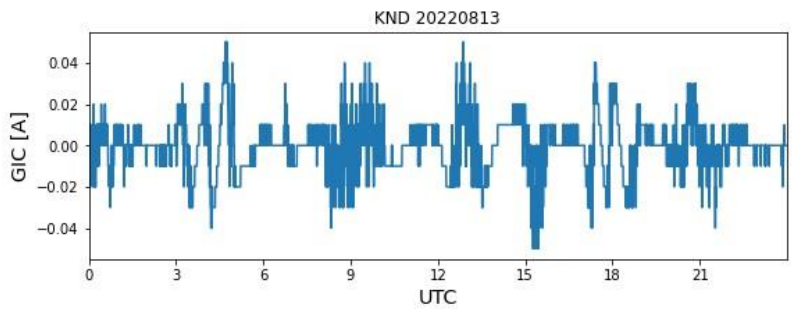


*Figure 8.* Neutral current in a disconnected transformer

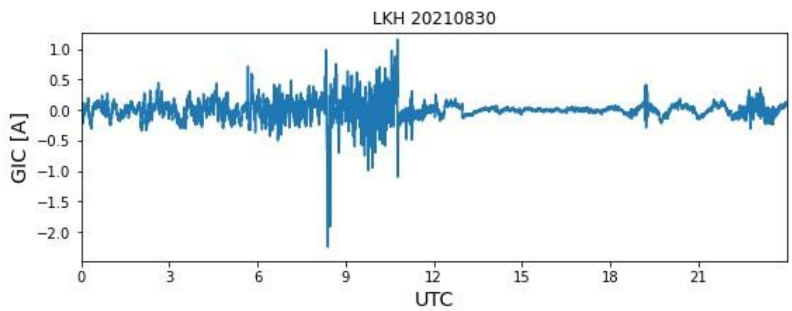


*Figure 9.* GIC variation in the transformer neutral as the electrical grid topology changes

## 4. EXAMPLES OF USING GIC BD

The GIC database contains records from mid-2011 to the end of 2022. Table 2 gives a brief summary of the events of solar cycles 24 and 25, which caused relatively strong GICs in transformer neutrals at the substations of the 330 kV main electric power transmission line “Northern Transit”.

In normal operation of the electrical grid when all overhead lines and transformers work, GICs at Vykhodnoy are approximately an order of magnitude stronger than those at Lokhi and Kondopoga. This is due to the topology of the electrical grid and the orientation of the overhead lines relative to the disturbance vector of the geomagnetic field's horizontal component. If the overhead lines going in and from the intermediate substation do not change their direction globally, as at Loukhi, Vykhodnoy, and other intermediate Northern Transit substations, the GICs flowing in and out of the transformer neutral compensate each other and the resulting currents are weak. At the Vykhodnoy substation, the overhead lines change their direction from meridional to latitudinal. GICs in perpendicular lines usually differ significantly due to the difference between active geomagnetic field components, which leads to high values of resulting GICs in the transformer neutral.

For example, during the September 7–10, 2015 event, the overhead line going to the south from the Loukhi substation was disconnected; therefore, only current from the overhead line coming from the north flowed in the transformer neutral. This explains the high-ampere current at this substation, and the equality of currents at Vykhodnoy and Loukhi results from the spatial homogeneity of the geomagnetic disturbance over the territory of Northern Transit.

Belakhovsky et al. [2018] have applied a vector technique for representing variations in the geomagnetic field's horizontal component and its derivative to the description of the geomagnetic field variability during the March 17, 2013 magnetic storm. They compared data from IMAGE magnetic stations with the GIC DB data obtained in power transmission lines on the Kola Peninsula and in Karelia. The vector technique has shown much lower variability of the geomagnetic field's horizontal component than its derivative. These findings cannot be explained by the simple model of extended ionospheric current and suggest that it is important to take into account the fields of small-scale current struc tures for calculating GICs. Thus, GICs pose serious hazard to technological systems oriented not only in the latitudinal direction, but also in the longitudinal one.

The strongest GICs were recorded during the main phase of the June 28–29, 2013 magnetic storm. Apatenkov et al. [2020], after analyzing ground-based magnetic observations and GIC DB data, as well as reconstructing ionospheric currents and auroral data, concluded that auroral omega bands are an important mechanism for generating strong variations in the magnetic field and geomagnetically induced currents due to rapid propagation of ionospheric currents in the azimuthal direction.

Despirak et al. [2022] have studied several events of intense GICs in two monitoring systems: in the main electric power transmission line “Northern Transit” and in the gas pipeline near Mäntsälä (Finland). The use of the two different GIC monitoring systems, located in the auroral and subauroral zones, made it possible to trace the occurrence and propagation of GICs from subauroral to high geomagnetic latitudes and compare them with the motion of the substorm westward electrojet. Two events have been selected for the study — March 15, 2012 and March 17, 2013, when intense GICs were observed at the Mäntsälä and Vykhodnoy substations. The GICs in the meridional profile of observations have been shown to develop in accordance with the development

Table 2

Events during solar cycles 24 and 25 with strong GICs

| Dates | *K*-index Lovozero | GIC amplitude at the substation, A | | |
|---|---|---|---|---|
| | | Vykhodnoy | Loukhi | Kondopoga |
| October 25, 2011 | 7 | 19.0 | 7.1 | 34.8 |
| March 15, 2012 | 6 | 23.1 | no data available | 10.2 |
| April 24, 2012 | 8 | 46.4 | 3.2 | 4.3 |
| October 1, 2012 | 8 | 25.7 | 18.5 | 4.8 |
| October 9, 2012 | 8 | 30.2 | 7.2 | 28.2 |
| March 17, 2013 | 7 | 49.2 | 4.7 | 12.0 |
| March 27, 2013 | 7 | 62.8 | 6.3 | 5.1 |
| June 1, 2013 | 8 | 51.6 | 5.5 | 3.9 |
| June 7, 2013 | 8 | 59.3 | 7.7 | 4.1 |
| June 29, 2013 | 8 | 125.0 | 6.5 | 33.7 |
| October 2, 2013 | 8 | 56.4 | 19.3 | 7.5 |
| March 17, 2015 | 8 | 72.9 | 6.1 | 24.0 |
| September 7–10, 2015 | 9 | 51.1 | 54.6 | 32.7 |
| September 2, 2016 | 8 | 94.4 | 6.1 | 2.8 |
| May 28, 2017 | 8 | 49.4 | 8.1 | 10.0 |
| September 8, 2017 | 9 | 92.3 | 31.5 | 22.9 |
| April 24 , 2023 | 8 | 52.3 | 9.7 | 22.6 |

of the fine spatio-temporal substorm structure. A good correlation was found between the occurrence of GICs and an increase in the geomagnetic indices *IL* (shows the intensity of the westward electrojet on the IMAGE meridian) and $W_p$ (characterizes substorm wave activity).

## CONCLUSION

OHLs are giant antenna systems that receive electromagnetic waves over a large area. Measuring currents flowing from lines into the ground makes it possible to collect and analyze data directly or indirectly characterizing various external effects on the operation of electrical grids and to examine their response to these effects. Experimental data on the impact of geomagnetic disturbances on ground-based technical objects is of great practical and scientific value as evidence of the relationship between geomagnetic disturbances and system malfunctions, as well as an indirect method for studying processes in Earth's ionosphere.

Continuous monitoring of GICs in neutrals of several transformers for more than 11 years has allowed us to obtain qualitatively new information about the impact of GICs on substation equipment during strong and moderate disturbances. The database stored since 2011 and updated in real time is already being used by many geophysicists and power engineers to obtain important information about phenomena in the ionosphere and the impact of space weather on technological systems.

The database is publicly available [http://gic.en51.ru]. When using the database, please refer to this paper.

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