E3S Web of Conferences **542**, 02002 (2024) https://doi.org/10.1051/e3sconf/202454202002
YIFHG 2024

Assessment of the geomagnetically induced currents impact on the power transformers cores of the Altai Republic 110 kV power grid

Evgeniy Uchaikin[1, *], *Alexey* Gvozdarev[2], and *Nikolay* Kudryavtsev[1]

[1]Robotics laboratory, Gorno-Altaisk State University, Gorno-Altaisk, Russia
[2]Complex geophysical observatory "Paratunka", Federal State Budget Research Institution Institute of Cosmophysical Research and Radio Wave Propagation, Far Eastern Branch of the Russian Academy of Sciences, Paratunka, Russia

Abstract. Based on the Baigazan magnetic station data located in Altai, geomagnetically induced currents (GIC) in primary windings of transformers in the southern part of the Altai Republic power system were calculated during a strong magnetic storm on April 24, 2023 (geomagnetic activity index Kp=8). It is shown that the calculated currents in the primary windings of 110 kV power transformers can reach values of more than 0.4 A. At the same time, magnetizing fields are formed in the transformers cores. They make up to 70% of the working field created by the no-load current, that should negatively affect the efficiency of their operation. To assess the GIC effect on the transformer core, a GIC core magnetization coefficient is used. It represents the ratio of the magnetic field strength generated by GIC at the transformer core to the no-load current magnetic field strength. The greatest effect is observed in 2.5 MVA installed capacity transformers at the Ininskaya substation. The GIC effect decreases with an increase of transformer power. To increase the Altai Republic power system stability to GIC, it is proposed to shift the grounding point from the Ininskaya substation to the Ongudayskaya substation. The core magnetization coefficients in this case do not exceed 0.4.

1 Introduction

After the power blackout for 6 million people in Quebec (Canada) on March 13, 1989, which was caused by a strong magnetic storm and a transformer loss, the interest in studying the influence of geomagnetically induced currents (GIC) on power grids has significantly increased [1]. In the USA, Canada, European countries, New Zealand, Japan, GIC registration systems have been created in power grids. 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

---

[*] Corresponding author: evgeniy_uch@mail.ru

operation or failure of automation and relay protection, massive power supply disruptions in load nodes [2]. The effect depends on the location latitude (at high latitudes, the rate of change of the magnetic field is much higher), orientation, length, linear resistance of power transmission lines, type of transformer core, service life, level of congestion and power grid topology. The main events leading to rapid changes in the field and GIC generation were revealed, they are: shock waves in the solar wind and auroral sub-storms, generation of Pc5 and Pi3-Ps6 geomagnetic pulsations. For 25 years (and this is the standard operating life of a power transformer), about 5,000 such events of various intensity occur.

At the same time, it is noted that sudden impulses arising at the shock wave fronts in the solar wind plasma affect even low-latitude power grids. In recent years, the influence of geomagnetically-induced currents on power grid located in the middle and low latitudes has been actively studied: Central Europa [3], Austria [4], the Czech Republic [5], Spain [6], Brazil [7], Mexico [8], Iran [9], Japan [10], South Africa [11]. Modeling of the consequences of a strong magnetic storm for the Central Unified Power System in Russia (including Moscow and St. Petersburg) showed the possibility of a systemic accident [12]. Usually, these works consider high-voltage power grid (550, 400, 230 kV), characterized by a large length and low resistance of power lines and transformers.

Meanwhile, in a number of sparsely populated regions, including the Altai Republic, a 110 kV power grids with the line length of more than 500 km are used for power supply. The voltage for such a length of the transmission line is not typical, because the load of villages is small (up to 40 MW) and it is economically justified to build a line with a voltage of 110 kV, which in industrialized regions is used for the district network. For safe operation, a neutral grounding circuit of 110 kV power transformers is used, using special switches of a grounding device. Therefore, according to the normal operation scheme, the line is grounded at the ends and in intermediate substations. The line has a large length, that makes it susceptible to magnetic storms. This article considers the GIC influence on the Altai Republic's energy system.

2 Assessment of GIC impact on power transformers of Altai Republic power grid

2.1 About core magnetization coefficient

It is known, that GIC affects the power transformers cores of power substations with grounded neutrals and extended power lines. The quasi-direct GIC flows through high-voltage primary transformers windings from the power line phase wires to the neutral and causes core magnetization and, as a result, the hysteresis loop is shifted. The induced current of GIC is summed with the operating current, which forms the magnetic flux in the core. The magnetic flux does not change regardless of the transformer load, thus, more then a half of the linear dependence of transformer iron induction curve is used in the transformer design. Therefore, the induced GIC equal to the no-load current will definitely lead to an exit from the linear magnetization mode of the transformer iron.

In the 110 kV Altai Republic power line, W-shaped TMN-X/110 transformers are used (Fig. 1). When quasi-DC flows through the transformer windings, the magnetic field induction is compensated at the edge rods, and acts in the central core of the magnetic core (Fig.1). Since the GIC effect on the edge elements of the W-shaped core is compensated, and the GIC effects only on the central element, the GIC influencing current will be equal to 1/3 of the total GIC.

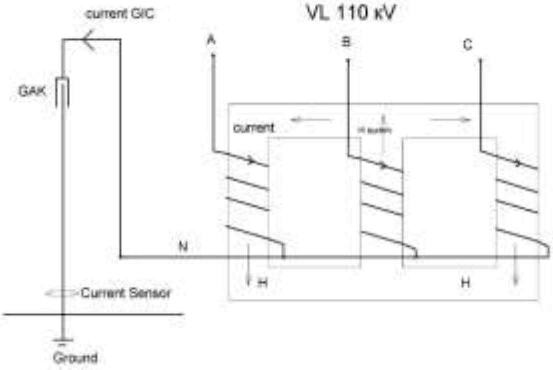

Fig. 1. Diagram of the magnetic field strength directions of the GIC in a grounded transformer with the W-shaped core.

It was decided to calculate the ratio between the GIC magnetic field strength *H* and the magnetic field strengths of the alternating no-load current *Hx*. It named GIC core magnetization coefficient

$$\mathrm{CMC}=H/Hx. \tag{1}$$

The calculation of the magnetic field strengths *Hx* and *H* generated by the no-load current *Ix* and the GIC current $I/3$, respectively, was carried out according to the following formulas:

$$Hx=\frac{wI_x}{L}, \qquad H=\frac{wI}{3L} \tag{2}$$

where *L* is the average length of the magnetic circuit, *w* is the number of turns.

2.2 Calculation of GIC at Altai Republic power system

A model based on [13] and described in [14], was developed to calculate the GIC in the region power system based on the data from the Baigazan magnetic station located in the Altaiskiy Nature Reserve [15]. The parameters of transformers installed at Altai Republic power system substations [16] were taken from the website https://electricps.ru/base/trans/. The one phase linear resistance of the 110 kV power line is assumed to be 0.249 Ohm/km (https://powersystem.info/index.php?title=Справочные_данные_параметров_ЛЭП). Characteristics of the power lines are shown in Table 1 (values to the left of the slash).

Table 1. Characteristics of the power lines for GIC calculation with the actual and proposed grounding scheme.

Branch	Ulagan - Inya/Ongudai	Kosh-Agach - Inya/Ongudai	Ust-Koksa - Inya/Ongudai	Cherga - Inya/Ongudai
Length (km)	142.0/206.7	181.2/245.9	241.7/177.0	200.6/135.9
Line resistance (Ohm)	35.4/51.47	45.2/61.23	103.0/44.07	56.0/33.84
Transformers resistance (Ohm)	28.65/14.7	25.13/11.19	28.65/14.7	28.65/14.7
Overall resistance (Ohm)	64.05/66.17	70.33/72.41	131.65/58.77	84.65/48.54

Based on this model, the GIC in the phase wires of the transformers primary windings at the terminal substations and the Ininskaya substation were calculated during the strongest magnetic storm in 2023. This storm occurred on April 24, 2023, while the geomagnetic activity index reached the value Kp=8, and auroras were observed to the south of Moscow. During the storm sudden commencement (SSC) at 03:53:30 UT, the geomagnetic field change rate dB/dt reached a value of 3.8 nT/sec, the calculated GIC in the Ininskaya substation for one phase was I=0.425 A (Table 2). It can be seen from the Table 2 that the horizontal geomagnetic field component oriented along the magnetic meridian changes the fastest. Consequently, the eastern geoelectric field component is predominant, its maximum amplitude exceeds 200 mV/km. This pattern is typical for the SSC and maximal GIC are associated to the SSC at mid-latitudes in the first place. Similar estimates were obtained for Altai, as the periphery of Kazakhstan, when modeling the maximum field based on the results of registration of 4 storms with K>7, which occurred during the period 2011-2021 [17]. In this work, the eastern component of the geoelectric field was estimated at about 250 mV/km, and the northern one — 130 mV/km.

Previously, we performed calculations for the magnetic storm on August 5, 2023 [14]. The results of calculations for this storm are also shown in the Table 2.

Table 2. Calculated values of geomagnetic field components change rates, geoelectric field components and GIC for one phase at the time of GIC maximum for two geomagnetic storms.

Date	August 5, 2023		April 24, 2023	
Time, UT	03:14:44	03:59:24	03:53:28	03:53:30
Geomagnetical activity index Kp	5		8	
Horizontal geomagnetic field component change rate dH/dt (nT/min)	-46.1	-21.4	-300.4	-223.1
Declination geomagnetic field component change rate dD/dt (nT/min)	14.6	-27.3	29.5	33.7
Eastern geoelectric field Ex (mV/km)	-91.2	-41.3	-214.5	-215.1
Northern geoelectic field Ey (mV/km)	-34.9	65.6	17.0	14.1
GIC at substations (mA)				
Kosh-Agachskaya	-158.8	-128.9	-442.4	-443.3
Ulaganskaya	-139.5	-38.8	-300.2	-298.5
Ust-Koksinskaya	53.8	11.9	112.1	111.4
Cherginskaya	29.3	128.3	205.7	209.3
Ininskaya	-215.1	27.5	-412.2	424.8

The model of uniformly conducting Earth [14] underestimates values of the geoelectric field spectrum at high frequencies (above 0.01 Hz) and overestimates at low frequencies (below 0.001 Hz). Therefore, GIC value can be underestimated for fast process such as SSC. The authors of the article [8] came to similar conclusion. When using the homogeneous Earth resistivity model, the maximum deviations of GIC measurements from the model were observed during the SSC. When using a one-dimensional model of the Earth's conductivity, these deviations were significantly reduced, but the real GIC values were still about 1.4 times higher than the calculation results. Therefore, the values given in Table 1 for SSC must be considered as low estimates, which can be exceeded several times in real measurements.

The article [8] reports on the GIC registration of 12.5 A during G2 level geomagnetic storm (on November 4, 2021) at 400 kV substation Laguna Verde (Mexico, 28.2°N of geomagnetic longitude). The maximum GIC value registered in Austria (42.95°N of geomagnetic longitude) since 2014 (on May 12, 2021) is about 14 A [4], in Japan – about 3A [11]. All these values exceed our estimates by an order of magnitude. These results were obtained for 400 kV power lines, which are characterized by low resistance, therefore high GIC values are observed there. GIC in the isolated 115 kV Baja California Sur power system (Mexico), which is closer in parameters to the Altai power system, was estimated to be up to 2 A during the G2 level geomagnetic storm on November 4, 2021 [8]. Note that the calculation at [8] carried out for neutral grounding, so this current must be divided by 3 and single-phase current is about 0.7 A. The lower GIC values in Altai (Table 2) are probably related to the higher resistance of 110 kV power lines (0.249 Ohm/km for 110 kV at Russia vs 0.061 Ohm/km for 115 kV at Mexico).

2.3 Calculation of GIC core magnetization coefficient for Altai Republic power system transformers

The geometric dimensions and electrical parameters of power transformers installed at 110 kV power substations in the southern part of the Altai Republic are shown in Table 3 [16]. Here *P* is the transformer installed capacity, *S* is the core area, w is the tums number, *L* is the magnetic circuit average length, *R* is the magnetic circuit radius, *Ix* is the no-load current, *Hx* is the field strength in the magnetic circuit, *I* is the GIC, *H* is the field strength generated by GIC, *H/Hx* is the magnetization coefficient.

Table 3. Calculation of the GIC core magnetization coefficient.

Sub-station	Inya	Ulagan	Ust-Koksa	Cherga	Kosh-Agach
P (MVA)	2.5	6.3	6.3	6.3	10
Transfor-mer	TMN-2500/110	TMN-6300/110	TMTN-6300/110	TMTN-6300/110	TMN-1000/110
S (m^2)	0.05	0.08			0.1
w	3175	2000			1588
L (m)	5.40	8.57			10.80
R (m)	0.23	0.16			0.18
Ix (mA)	200	260			370
Hx (A/m)	116	62			54
I/3 (mA)	142	100	37	70	147
H (A/m)	83	23	9	16	22
H/*Hx*	0.72	0.38	0.14	0.26	0.40

It can be seen that TMN-2500/110 transformer located on the Ininskaya substation is more susceptible to GIC than others, since its core magnetization coefficient is maximal. It reached the value of 0.72, which is much higher than that of more powerful transformers. Their core magnetization coefficient was within in the range of 0.14 – 0.40. This is due to the smaller magnetic circuits size L in transformers of lower power. It can be concluded that the lower the transformer installed power is, the more it is susceptible to GIC effect.

Since the no-load current for the Ininskaya substation transformer with the installed power of 2.5 MVA is 0.2 A, GIC of 0.6 A is sufficient for the magnetic flux generated by GIC to become equal to the working magnetic flux. The core magnetization is accompanied by an increase in even harmonics in the magnetic field of the transformer scattered flow. We showed in [18] that even during a magnetic storm on August 5, 2023, with Kp=5-6, correlation arose between the even harmonics amplitude in the magnetic field of the Ininskaya transformer and the geomagnetic field change rate dB/dt. At the same time, the calculated GIC in the winding of the transformer did not exceed 215 mA, and its RMS value during the storm (Kp>5) was 33 mA (during the undisturbed period – 13 mA). Thus, nonlinear effects of the transformer operation are observed at GIC core magnetization coefficients as low as 0.05-0.1.

It is known that electrical steel magnetization curve is linear in the range of 0-5 A/cm (Fig. 2). Calculations show that the total field strength generated by the no-load current and GIC *H+Hx* reaches a value of about 5 A/cm at GIC equal to 2 A. The core entering saturation mode at such a current should trigger current cut-off protections and gas protection, when transformer oil boils, and turn off the core and windings temperature. Estimating the probability of such a GIC in the Altai power system requires additional research. It is only clear that such currents can occur during extra strong magnetic storms at Kp = 9. It should be noted that power transformers failures as the result of the impact of SSC series was observed even at low latitudes – in South Africa [1]. However, even in the absence of energy accidents, the transformer transition to a non-linear mode leads to power supply quality degradation. All of the above confirms the need to predict GIC and revise the grounding schemes in the power system of the Altai Republic, at least for the Iniskaya substation.

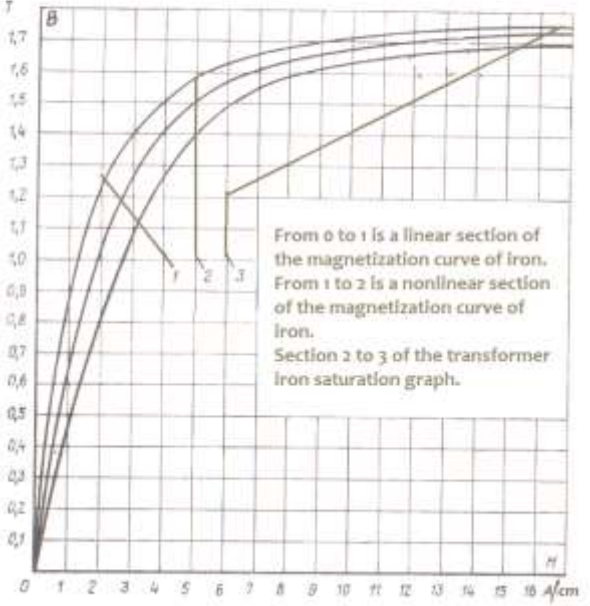

Fig. 2. Graph of the dependence of magnetic induction on magnetic field strength for electrical steel.

3 New grounding scheme

A pecularity of the power system of the Altai Republic is a strong bias in the resistance of power lines to the east and to the west of the Ininskaya substation (Table 1, values to the left of the slash). When generating a geoelectric field of the latitudinal direction, which is usually observed at SSC (Table 2 for April 24, 2023) voltages are generated mainly in the Ust-Koksa – Inya power lines and in the opposite direction, – in the Kosh-Agach – Inya and Ulagan – Inya power lines. The last two lines can be considered connected in parallel, so their total resistance drops significantly. As can be seen from the Table 1, the resistance of the line to Ust-Koksa is the largest. As a result, the currents of these lines are practically not compensated.

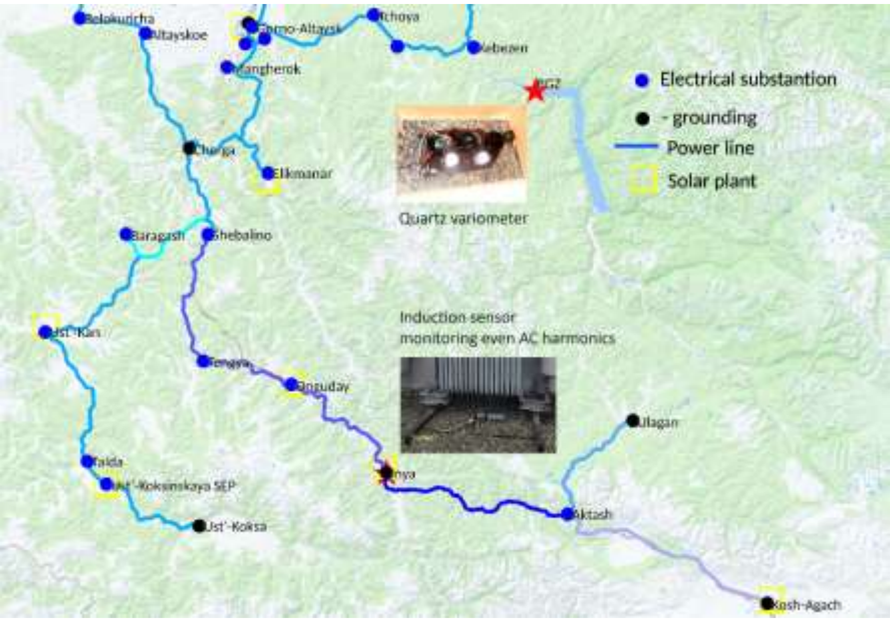

Fig. 3. Diagram of the Altai Republic power system. The 110 kV power transmission lines, electrical substations, solar power plants, as well as monitoring points for geomagnetic variations (BGZ) and amplitude of even harmonics of alternating current in the power system of the Altai Republic (Inya) are shown.

To increase power system stability, it is desirable to shift the grounding point to a substation located to the west of Ininskaya and equipped with more powerful transformers. As an option, the Ongudayskaya substation is considered. It is equipped with TMN-6300/110 transformers. Table 1 (values to the right of the slash) shows the parameters required to calculate the GIC in this case. It can be seen that the resistance of the eastern branches has practically not changed, because the branches length increase was compensated by a decrease in the resistance of the transformer primary winding. In opposite, the resistance of the western branch (to Ust-Koksa) and the northern one (to Cherga) decreased significantly.

A comparative calculation of the GIC for April 24, 2023 for the current and the proposed grounding scheme was performed. The calculation results are shown in Fig. 4. It can be seen that currents in the eastern branches did not change and GICs increase in the western and northern branches. The GIC at the central grounding point significantly decreases, since it is better compensated then. Table 4 shows the values of the maximum GIC core magnetization coefficients for the transformers of the substations in the southern part of the Republic Altai power system for the proposed grounding option. It is seen, in this case, the transformers are loaded more evenly by the GIC. The GIC core magnetization coefficient varies from 0.25 for Ust-Koksinskaya substantion to 0.40 for Ongudaskaya and Kosh-Agachskaya substations. Thus, we can make a preliminary conclusion that the transfer of grounding to the Ongudayskaya substation will increase the stability of the power system to GIC.

Nevertheless, additional studies are required to confirm this conclusion, since the length of the northern branch is significantly reduced with such a grounding scheme. GIC at this line is exited during the generation of high-amplitude geomagnetic field pulsations. It is a less intense, but longer-lasting source of GIC generation than SSC. It is planned to simulate GIC further during all disturbances recorded by the Baigazan magnetic station in Altai for both grounding circuits.

Table 4. Calculated maximum GIC values and the GIC core magnetization coefficient when the grounding point transfers from Inya to Ongudai for the conditions of the magnetic storm on April 24, 2023.

Power Substation	Power (MVA)	GIC for one phase (mA)	GIC core magnetization coefficient
Ongudayskaya	6.3	316	0.40
Ulaganskaya	6.3	300	0.38
Kosh-Agachskaya	10	439	0.40
Ust-Koksinskaya	6.3	148	0.25
Cherginskaya	6.3	332	0.30

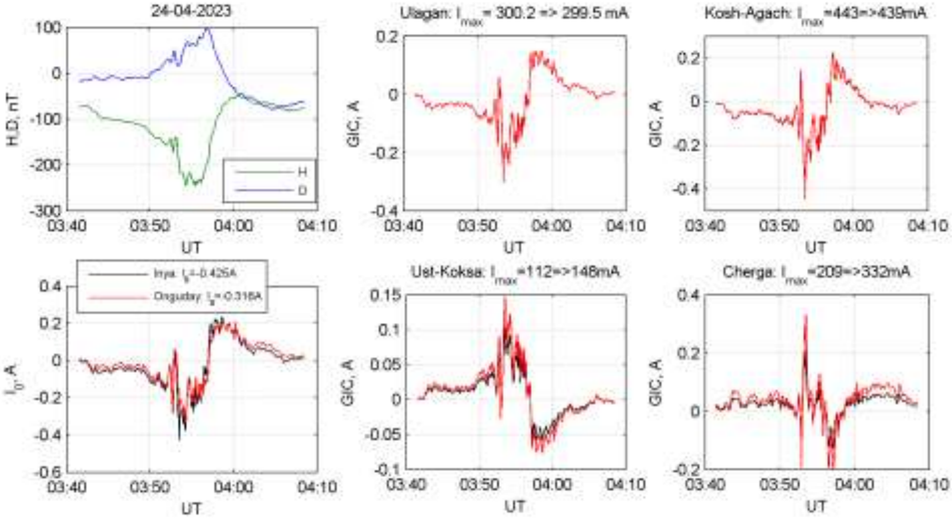

Fig. 4. Dynamics H-, D-components of geomagnetical field at Altai on April 24, 2023 during SSC (left upper) and dynamics of GIC calculated values in phase wires at substations in the southern part of the Altai Republic power system. The calculation result for the current grounding scheme is shown in black, and the red color shows calculation result when transferring the grounding point from Inya to Ongudai. The headings show the GIC peak values.

4 Conclusion

Based on data from the Baigazan magnetic station located in Altai, the GIC in the southern part of the Altai Republic power system was calculated during the strong magnetic storm on April 24, 2023. It is shown that the calculated currents in the primary windings of 110 kV power transformers can reach values of more than 0.4 A. At the same time, magnetizing fields are formed in the cores of transformers. They make up to 70% of the working field created by the no-load current. It should negatively affect the efficiency of transformer operation. To assess the GIC effect on the transformer core, a GIC core magnetization coefficient is used. It represents the ratio of the magnetic field strength generated by GIC at the transformer core to the no-load current magnetic field strength. The greatest effect is observed for the transformers of 2.5 MVA installed capacity at the Ininskaya substation. As transformer power increases, the GIC effect becomes weaker. To increase the stability of the Altai Republic's energy system to GIC, it is proposed to shift the grounding point from the Ininskaya substation to the Ongudayskaya substation.

This work was supported by Russian science foundation grant № 23-27-10055 (https://rscf.ru/project/23-27-10055/) and Department of Science and Education of Altai Republic Government. The authors are grateful to the inspector of the Altaiskiy Nature Reserve Igor Svetloyar for ensuring the operation of the magnetic station "Baigazan".

References

1. V. A. Pilipenko, Sol.-Terr. Phys. **7(3)**, 68–104 (2021)
2. R. Pirjola, IEEE Trans. on Power Systems **104**, 2825–2831 (1985)
3. A. Gil, M. Berendt-Marchel, R. Modzelewska, A. Siluszyk, M. Siluszyk, A. Wawrzaszek, A. Wawrzynczak, Energies **16**, 7406 (2023)
4. R. L. Bailey, R. Leonhardt, C. Möstl, C. Beggan, M. A. Reiss, A. Bhaskar, A. J. Weiss, Space Weather **20**, e2021SW002907 (2022)
5. M. Švanda, A. Smičková, T. Výbošťoková, Earth Planets and Space **73(1)**, 229 (2021)
6. S. Marsal, J. M. Torta, J. J. Curto, V. Canillas-Pérez, O. Cid, M. Ibañez, A. Marcuello Space Weather **19(12)**, e2021SW002905 (2021)
7. S. C. Barbosa, G. A. Hartmann, K. Jasbinschek Pinheiro, Adv. in Space Research **44**, 1168–1179 (2015)
8. R. Caraballo, J. A. González-Esparza, C. R. Pacheco, P. Corona-Romero, Space Weather **21(10)**, e2022SW003202 (2023)
9. S. Taran, N. Alipour, K. Rokni, S. H. Hosseini, O. Shekoofa, H. Safari, Adv. in Space Research **71(12)**, 5453-5465 (2023)
10. S. Watari, S. Nakamura, Y. Ebihara, Earth, Planets and Space **73**, 102 (2021)
11. E. Matandirotya, P. J. Cilliers, R. R. Van Zyl, Space Weather **13(3)**, 185–195 (2015)
12. A. A. Tren'kin, S. V. Voevodin, O. N. Koblova, V. D. Selemir, V. V. Vahnina, A. A. Kuvshinov, A. N. Chernenko, Elec. Techn. Rus. **(2)**, 37-49 (2023)
13. D. H. Boteler, R. J. Pirjola **10**, 930-949 (2019)
14. A. Y. Gvozdarev, O. V. Kazantzeva, E. O. Uchaikin, E. G. Yadagaev, Bulletin KRASEC. Phys. and Math. Sci. **45(4)**, 190-200 (2023)
15. A. I. Bakiyanov, A. A. Betyov, A. Yu. Gvozdarev, E. O. Uchaikin, "Deep structure, geodynamics, thermal field of the Earth, interpretation of geophysical fields", in *6th science readings of Y.P. Bulashevich* (2011)
16. *Scheme and development program of the Altai Republic electric power industry for 2022-2026*. (Ministry of regional development Altai Republic, Gorno-Altaisk, 2021)
17. A. B. Andreyev, S. N. Mukasheva, V. I. Kapytin, O. I. Sokolova, Space Weather **21**, e2023SW003639 (2023)
18. E. O. Uchaikin, A. Y. Gvozdarev, *2023 IEEE XVI Intern. Sci. and Techn. Conf. Actual Problems of Electronic Instrument Engineering (APEIE)* (2023)