12

Simulator of operation of relay protection devices of high-voltage grid under the influence of geoinduced currents

© A.A. Trenkin,[1] A.B. Buyanov,[1] E.P. Grabchak,[2] S.V. Voevodin,[1] A.V. Limonov[1]

[1] Russian Federal Nuclear Center, All-Russia Research Institute of Experimental Physics,
607188 Sarov, Russia
[2] Joint Institute for High Temperatures, Russian Academy of Sciences,
125412 Moscow, Russia
e-mail: trenkin@ntc.vniief.ru

Received March 23, 2024
Revised July 31, 2024
Accepted July 8, 2024

A mobile simulator for experimental simulation of operation of relay protection devices in the high-voltage and ultrahigh voltage grid under the influence of geoinduced currents was developed. The simulator at the initial digital signature allows providing currents at the inputs of relay protection devices in the frequency range from 0 up to 50 kHz; the currents simulate signals from measuring current transformers. The simulator is developed on an easily accessible element base. The equipment weight is 20 kg, the power supply is 220 V/50 Hz, and the power consumption is not more than 1.6 kW. The initial signals for the simulator can be the currents recorded at the active power objects, and also obtained as a result of calculation simulation of the energy system operation or defined as standards.

Keywords: relay protection of high-voltage grid, simulation of influence, geoinduced current.

DOI: 10.61011/TP.2024.11.59756.98-24

Introduction

The task of studying the impact of magnetic storms on the operation of facilities and power supply systems is very relevant because of the danger of emergency situations in electric power systems (EPS) during geomagnetic activity periods [1–3]. Such accidents with high economic damage occur periodically, for instance, in North America and Northern Europe in 1989 and 2003 [1,2,4–6]. The significance of this problem increases with the development of the EPS — increasing load, increasing complexity of the structure, increasing the voltage class of facilities, electrification of the northern territories.

Low-frequency (about 10 mHz) geoinduced currents (GIC) arise in the Earth crust during geomagnetic storms, which flow into the solidly grounded neutrals of power transformers and cause their magnetization. This results in a significant increase of the magnetization current, an increase of the reactive power consumed by transformers, and excessive generation of higher harmonics [1–3]. The GIC impact can cause malfunction of relay protection and automation (RPA) systems in addition to other negative consequences, since their inputs receive signals of currents and voltages distorted by the presence of GIC, which, in turn, can initiate emergency situations [4,7,8]. For instance, the false actions of RPA the relay system resulted in the development of a major system accident in the Hydro-Quebec EPS in North America during a magnetic storm in March 1989 [4]. An emergency shutdown of the 330 kV overhead line Olenegorsk-Monchegorsk by the action of RPA system under the impact of GIC was observed in the Russian Federation in November 2001 [8].

Electromechanical relays previously used for designing RPA devices have been recently rapidly giving way to microprocessor relay protection devices (MRPD) in the process of technological transformation of the electric power industry. The latter may have specific features of the reaction to the GIC impact [9], which determines the importance of the relevant studies.

The study of operation of RPA systems in conditions of the GIC impact impact on the electrical grid is a challenging scientific and technical task. This study requires to have at least signatures of current and voltage signals expected at the outputs of measuring transformers, and hardware for supplying them to the inputs of the RPA system units. Signatures can be obtained either during the signal recording at operating energy facilities during the geomagnetic activity periods, or as a result of simulation modeling of the GIC impact on the EPS model, in the structure of which the studied PRA systems function. Also, it seems advisable to develop and use exemplary signals for the systematic testing of RPA systems and other electric power equipment, similar to the North American Standard regulating the resistance of power supply facilities and systems to the impact of intense geomagnetic disturbances [10].

The software and hardware system of RTDS Technologies Ltd (Canada) is the most powerful tool for modeling processes in the EPS, including real time modeling. Its main advantage is the possibility of modeling of real devices in the EPS model in a closed circuit of interaction with input and output electrical signals, which allows the complex to

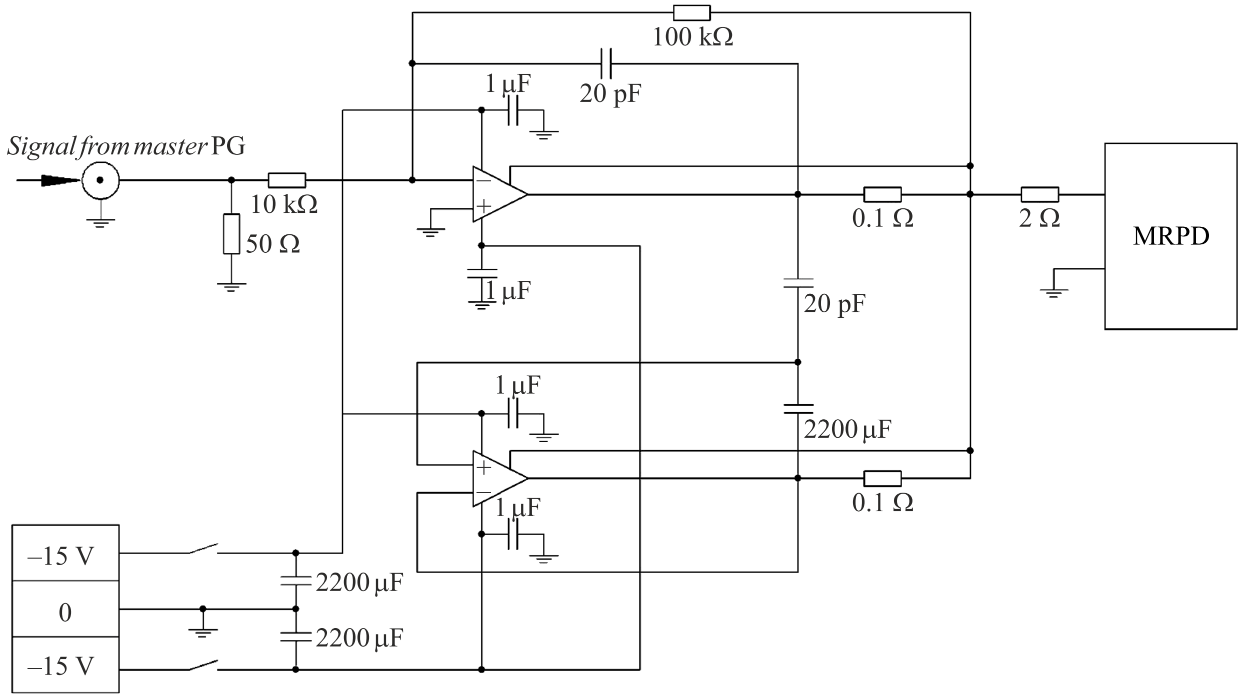

Figure 1. Schematic diagram of the amplifier channel. MRPD — microprocessor relay protection device.

be used for testing and certification of relay equipment and a number of other devices [11,12].

However, in addition to high cost, the manufacturer also does not support the operation of these systems in Russia in the current conditions of the sanctions policy. Moreover, in many cases there is no need to use such complex information technology tools, for example, when there is a typical signal signature and it is necessary to determine the reaction of a number of RPA system units. For this reason, it is an important task to develop a relatively simple and inexpensive device that ensures generation of signals based on a given digital signature at the inputs of RPA systems unit, expected in case of GIC impact on the electrical grid. This paper presents the result of the development and testing of such a device — simulator.

1. Description of the simulator

The simulator contains a set of standard arbitrary waveform generators (in the current equipment, these are five two-channel generators with a frequency of up to 60 MHz), a synchro generator (a standard rectangular pulse generator) and two identical six-channel current amplifier units. The units are built based on low-frequency operational amplifiers OPA 541 PA operating using a voltage amplification circuit for a constant active load with a nominal value of 2 Ω. The schematic diagram of one channel of the amplifier is shown in Fig. 1.

The power is supplied to the amplifiers by ten compact independent sources of bipolar voltage ±15 V with a total rated power of 1.5 kW. A separate power supply comprises a sequential assembly of two unipolar mass-produced power supplies.

The simulator equipment is placed in a single moving rack (Fig. 2).

As a rule, six analog current inputs are used in the two-winding power transformer MRPD: three inputs each for connecting three-phase current transformers from the sides of the high and low voltage windings. Therefore, six channels are required to simulate the operation of two-winding transformer MRPD, and, accordingly, one amplifier unit is needed. The second unit is necessary for the formation of additional signals, for example, simulating the operation of three- and four-winding power transformer MRPD. Figure 3 shows a block diagram of a simulator with six channels.

The simulator operates as follows. The operator starts the synchro generator at a given time *A1*, which issues a common start signal for generators over the communication lines *A2–A4*. Upon receiving such a signal, the generators reproduce analog voltage signals at their outputs corresponding to the original signatures previously recorded in memory. Next, the voltage signals are transmitted to the inputs of the amplifier unit *A5*. The amplifiers convert these signals into currents with the same shape, which are transmitted to the inputs of the studied protection device. The values of these currents are regulated by the amplitudes of the output signals of the generators *A2–A4*.

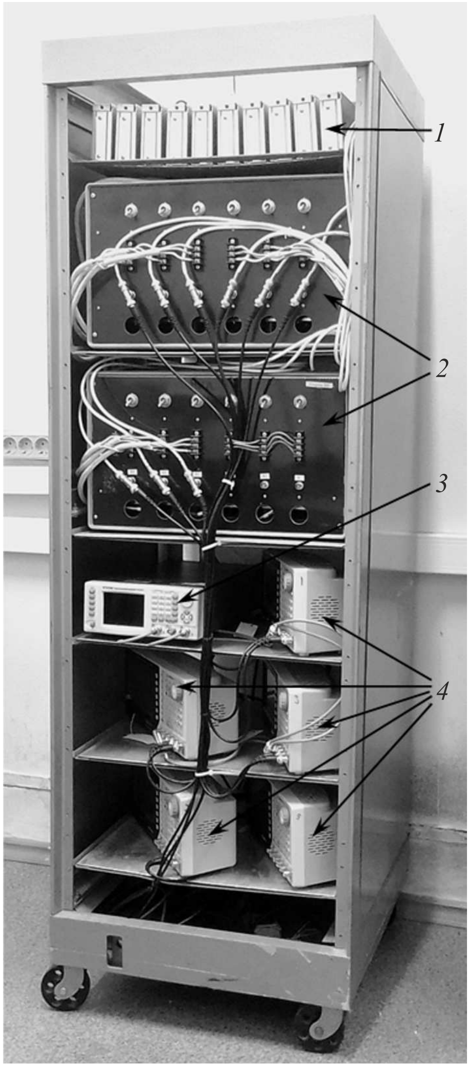

Figure 2. Simulator equipment in a moving rack: *1* — amplifier power supplies, *2* — current amplifier units, *3* — synchro generator, *4* — arbitrary waveform generators.

2. Testing the simulator

The simulator was used for the study of the operation of a number of Russian-made relay protection devices in the conditions of the geoinduced current effect on ultra-high voltage electrical grid. In particular, the tests involved electromechanical relays RT-40 and RT-140 (CJSC „CHEAZ"), as well as microprocessor relay protection devices for power transformers BE 2704 V041 and BE 2704 V542 (LLC NPP „EKRA"), „Sirius-UV-1A-220V-I1" and „Sirius-T-1/1-220V-I1" (CJSC „RADIUS Avtomatika"). The oscillograms of the currents generated by the simulator at the inputs of the RT-40 relay and MRPD BE 2704 V041 are presented below as an example of the simulator operation. The initial signatures were obtained as a result of computational modeling of the functioning of the United Power System of the North-West during an emergency shutdown of its overhead line 330 kV Olenegorsk-Monchegorsk with zero-sequence current protection (ZSCP) during a magnetic storm in November 2001 [9]. At the same time, it should be noted that the device BE 2704 V041 has similar circuit design and logic of operation with MRPD lines and can be used in these studies to implement basic line protections, including ZSCP, which is also supported by the opinion of experts of NRU „MPEI".

Figure 4 shows the initial signal and the oscillogram of the input current of the RT-40 relay, which performs the ZSCP function, as well as a discrete signal indicating the start of this protection. The relay operation setpoint was set as for the ZSCP of the 330 kV overhead line Olenegorsk-Monchegorsk [8].

Figure 4 shows that the current forms of the simulator and the source signal are almost identical. It can also be noted that ZSCP should operate and, as a result, the protected facility should be shutdown after a specified time delay at the time moment of $t = 3.5$ s according to the emergency control logic. This operation is consistent with the operation of the ZSCP during the emergency shutdown of the Olenegorsk-Monchegorsk overhead line [8].

Figure 5 shows the initial signal and the oscillogram of the current generated by the simulator at the input of the MRPD of BE 2704 V041. This current is the secondary current of the measuring transformer installed in the phase of the distribution substation. The waveforms in Fig. 5 show that the original signal and the current of the simulator are practically indistinguishable from each other. There is also a short-term current surge on the oscillograms at time $t = 0$. This surge is artificially added to the signals and is needed for a forced starting of the „emergency" oscilloscope built into the MRPD, which allows recording input currents and output logic signals of the protection relay. The current surge and the associated operation of protection systems are not taken into consideration.

Figure 6 shows „emergency" oscillograms of phase currents of the substation and logical signals of operation of the MRPD protection. The zero sequence current is calculated by the device as the sum of the corresponding phase currents.

Figure 6 shows that, unlike the experiment with the RT-40 relay, there are no starts and, accordingly, the protection systems, including ZSCP, do not operate. It is shown in Ref. [9] that this is attributable to the blocking of the low-frequency GIC by secondary measuring transformers installed inside the MRPD.

A Fourier analysis of the input signal and the MRPD input current generated by the simulator was also conducted. Figure 7 shows the frequency spectra of these signals.

The relative values of the corresponding harmonics of the original signal and the current of the simulator differ by less than 4%, which indicates good accuracy of reproduction of the original signatures using the developed simulator.

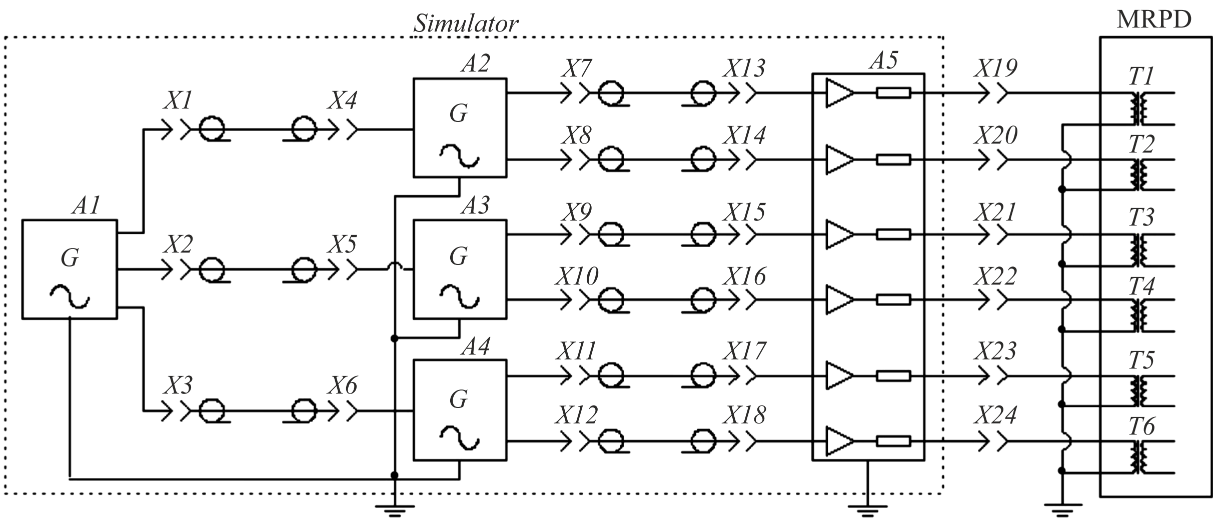

Figure 3. Block diagram of the simulator: *A1* — synchro generator; *A2–A4* — arbitrary waveform generators; *A5* — amplifier block; *X1–X24* — connection points of communication lines; *T1–T6* — secondary measuring transformers of MRPD.

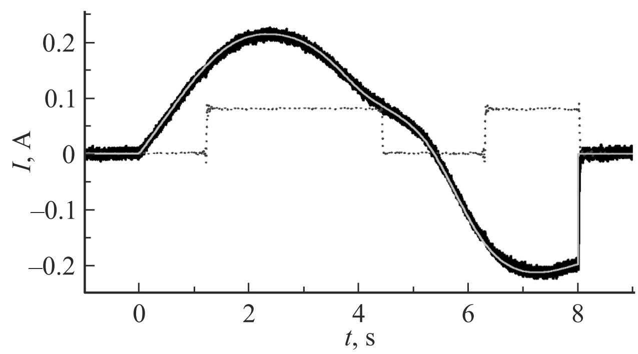

Figure 4. Initial signature (gray solid line), the simulator current (black line), the start signal of the ZSCP (dark gray dotted line).

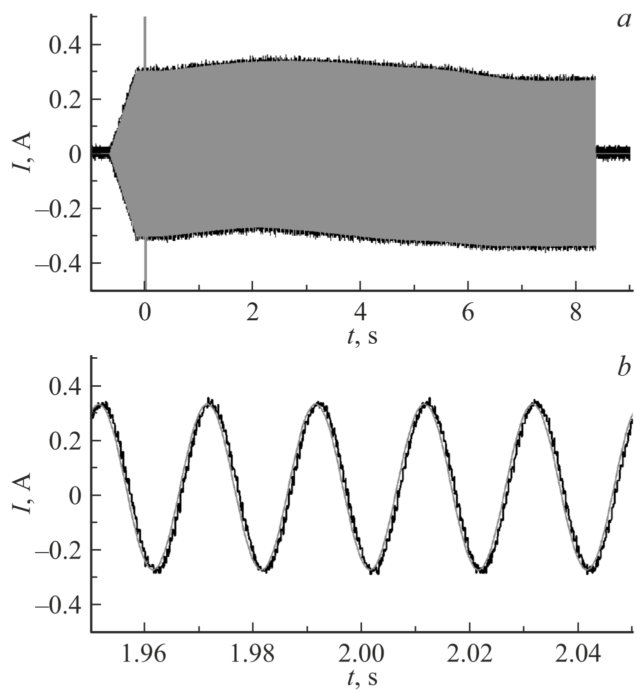

Figure 5. Input signal (gray) and the simulator current (black) (*a*) and their sweep (*b*) in the time interval $1.95 \le t \le 2.05$ s.

Conclusion

1. A mobile simulator was developed to study the functioning of relay protection and automation devices in case of the geoinduced currents effect on electrical grid. The simulator based on the original digital signature of the signal allows reproducing currents in the frequency range from 0 to 50 kHz at the inputs of relay protection devices with good accuracy, simulating signals from measuring current transformers, both in normal mode and with distortion as a result of exposure to geomagnetically induced currents.

2. The simulator includes a synchro generator, arbitrary waveform generators, current amplifier units, and amplifier power supplies. The simulator equipment can be placed in a single moving rack with a size of $0.5 \times 0.5 \times 1.5$ m. The weight of the equipment is about 20 kg. The power is supplied from a 220 V/50 Hz mains, power consumption is no more than 1.6 kW.

3. Currents recorded at operating electric power facilities can be used as input signals for the simulator, as well as currents obtained as a result of computational modeling of the operation of power systems or set in the form of standards. The simulator was tested in the studies of the operation of a number of Russian-made electromechanical and microprocessor relay protection devices in the conditions of the geoinduced current impact on ultrahigh voltage electrical grid [9]. This device can also be used to simulate the normal operation of RPA systems in electrical grids of high and ultrahigh voltage classes for determining electromagnetic

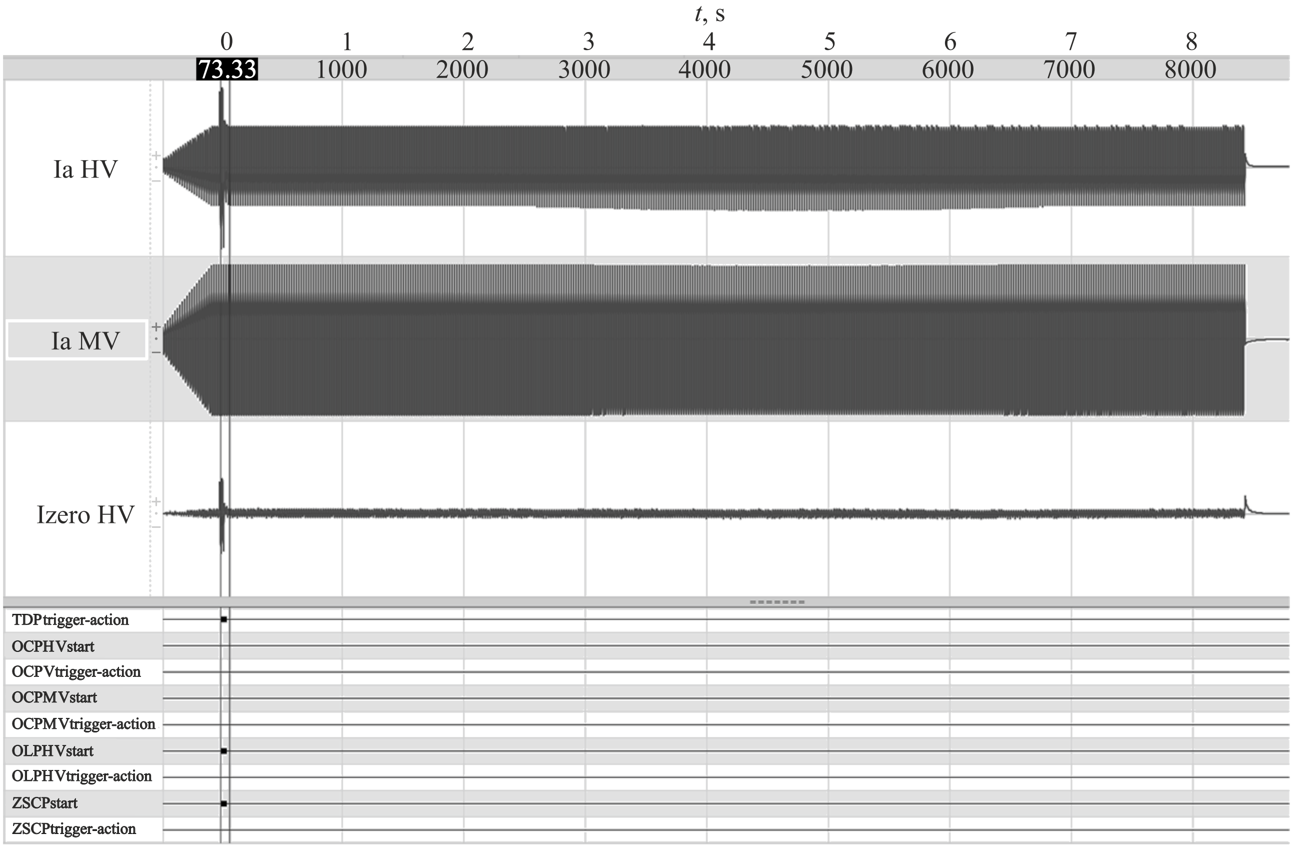

Figure 6. Currents in phases (1st and 2nd lines) from the side of high (HV) and medium (MV) voltage, in the neutral (3rd line) of the substation, logical signals for starting (start) and operation (trigger-action) of protection (from the 4th to the 12th lines): TDP — differential protection, OCP — overcurrent protection, OLP — overload protection, ZSCP — zero sequence current protection.

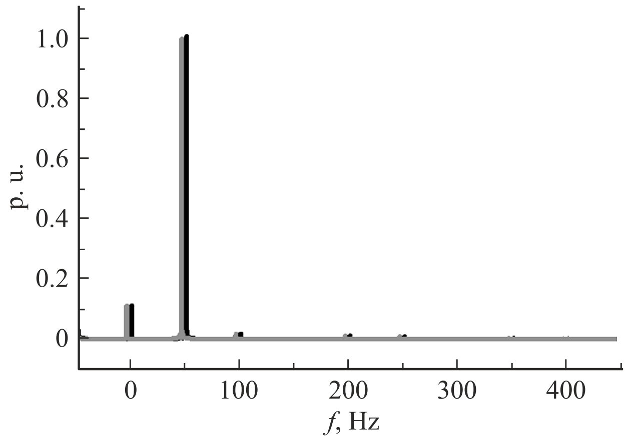

Figure 7. Spectra of the input signal (gray) and the MRPD input current (black).

compatibility in the conditions of external factors action at RPA systems. Other applications of the simulator are also possible.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] O. Sokolova, N. Korovkin, M. Hayakawa. *Geomagnetic Disturbances Impacts on Power Systems Risk Analysis and Mitigation Strategies* (CRC Press, 2021)

[2] V.A. Pilipenko. Solnechno-zemnaya fizika, **7** (3), 72 (2021 (in Russian). DOI: 10.12737/szf-73202106

[3] A.A. Trenkin, V.V. Vakhnina, S.V. Voevodin, O.N. Koblova, A.A. Kuvshinov, V.D. Selemir, A.N. Chernenko. Elektrichestvo, **2**, 37 (2023) (in Russian). DOI: 10.24160/0013-5380-2023-2-37-49

[4] L. Bolduc, P. Langlois, D. Boteler, R. Pirjola. IEEE Transactions on Power Delivery, **15** (1), 272 (2000). DOI: 10.1109/61.847262

[5] J.G. Kappenman. Space Weather, **3** (8), SO8C01 (2005). DOI: 10.1029/2004SW000128

[6] A. Pulkkinen, S. Lindal, A. Viljanen, R. Pirjola. Space Weather, **3** (8), S08C03 (2005). DOI: 10.1029/2004SW000123

[7] V. Sushko, D. Kosykh. Novosti elektrotekhniki, **3** (81), (2013) (in Russian).

[8] V.I. Pulyaev, Yu.V. Usachev. Energetik, **7**, 18 (2002) (in Russian).

[9] A.A. Trenkin, E.P. Grabchak. ZhTF, **94** (2), 299 (2024) (in Russian). DOI: 10.61011/JTF.2024.02.57086.265-23

[10] NERC Standard TPL-007-4: Transmission System Planned Performance for Geomagnetic Disturbance Events. March 19, 2020.
[11] Ya.V. Zakonshek, A.L. Slavutsky. Releynaya zashchita i avtomatizaciya, **1** (06), (2012) (in Russian).
[12] D.O. Mochalov, Ya.V. Zakonshek, M.A. Shamis. Releynaya zashchita i avtomatizaciya, **1** (10), (2013) (in Russian).

Translated by A.Akhtyamov