



Estimation of Geomagnetically Induced Currents in the Altai Republic Power System According to the Baygazan Magnetic Station Data

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Abstract. A geoelectric field, voltages between grounding points of the Altai Republic power grid and geomagnetically induced currents (GIC) in power lines and grounding nodes were calculated in homogeneously conducting Earth's crust model with the resistivity of $5 \cdot 10^2 \text{ Ohm} \cdot \text{m}$ based on the magnetic station "Baygazan" data in the Russian Altai. These estimations have shown that the geoelectric field increased up to 30 mV/km, the potential difference between the power line grounding points reached value of 3.5 V and GIC value reached 0.12 A during the geomagnetic storm on August 5, 2023 (Kp=5–6) with geomagnetic field change rate increasing up to 10–15 nT/min. The GIC value in power line depends on the geoelectric field orientation. High rate of the north geomagnetic field component change causes GIC in latitude-oriented lines (Kosh-Agach – Inya, Ulagan – Inya, Ust-Koksa – Inya), high one for east component causes GIC in meridian-oriented line (Cherga – Inya). The resistances asymmetry of the 'Ulagan – Inya' and 'Ust-Koksa – Inya' power lines causes an increase of GIC at Ininskaya substation grounding node with latitude-oriented geoelectric fields. The calculated data are compared with the results of monitoring of even harmonics amplitudes at the Ininskaya power substation. It is shown that the calculated value of the GIC in the grounded neutral of the power transformer at the Ininskaya substation correlates with the amplitude of even harmonics during the geomagnetic storm.

Key words: Geomagnetically induced currents, Altai, geoelectric field, simulation, Earth's crust resistivity, even AC harmonics.

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ПРИБОРЫ И МЕТОДЫ ИМЕРЕНИЙ

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Оценка геомагнитно-индуцированных токов в электроэнергетической системе Республики Алтай по данным магнитной станции Байгазан

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Аннотация. На основе данных магнитной станции "Байгазан" в Горном Алтае для модели однородно проводящей земной коры с удельным электрическим сопротивлением $5 \cdot 10^2 \text{ Ом} \cdot \text{м}$ произведен расчёт геоэлектрического поля, напряжения между точками заземления энергетической системы Республики Алтай и геомагнитно-индуцированных токов (ГИТ) в линиях электропередач и узлах заземления. Эти оценки показали, что во время геомагнитной бури 05.08.2023 (Кр=5-6) при скорости изменения геомагнитного поля до 10-15 нТл/мин геоэлектрическое поле достигало значения 30 мВ/км, разность потенциалов между точками заземления - 3.5 В, а геомагнитно индуцированные токи - 0.12А. Значения ГИТ в линиях электропередач зависят от ориентации геоэлектрического поля. Высокая скорость изменения северной компоненты геомагнитного поля порождает ГИТ в широтно ориентированных линиях (Кош-Агач – Иня, Улаган – Иня, Усть-Кокса – Иня), а у восточной компоненты – для ориентированных вдоль меридиана (Черга – Иня). Асимметрия сопротивлений линии 'Усть-Кокса – Иня' и пары широтно ориентированных линий 'Улаган – Иня' и 'Кош-Агач – Иня' приводит к увеличению ГИТ в заземлении подстанции 'Ининская' при ориентированном вдоль широты геоэлектрическом поле. Расчётные данные сравниваются с результатами мониторинга чётных гармоник на электрической подстанции "Ининская". Показано, что во время геомагнитной бури наблюдается корреляция между расчётными значениями ГИТ в заземленной нейтрали силового трансформатора на подстанции и амплитудой чётных гармоник.

Ключевые слова: геомагнитно-индуцированные токи, Горный Алтай, геоэлектрическое поле, удельное электрическое сопротивление земной коры, чётные гармоники переменного электрического тока, моделирование

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Introduction

After the power blackout of 6 million people in Quebec (Canada) on March 13, 1989, which was caused by a strong geomagnetic storm and a transformer loss, the interest in studying the influence of geomagnetically induced currents (GIC) on power grids has significantly increased [1]. It was found that at the rate of change of the geomagnetic field components in tens and hundreds of nT/min, the magnitude of these currents in the grounded neutrals of power transformers can reach tens and hundreds of amperes. This leads to magnetization of power transformers cores and a decrease in their magnetic permeability, generation of AC harmonics, voltage fluctuations in network nodes, fluctuations in active and reactive power in the power system and, as a consequence, to false operation or failure of automation and relay protection, massive power supply disruptions in load nodes. These effects are usually observed at high geomagnetic latitudes. However, it is noted that sudden impulses arising at the shock wave fronts in the solar wind plasma affect even low-latitude networks. There is also an increase in the probability of high values of GIC in mountainous regions with their high-resistance basement.

GIC measurements at the auroral zone on the Russia territory have been carried out at the Northern Energetics Research Centre of Kola Scientific Center of the Russian Academy of Sciences since 2010 [2]. Direct measurements of the GIC are not carried out in the middle latitudes, however V.P. Sivokon organized monitoring of even AC harmonics at Kamchatka in 220 kV power lines, the amplitude of which is correlated with the GIC [3]. Similar measurements have been organized at the Ininskaya electric substation in the Altai Republic since July 28, 2023 [4].

The magnetic observatories 'Lovozero' (LOV) at the Kola Peninsula and 'Paratunka' (PET) at Kamchatka play an important role in the study of GIC. The presence of a magnetic station 'Baygazan' at Altai makes it possible to study GIC there. The purpose of this article is to estimate geoelectric fields and geomagnetically induced currents in the Altai Republic power system based on geomagnetic variations data of the Baygazan magnetic station [5], [6]. The article by Boteler and Pirjola [7] describes methods for calculating GIC for the case of homogeneous conductivity of the Earth crust and layered Earth crust. In the approximation of the vertical incidence of a plane wave creating geomagnetic variations, and in the case of small spatial derivatives for the variation geoelectric field $\partial E_z / \partial y = 0$, $\partial E_z / \partial x = 0$, and the vertical component of the geomagnetic field variation $B_z(f) = 0$, the components of the geoelectric field of variations can be calculated using the formulas

$$E_x(f) = K(f)B_y(f), E_y(f) = -K(f)B_x(f), \quad (1)$$

where $E_x(f)$, $E_y(f)$, $B_x(f)$, $B_y(f)$ are the Fourier images of the eastern, northern components of the geoelectric field and the eastern, northern components of the geomagnetic variation field respectively, f is the frequency, $K(f)$ is the transfer function. In the case of a model of homogeneous Earth conductivity, the transfer function is

determined by a simple relation

$$K = \sqrt{\frac{i2\pi f \rho}{\mu_0}} \quad (2)$$

where ρ is Earth crust resistivity, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the magnetic constant.

To use these formulas, it is necessary to know the electrical resistivity of the Earth's crust at Altai. The dependences of the resistivity on the the period of probing waves for various areas of the Southeastern Altai are given in [8]. The resistivity for 1 sec period changes by two orders of magnitude. It arise a value of $10^4 \text{ Ohm} \cdot \text{m}$ for the North Chui Ridge and is equal to $2 \cdot 10^2 \text{ Ohm} \cdot \text{m}$ for the Kurai depression. For the period of 100 s, the resistivity is lower by an order of magnitude both for the depressions and for its mountain framing. The minimum of resistivity is observed for the period of 1000 s and resistivity for period of 10^5 s is equal to $40 \text{ Ohm} \cdot \text{m}$.

Therefore, the resistivity can be approximated for the frequency range 0.01 – 1 Hz by a power dependence taking the value $\rho_0 = 10^3 \text{ Ohm} \cdot \text{m}$ for the period of 1 s ($f_0 = 1 \text{ Hz}$) and $10^2 \text{ Ohm} \cdot \text{m}$ for the period of 100 s:

$$\rho = \rho_0 \cdot \sqrt{\frac{f}{f_0}},$$

In this case, the value of the resistivity will take an intermediate value between the resistivity of the basins and mountain ranges. Thus, it will be taken into account that the power line runs both throw the basins and throw the ridges. The mean value can be calculated by the formula

$$\langle \rho \rangle = \frac{1}{f_2 - f_1} \int_{f_1}^{f_2} \rho(f) df = \frac{2\rho_0 (f_2^{3/2} - f_1^{3/2})}{3f_0^{1/2}(f_2 - f_1)} = 5 \cdot 10^2 \text{ Ohm} \cdot \text{m}, \quad (3)$$

where $f_1 = 3.05 \cdot 10^{-5} \text{ Hz}$, $f_2 = 0.5 \text{ Hz}$ are the border frequencies for spectrum calculation.

The following GIC calculation algorithm was used.

1. The average and linear trend are subtracted from the Baygazan data on geomagnetic variations, Humming windows are used to reduce the Gibbs phenomenon at the edges, the data are recalculated in Tesla.

2. A fast Fourier transform of the horisontal (H), and declination (D) components of the geomagnetic field are calculated.

3. The H- and D-spectra are multiplied by the transfer function according to (1),(2) with resistivity estimation (3), the inverse Fourier transform is taken.

4. The components of the electric field are recalculated from the geomagnetic coordinate system to the geographical one by the formulas:

$$E_x = E_D \cos D_0 + E_H \sin D_0, E_y = -E_D \sin D_0 + E_H \cos D_0,$$

where D_0 is magnetic declination.

5. The potential difference between the grounding points is calculated according to its geographical coordinates (x_j, y_j) , (x_0, y_0)

$$U_{0j} = E_x(x_i - x_0) + E_y(y_j - y_0) \quad (4)$$

6. Based on the data on the resistances of power lines and primary windings of power transformers R_{0j} , the values of the GIC between the grounding points I_{0j} are calculated:

$$I_{0j} = U_{0j}/R_{0j}, j = 1, 2, 3, 4.$$

Summ of currents I_{0j} is a current in the grounded neutral at Ininskaya power substation

$$I_0 = I_{01} + I_{02} + I_{03} + I_{04}.$$

The monitoring points of geomagnetic variations and even AC harmonics at Altai Republic power grid

The magnetic station of Gorno-Altai State University "Baygazan" at northern shore of Teletskoye lake has been recording geomagnetic field components variations since December 2009 by means of quartz variometer [5], [6]. The measurement accuracy of second mean values is about 0.02 nT.

Monitoring of even AC harmonics amplitudes was organized at the Ininskaya power substation in the Altai Republic since 28 July 2023 [4]. An induction sensor is located near the power transformer of 2.5 MVA capacity. Digital recorder with 24 digit ADC records signal with the rate of 1 kHz and the signal-to-noise ratio of 63 dB. The averaged spectrum is calculated from 15 one-second intervals measured in a minute. According to it, the amplitudes of even harmonics are determined once a minute.



Fig. 1. Scheme of the location of the monitoring points of geomagnetic variations (BGZ) and the even AC harmonics amplitude in the power grid of the Altai Republic (Inya). There are shown the power lines 110 kV, power substations, solar plants.

The power grid of 110 kV of Altai Republic is grounded in electrical substations at Kosh-Agach, Ulagan, Inya, Ust-Koksa, Cherga and Maima (see Fig.1). The geoelectric field induces the potential difference between grounding points according to (4). It causes the geomagnetically induced currents in the power lines between the grounding points. Therefore, the currents from the four power lines are summed up in the grounded neutral of the power transformer at Ininskaya power substation. Its parameters calculated according to the date of [9] are shown in Table 1.

Table 1

No	Power line	Length, km	Resistance, Ohm
1	Inya - Ulagan	142.0	35.4
2	Inya - Kosh-Agach	181.2	45.2
3	Inya - Ust'-Koksa	241.7	103.0
4	Inya - Cherga	200.6	56.0

Results and discussion

The geoelectric field components were calculated for the geomagnetic storm ($K_p=5-6$) occurred on 05 August 2023 based on Baygazan station measurement results. The field components dynamics and their spectra are shown at Fig.2.

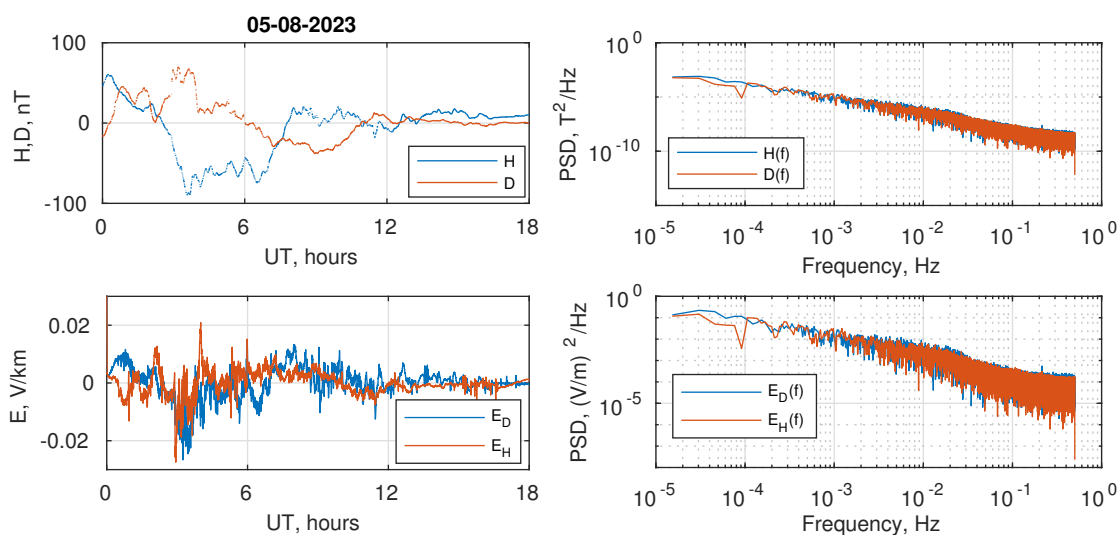


Fig. 2. The calculation results: top left — geomagnetic field components variations, top right — their spectra, bottom right — geoelectric field spectrum, bottom left — its components dynamics.

It can be seen that geomagnetic disturbance is observed at 0-12 UT, then geomagnetic variation amplitude decreases significantly. The spectrum of geomagnetic variations is similar to a power function $S = S_0/f^{-\beta}$ with a slope coefficient β equal to

1. The slope coefficient of the geoelectric field is smaller, because the transfer function in the homogeneous Earth model is proportional to the root of the frequency. In the lower part of the spectrum up to 0.01 Hz, the slope coefficient is close to 1/2, then it increases slightly. It is seen that the calculated geoelectric field reaches 27 mV/km for the geomagnetic horizontal component range of up to 150 nT during the storm.

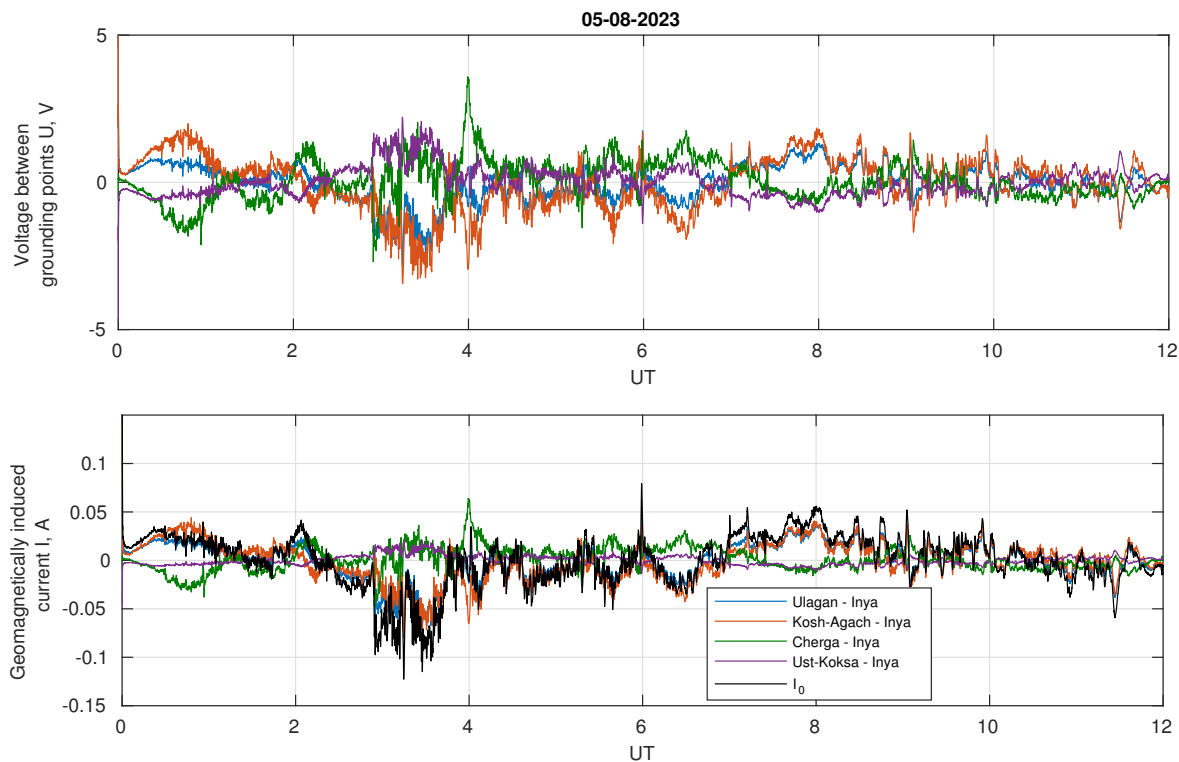


Fig. 3. Dynamics of calculated voltage between the grounding points (upper) and one of geomagnetically induced currents (below) during the geomagnetic storm on August 05, 2023.

The calculated potential differences between power line grounding points are shown in Fig. 3 (upper panel). They reach the values of 3.4–3.5 V during geomagnetic storm on 'Cherga – Inya' and 'Kosh-Agach – Inya' lines. These voltages depend on geoelectric field orientation. The potential difference between the grounding points for the eastern pair of lines "Kosh-Agach - Inya" and "Ulagaan - Inya" is usually opposite in sign to the voltage between the grounding points for the western pair "Ust-Koksa - Inya" and "Cherga - Inya".

GIC dynamics is shown in Fig.3 (lower panel). The maximal GIC value of 0.12 A was reached at 03:14:46 UT. The geoelectric field components were $E_x = -27.7 \text{ mV/km}$, $E_y = -11.8 \text{ mV/km}$ at that time, rates of geomagnetic field components change were $dD/dt = -8.8 \text{ nT/min}$, $dH/dt = -6.4 \text{ nT/min}$, $dB/dt = 10.9 \text{ nT/min}$. The GIC values at power lines at that moment are shown in Table 2. Note that the voltages on the 'Ust-Koksa - Inya' line and the 'Ulagaan-Inya' line are close in amplitude, but the resistance

of the first one is about three times higher than that of the 'Ulagan-Inya' line. These lines are oriented oppositely in plane. Their resistances difference leads to the currents imbalance and high I_0 value with the SWW field orientation, along the 'Ulagan - Ust-Koksa' line. Such an orientation of the geoelectric field is observed during a rapid change in the horizontal component.

The maximal GIC value of 0.064 A in 'Inya - Cherga' line is observed at 03:59:24. The geoelectric field components were $E_x = -12.3 \text{ mV/km}$, $E_y = +21.7 \text{ mV/km}$ at that time, rates of geomagnetic field components change were $dD/dt = 4.5 \text{ nT/min}$, $dH/dt = -13.7 \text{ nT/min}$, $dB/dt = 14.5 \text{ nT/min}$. Thus, high GIC value at this line is observed with geoelectric field oriented along a meridian, which occurs when the D-component changes rapidly.

Table 2

Estimations of geomagnetically induced voltages and currents in the 110 kV power line at 03:14:46 UT on August 5, 2023

No (j)	Power line	Voltage U_{0j} , V	GIC I_{0j} , A
0	Ininskaya grounding node	-	-0.123
1	Inya - Ulagan	-2.83	-0.080
2	Inya - Kosh-Agach	-3.41	-0.075
3	Inya - Ust'-Koksa	2.21	0.022
4	Inya - Cherga	0.62	0.011

The obtained estimations of geoelectric field and geomagnetically induced currents are rather small. The article [2] indicates that geoelectric fields can reach 15 V/km, and geinduced currents can reach 300 A at the polar regions. For example, during a geomagnetic storm on March 15, 2012, when $K = 6$, a GIC at the 'Vykhodnoy' electrical substation was equal to 23.1 A, and that at the 'Kondopoga' substation was equal to 10.2 A. This difference is explained by two factors. On the one hand, Altai is far from the auroral zone, so geomagnetic disturbances during storms have a smaller amplitude here. In particular, the geomagnetic field change rate during the geomagnetic storm on September 08, 2015 at $K = 6$ was 220 nT/min with an observed GIC of 48 A [10]. It is an order of magnitude less than the field change rate during the storm August 05, 2023 in Altai. On the other hand, 110 kV power lines at Altai have more resistance than 330 kV lines, on which the measurements of [2], [10] were made.

Currents of 0.1 A magnitude usually do not pose danger to the transformers installed in a 110 kV power grid. These transformers with capacities smaller than 100 MVA are the most resistant to GIC [11]. Nevertheless, these currents magnetize the transformer core and cause generation of even harmonics. Correlation coefficients for calculated GIC module values averaged over 1 minute and even AC harmonics amplitudes in Ininskaya electric station were calculated. Since both variables followed the logarithmically normal distribution, the correlation coefficients were considered for their logarithms. The results are shown in Table 3 and Fig.4. It can be seen that there is a statistically significant correlation for these characteristics.

Table 3

The values of the correlation coefficients for the logarithms of the calculated geomagnetically induced current I_0 with the measured amplitudes of even harmonics A_n , $n = 2, 4, 6$ in Ininskaya electric substation

	$\lg(A_2)$	$\lg(A_4)$	$\lg(A_6)$
$\lg(I_0)$	0.246	0.411	0.344

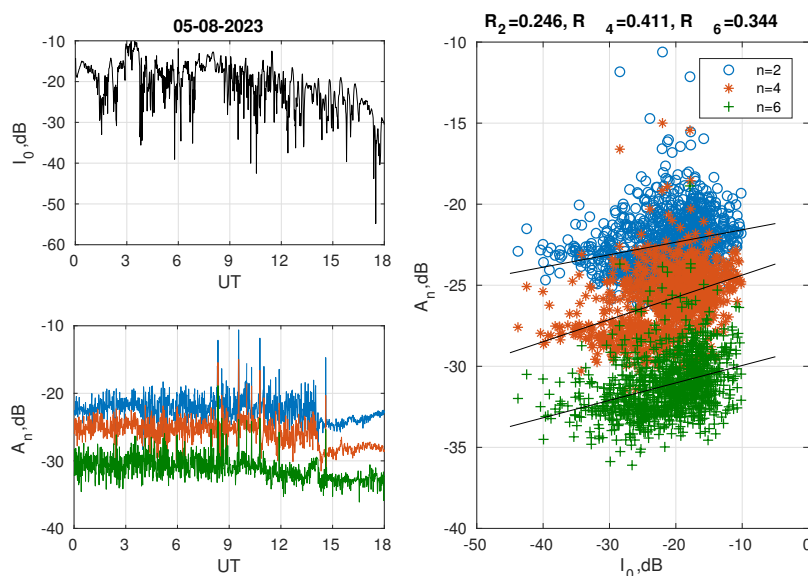


Fig. 4. Results of correlation analysis between the measured amplitudes of even harmonics in the power transformer of the Ininskaya substation and the calculated value of the geomagnetically induced current module during the geomagnetic storm on August, 2023 ($K_p=5-6$). The correlation coefficients are shown in the title of left panel.

The model of uniformly conducting Earth results in underestimated values of the geoelectric field spectrum at high frequencies (above 0.01 Hz) and overestimated at low frequencies (below 0.001 Hz).

It is necessary to know the distribution of resistivity along all power lines for a more accurate model, but the authors do not have such information. The geoelectric profile along the Aktash – Ulagan section is described in [12], and that along the Aktash – Kosh-Agach section is considered in [13]. These works were done as a part of the study of the epicentral zone of the Altai earthquake. It is also necessary to take into account the presence of permafrost in the Chuya depression. According to the results of [14], blocks of permafrost pebbles and sands with a resistivity of $15 - 20 \text{ k}\Omega \cdot \text{m}$ with a capacity of up to 50 m were found in the upper part of the geoelectric section. The presence of permafrost can also affect the grounding resistance in Kosh-Agach, in particular, for the winter months calculations.

Conclusion

Based on the Baygazan magnetic station data, the geoelectric fields for uniformly conducting Earth with resistivity of $5 \cdot 10^2 \text{ Ohm} \cdot \text{m}$ were calculated during the geomagnetic storm on August 5, 2023 (Kp=5-6). That allowed us to estimate the geinduced currents in the Altai Republic power grid and grounding node of the power transformer at the Ininskaya substation. At the rate of the geomagnetic field change $\text{dB/dt} = 10 - 15 \text{ nT/min}$, the GIC value reached 0.12 A. The GIC value in power line depends on the geoelectric field orientation. High rate of the horizontal geomagnetic field change dH/dt causes GIC in latitude - oriented lines (Kosh-Agach – Inya, Ulagan – Inya, Ust-Koksa – Inya), high dD/dt causes GIC in meridian - oriented line (Cherga – Inya). The resistancies asymmetry of the 'Ulagan – Inya' and 'Ust-Koksa – Inya' power lines causes an increase of GIC at Ininskaya substation grounding node with latitude-oriented geoelectric fields. Correlation of the GIC calculated values with the even harmonics amplitudes, recorded at Ininskaya substation, was found.

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