Journal of Electrical Engineering, Vol. 74, No. 4, 2023, pp. 321-327

sciendo
PAPER

Simulation of electrical system protection against the effects of a magnetic storm

[1]Milan Stork and [2]Daniel Mayer

In the introduction of the presented work, the physical nature of the collapse of electrical energy transmission systems due to the influence of a magnetic storm is recalled. A mechanism is described by which, due to the non-linearity of the magnetic circuit of the system's power transformers, quasi-direct currents are induced into the high-voltage part of the system, which cause thermal overload of these transformers. The article then suggests one of the possible ways to prevent these accidents. On the single-phase and then on the three-phase model, it is shown how these currents can be compensated. Using laboratory models, the compensation process was simulated and verified by measurements.

Keywords: magnetic storm, geomagnetically induced currents, transformer protection, transmission system simulation

1. Introduction

Solar activity is manifested by rapid variations in the Earth's external magnetic field. While during calm solar activity the intensity of this magnetic field is 20 to 30 nT, during strong activity it increases and if it reaches hundreds of nT, we are talking about a magnetic storm. No one in Central Europe remembers a magnetic storm with catastrophic effects on the transmission of electricity, so it can be assumed that magnetic storms are rather one of the horror themes of science fiction literature than a real and dangerous natural phenomenon. The energy experts of some Nordic countries, where magnetic storms caused severe collapses of the energy grid, have a different opinion. Let us recall, for example, the crash of the power grid in the province of Quebec (Canada) in 1989, where a magnetic storm with an intensity of 540 nT caused a power outage for 6 million inhabitants, or the crash of the network for half a million consumers in the Malmö region (Sweden) in 2003. Magnetic storms cannot be prevented, but they can at least be predicted in the short term [4], or their effects on the transmission system can be monitored online [5].

In the presented papers, based on the model of the electrical system, one of the possible methods of protection against a magnetic storm is indicated.

2. The impact of a geomagnetic storm on the transmission system

The source of the geomagnetic field is on the one hand physical processes inside the Earth, on the other hand physical events in the ionosphere of the Sun. Thus, according to the source, we distinguish between internal and external geomagnetic fields. Both magnetic fields are superimposed [1-5].

The internal geomagnetic field is physically explained by a model known as the geodynamo [6-8]. The complex turbulent rotational flow of the Earth's liquid core in the Sun's magnetic field induces strong electric currents in it, which generate the geomagnetic field. Its magnetic axis, and thus also the magnetic intensity on the earth's surface, changes with time – we speak of secular variations. Secular variations are very slow, detected on a scale of tens of years, and have a value of about 44 μT at central European latitudes. Due to their very slow time course, they have no effect on the electricity system.

The external magnetic field is a result of solar activity. This is manifested by solar eruptions during which intense electromagnetic radiation is produced in a wide range of the spectrum. The solar mass, containing electrically charged particles with high energies, is torn off, which then spreads at high speed through interplanetary space. This is called the solar wind. If a wave of the solar wind arrives near the Earth, its internal geomagnetic field prevents the impact of electrically charged particles on the Earth. Under the action of the Lorentz force, electrically charged particles move in the direction of the magnetic field lines of the magnetosphere, surround the Earth and deform the original symmetrical shape of the internal geomagnetic field. The Earth's magnetosphere thus shields the Earth from the solar wind and thus protects the Earth's biosphere. Part of the electrically charged particles of the solar wind penetrates into the upper layers of the Earth's atmosphere, their movement represents an electric current that induces an external magnetic field in its surroundings. Waves of the solar wind are reflected on Earth by rapid variations of the external geomagnetic field. The magnetic induction at the Earth's surface changes on the order of seconds. Their amplitude varies from small disturbances, 20 to 30 nT, to strong variations during a geomagnetic storm, reaching up to

[1]Deptartment of Electronics and Information Technology, University of West Bohemia, Plzen, and Research Institute RICE in Plzen, Czech Republic
[2]Department of Electrical and Computational Engineering, University of West Bohemia, Plzen, Czech Republic
stork@fel.zcu.cz, mayer@fel.zcu.cz

https://doi.org/10.2478/jee-2023-0039, Print (till 2015) ISSN 1335-3632, On-line ISSN 1339-309X

hundreds of nT. The frequency and intensity of magnetic storms is higher near the Earth's magnetic poles, i.e., in the Nordic countries.

The external magnetic field $B(t)$ acts both on the earth's crust and on the conductors of the high-voltage (HV) transmission system. According to the law of electromagnetic induction, an electric field $E(t)$ is induced in this environment

$$\mathrm{rot}\,\boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{1}$$

and since it is an electrically conductive environment ($\gamma \neq 0$), currents of density J are induced in it:

$$\boldsymbol{J} = \gamma\,\boldsymbol{E}\,. \tag{2}$$

These currents are denoted by the abbreviation GIC (Geomagnetically Induced Currents). Note that the size of the GIC depends on the size of the derivative of the geomagnetic induction $B(t)$, i.e., on the rate of variation of the external magnetic field, not on its size [9-17].

The magnetic flux $\Phi(t)$ is coupled to the loop c, which consists of the winding of the HV transformer of the source, HV line and winding of the HV transformer of the distribution network

$$\emptyset(t) = \iint_S \boldsymbol{B}(t).d\boldsymbol{S} \tag{3}$$

where S is the area bounded by this loop c. Voltage V_{GIC} is induced into the loop c

$$V_{GIC} = \oint_c \boldsymbol{E}.d\boldsymbol{l} \tag{4}$$

and current I_{GIC} passes through it,

$$I_{GIC} = \frac{1}{R_v}\frac{d\Phi(t)}{dt}, \tag{5}$$

where R_v is the ohmic resistance of the loop c. The current in the I_{GIC} loop is the cause of the breakdown of power transformers during geomagnetic storms, as we will show further.

The magnetic induction $B(t)$ and therefore the I_{GIC} current have a temporally random course (not periodic), and although we talk about fast variations of the external magnetic field, they change relatively very slowly, compared to industrial frequency currents. In magnetic storms, these are changes in units of nT/min. The time course of the I_{GIC} currents is therefore quasi-stationary – these currents essentially behave as direct currents. The I_{GIC} current in the wires of the HV transmission system is limited only by the ohmic resistances of the loop and the inductances and capacities of the electrical network are not applied.

Quasi-stationary I_{GIC} currents in the conductors of the HV transmission system and in the windings of HV transformers induce direct current (DC) premagnetization of the magnetic circuits of power transformers. If the operating point of one half of the operating current $i(t)$ shifts to the non-linear part of the magnetization characteristic, the inductance of the winding decreases (for one half period) and the magnetizing current, which has an alternating (working) component $i(t)$ and a direct component I_{GIC}, increases significantly – the so-called semi-oversaturation occurs. The current $i(t) + I_{GIC}$ has a higher effective value and thus thermally endangers the HV windings of the transformers; in case of magnetic storms, the cause of the accident is Fig. 1, which shows the normal operation of the transformer, without GIC (Fig. 1a) and the operation with the effect of GIC (Fig. 1b), which is manifested by a shift in the magnetization characteristic, distortion and an increase in the effective value of the current, which can thermally damage the transformer winding.

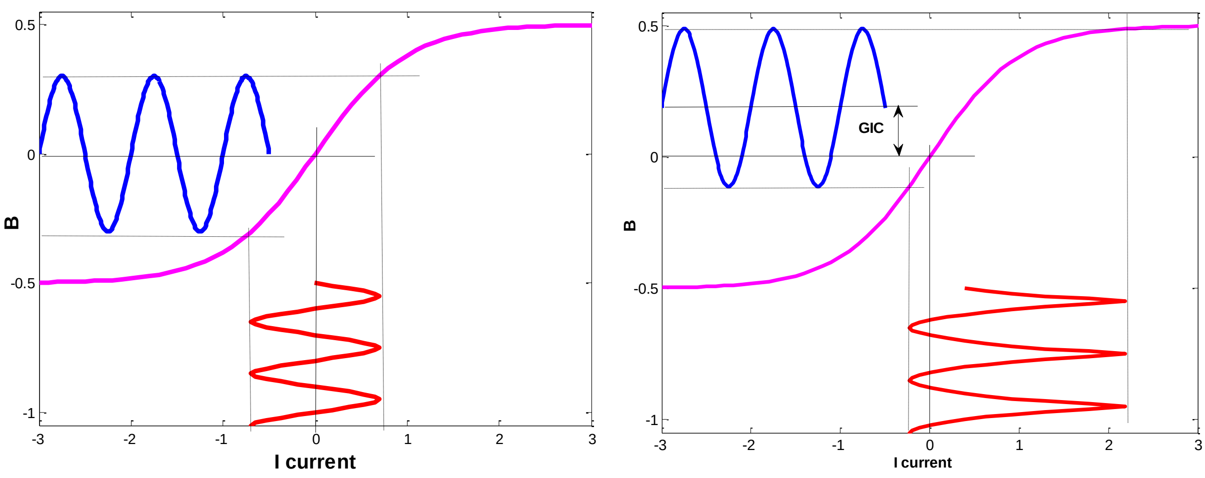

Fig. 1. (a) Without the effect of GIC, the transformer works in the linear part of the characteristic, the current is sinusoidal. (b) In the case of GIC, the transformer oversaturates, the current shape is distorted, has a DC component and a higher effective value.

3. The goal of this article

We have shown that magnetic storms induce I_{GIC} currents in the transmission system, which can cause a system crash due to their thermal effect on the HV windings of power transformers. Various methods have been proposed to reduce or eliminate I_{GIC} currents. One of them is to switch off the transmission system during a magnetic storm (the so-called artificial collapse), or to use robust power transformers with low saturation of the magnetic circuit and thereby shift the state of semi-saturation for high values of the I_{GIC} current. Another way is to use filters that prevent (or limit) the entry of I_{GIC} current into HV transformers [12, 13]. In this work, we will indicate another way of protecting HV transformers: using a transmission system model and we will show that I_{GIC} currents can be compensated using a controlled DC source.

4. Simplified models of electrical energy transfer under GIC action and GIC compensation options

The behavior of the transmission system and the formation of GIC can be studied, for example, using the model [14-18]. However, this section describes new models and possibilities for GIC compensation for a single-phase network and then for a three-phase network.

4.1. Simulation of GIC influence and its compensation model with single-phase transformers

Figure 2 shows a simplified transmission system. Transformers T_1 and T_2 are supplied with 230 V mains voltage at the input, and their secondary windings are connected to transformers T_3 and T_4 via resistors R_1, R_2 and DC voltage sources V_{GIC}. (Four identical transformers 230/16 V, 2 A, R_1, R_2 = 1 Ω, R_L = 5.55 kΩ were used). The output of transformers T_3 and T_4 is loaded with resistor R_L. The V_{GIC} voltage sources simulate the voltage induced by the GIC into the line connecting transformers T_1, T_2 and T_3, T_4. For simplicity, the V_{GIC} voltage is assumed to be DC. Current waveforms are read from resistors R_1 and R_2 with an oscilloscope. There is V_{GIC} compensation by voltage source V_{COMP}.

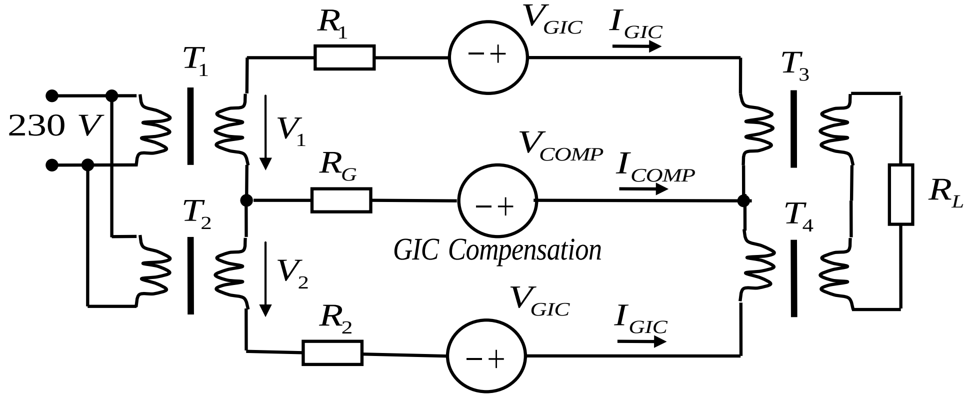

Fig. 2. System simulation using transformers and DC voltage source V_{GIC} representing induced voltage due to I_{GIC}. Alternating current (AC) voltages and currents are: V_1=V_2=16 V, V_3=V_4=15 V, V_{33}=V_{44}=186 V, I_1=I_2=1 A, I_L=0.067 A. For the system (R_1=R_2) with V_{GIC} sources and with the compensation of these voltages by the V_{COMP} source with internal resistor R_G=1 Ω. If V_{COMP} = V_{GIC}, then I_{GIC} = I_{COMP} = 0.

It can be seen in Fig. 2 that

$$I_{GIC} = \frac{V_{GIC}}{R_{1ALL}} + \frac{V_{GIC}}{R_{2ALL}} = 2\frac{V_{GIC}}{R_{ALL}}, \tag{6}$$

where R_{1ALL} = R_{2ALL} = R_{ALL} are the resistors in the two branches. If the voltage V_{COMP} = V_{GIC}, then the currents I_{GIC} = 0.

Table 1 shows the voltage V_1 and current I_1 for gradually increasing rms values of V_{GIC} and thus also increasing rms values of I_{GIC} current. The curves of voltage and current for V_{GIC} = 3.9 V, I_{GIC} = 1.2 A are shown in Fig. 3.

Table 1. Effective voltage and current values

V_{GIC} (V)	I_{GIC} (A)	I_1 (A) RMS
2.2	0.7	1.6
3.2	0.9	2.0
3.9	1.2	2.4

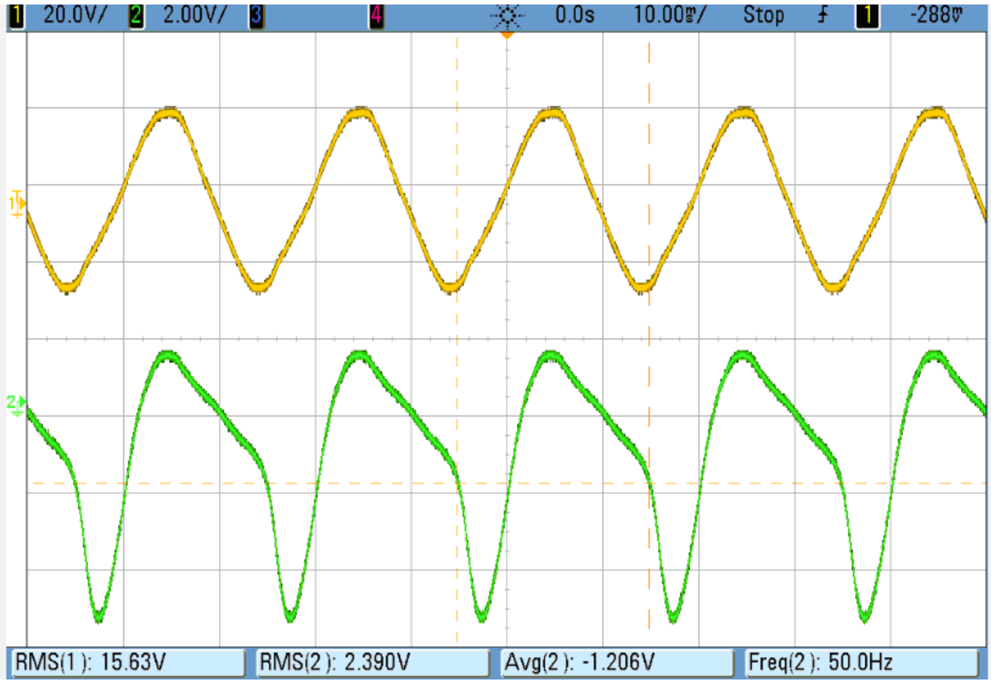

Fig. 3. Waveforms of voltage V_1 and current I_1 for V_{GIC} = 3.9 V, I_{GIC} = 1.2 A, I_{1ef} = 2.4 A

4.2. Simulation of a three-phase network under the influence of GIC and the possibility of compensation

In this section, the results of the simulations on the three-phase model are presented. In Fig. 4 is a simplified diagram of a three-phase electrical transmission network with a transformer *Tr1*, lines replaced by resistors R_X, R_Y and R_Z under the action of GIC represented by voltage sources V_{GIC}. In the diagram, there are also resistors R_M and R_N through which the transformers are grounded. If no compensation is used, the V_{GIC} voltage in each phase will cause I_{GIC} current. Fig. 4 contain V_{COMP} voltage source compensation. This source supplies the I_{COMP} current. The compensation source is connected to the transformer node *Tr2* between the resistor R_N and ground via a switch *S* that allows the GIC compensation to be turned off and on.

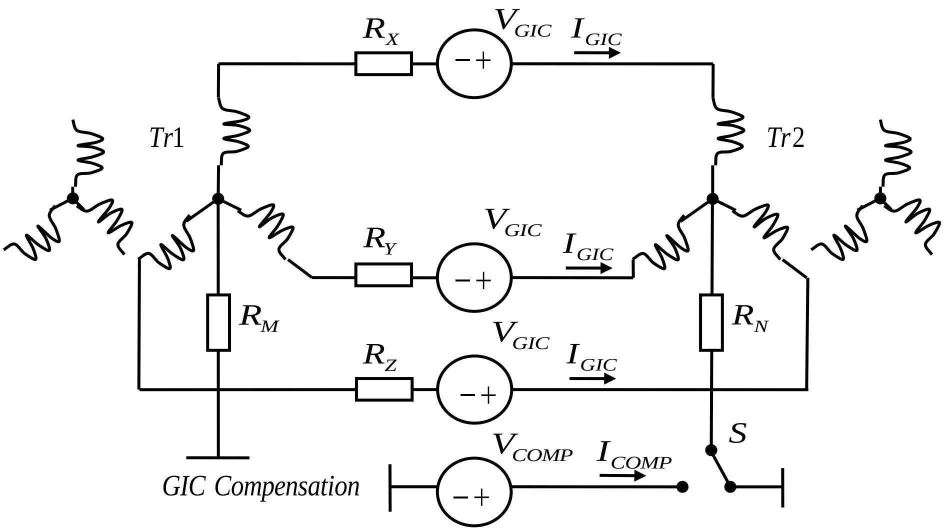

Fig. 4. The principle of GIC compensation of a three-phase network using the V_{COMP} source. Switch *S* connected to the R_N resistor allows the compensation source to be connected/disconnected. The switch is drawn in the disconnected compensation source state.

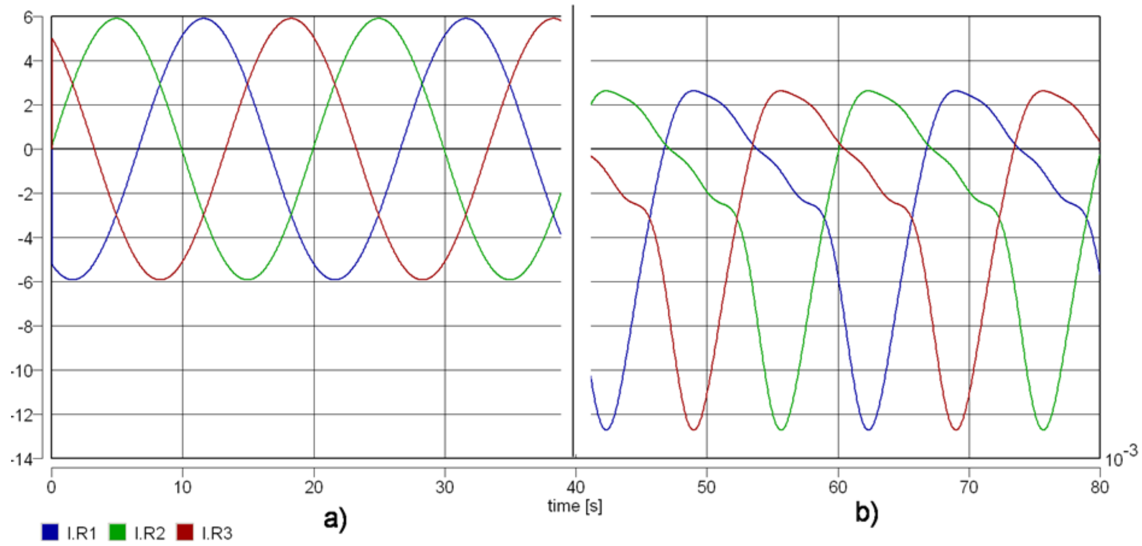

Fig. 5. Simulation of the course of currents in the case of a non-linear model of a three-phase transformer. Time is on the horizontal axis, current is on the vertical axis, a) the course of the currents without the action of GIC, at time $t \leq 40$ ms, b) the distortion of the courses due to the action of GIC at time $t > 40$ ms.

Figure 5 shows the simulation of the currents of a non-linear model of a three-phase transformer, where the DC voltage of the GIC is superimposed on the three-phase voltage waveform. The distortion of the waveforms and the creation of a DC component of the currents can be seen.

In the following simulations, linear models of the entire system are already used. Fig. 6 shows a simplified replacement diagram of a three-phase network under the action of GIC. This scheme was used for the simulations. Transformer *Tr1* is replaced by 3 voltage sources and transformer *Tr2* is replaced by 3 resistors. The time course of the three-phase voltage is given by the relations

$$E_1(t) = \sqrt{2} \cdot 230 \sin(2\pi.50.t)$$

$$E_2(t) = \sqrt{2} \cdot 230 \sin(2\pi.50.t + 2\pi/3)$$

$$E_3(t) = \sqrt{2} \cdot 230 \sin(2\pi.50.t + 4\pi/3)$$

Resistors R_M and R_N can be connected in series and the total value for the simulation is 0.1 Ω, the replacement resistor is marked as R_{MN}. Values of V_{GIC}, V_{COMP} and R_X, R_Y and R_Z are given for individual simulations. Switch S allows the compensation source to be connected/disconnected.

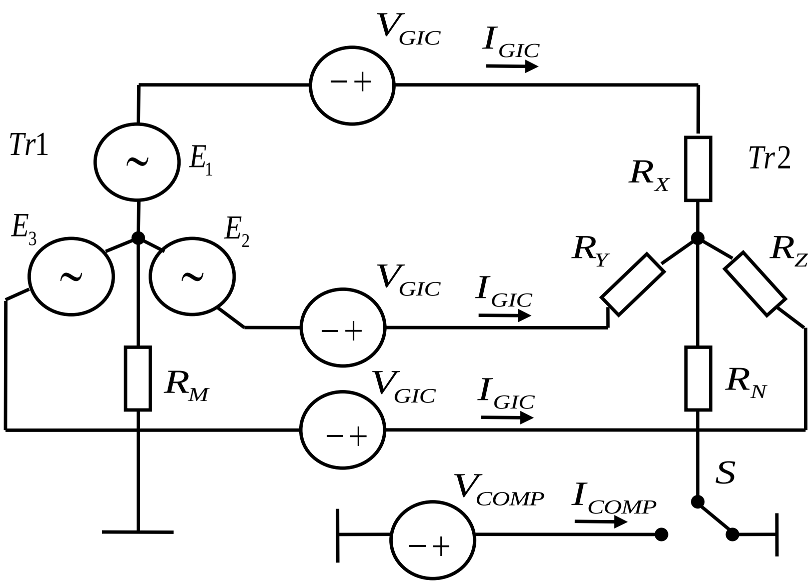

Fig. 6. A simplified replacement diagram of the three-phase network under GIC action, which is represented by the voltage sources V_{GIC} and the compensating source V_{COMP}. A switch S connected to the R_N resistor allows the compensation source to be connected/disconnected. The switch is drawn in state, when the compensation source is disconnected.

Figure 7 shows the simulation results for an asymmetric load. In the left part of Fig. 7 (for $t \leq 50$ ms) it is shown current progression without GIC compensation. In the right part of the picture, the time course of the currents after compensation is shown, where a lower value of the compensation voltage V_{COMP}=70 V is deliberately chosen (i.e., non-ideal compensation). The DC component of currents $I.R_X$, $I.R_Y$, $I.R_Z$ is only partially removed, and the currents have therefore a small DC component.

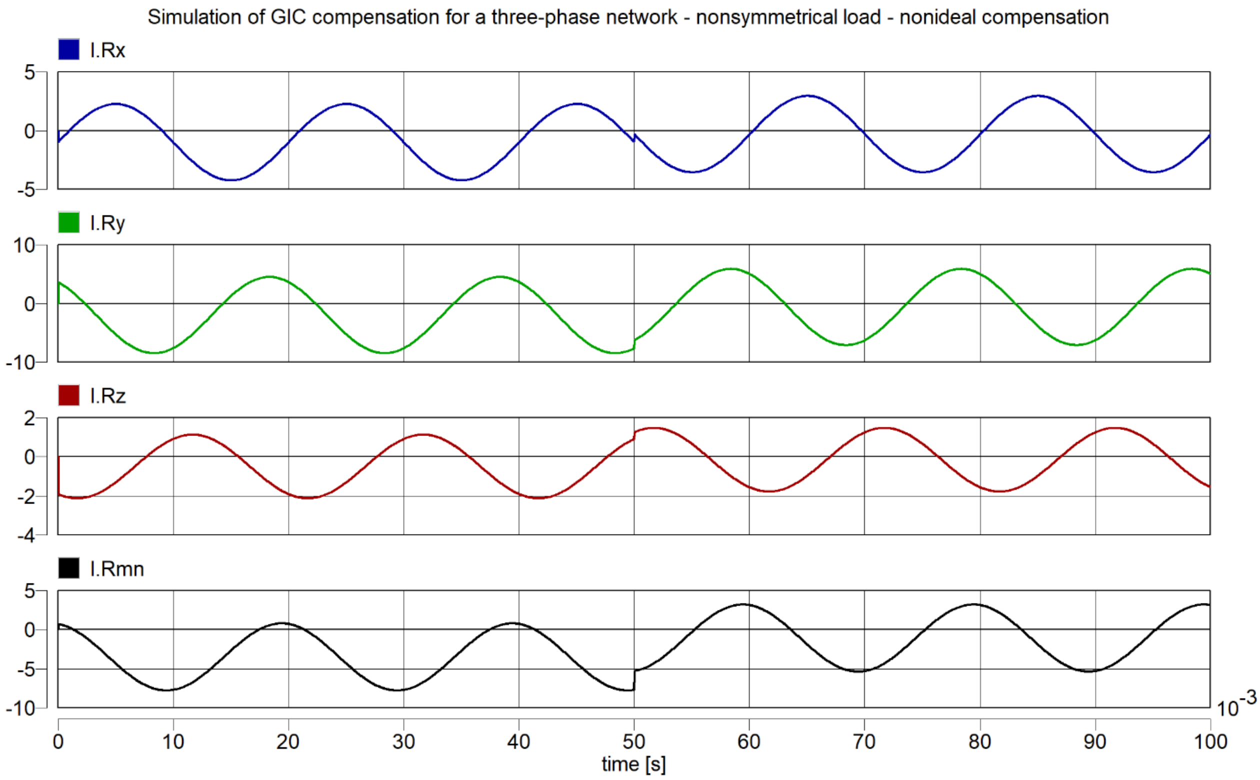

Fig. 7. Simulation of no ideal GIC compensation for unbalanced loads, R_X=100 Ω, R_Y=50 Ω, R_Z=200 Ω, R_{MN}=0.1 Ω, V_{GIC}=100 V. The course of currents without GIC compensation at time $t \leq 50$ ms and the course of currents after GIC compensation at time are shown $t > 50$ ms, while the compensation voltage V_{COMP}=70 V (instead of 100 V), so the compensation is not ideal. This results in a small DC component in the currents.

5. Conclusion

In this work, a method of GIC compensation using a source connected to a three-phase network node was described. The principle was simulated, implemented and measured on a single-phase model and then simulated on a three-phase connection. For compensation, it is necessary to know the V_{GIC} voltage values in order to set these voltages on the compensation source. The V_{GIC} value can be determined during network operation, in the time of a magnetic storm, using an indicator that is described in detail in [5]. If the voltage value is not available, one can proceed by adjusting the value of the compensation voltage V_{COMP} so that the currents have a minimum DC component.

It should be pointed out that this is only one of the principles of the method to deal with breakdowns of distribution systems due to magnetic storms. It is not addressed, for example, how to design a compensating voltage source.

Acknowledgments

This work was supported by Department of Electronics and Information Technology/RICE and Department of Electrical Engineering and Modeling, University of West Bohemia, Plzen, Czech Republic and by the Ministry of Education, Youth and Sports of the Czech Republic under the project OP VVV Electrical Engineering Technologies with High-Level of Embedded Intelligence, CZ.02.1.01/0.0/0.0/18_069/0009855 and by the Internal Grant Agency of University of West Bohemia in Plzen, the project SGS-2021-005.

6. References

[1] R. R. Benestand, *Solar activity and Earths climate*, Berlin, Springer-Verlag,2003.
[2] E. Priest, *Solar magnetohydrodynamics*, Dordecht, D. Reidel Publia Co., 1984.
[3] E. N. Parker, *Cosmical magnetic fields*, Oxford, Clarendon Press, 1979.
[4] D. Mayer, "Contribution to investigation of influence of geomagnetic storms on electrification system", Acta Technica, vol. 58, no. pp. 351-365, 2013.
[5] D. Mayer, M. Stork, "Indicator of the influence of a geomagnetic storm on the transmission system", Journal of El. Eng., vol. 74, 2023, No. 1, pp. 32–39, 2023.
[6] G. A. Glatzmaier and P. H. Roberts, "An anelastic evolutionary geodynamo simulation driven by compositional and thermal convection", Physica D, 97, pp. 81-94, 1996.
[7] G. A. Glatzmaier and P. H. Roberts, "Rotation and magnetism of Earth's inner core", Science, 274, pp. 1887-1891, 1996.
[8] U. R. Christensen, "Geodynamo models: Tools for understanding properties of Earth's magnetic field", Elsevier, Physics of the Earth and Planetary Interiors 187, pp.157–169, 2011.
[9] R. Price, "Geomagnetically induced currents effects on transformers", IEEE Transactions on Power Delivery, vol. 17, no. 4, pp. 1002-1008, October 2003.
[10] M. Stork, Mayer D.: Direct currents in power transformers. Journal of El. Eng., Vol. 17, No. 1, pp. 68-72, 2019.
[11] D. Mayer, "Protection of power transformers against the effect of magnetic storms", Journal of El. Eng., vol. 72, no. 4, pp. 249-255, 2021.
[12] L. J. Lanzerotti, "Space weather effects on technologies", Song P. et al (eds.): Space Wheater, American Geophysical Union, Geophys, Monograph. 125, pp. 11-25, 2001.
[13] K. Zheng, et al., "Effects on system characteristics on geomagnetically induced currents", IEEE Trans. Power Delivery, 29 (2), pp.890-898, 2014.
[14] D. Boteler, "Methodology for simulation of geomagnetically induced currents in power systems", J. Space Weather Clim. 4, A21, 2014.
[15] R. Pirjola, "Practical model applicable to investigating the coast effect on the geoelectric field in connection with studies of geomagnetically induced currents", Adv. Appl. Phys., 1, pp. 9-28, 2013.
[16] "GIC module to analyze geomagnetic disturbances on the grid", [online] https://assets.new.siemens. com/siemens/assets/api/uuid:86db972f70ef70b87fc5b96ffab1b31c04175b31 /psse-gic-module-flyer.pdf.
[17] A. Pulkkinen et al. "Geomagnetically induced currents: Science, engineering, and applications readiness", Space Weather, 15, pp. 828–856, 2017. doi:10.1002/2016SW001501.
[18] M. Svanda, D. Mourenas, K. Zertova, T. Vybostokova, "Immediate and delayed responses of power lines and transformers in the Czech electric power grid to geomagnetic storms", Journal of Space Weather and Space Climate 10, 26, 2020.

M. Stork received the M.Sc. degree in electrical engineering from the Technical University of Plzen, Czech Republic at the Department of Electronics in 1974 and Ph.D. degree in automatic control systems at the Czech Technical University in Prague in 1985. In 1997, he became Associate Professor at the Department of Electronics and Information Technology, Faculty of Electrical Engineering of the University of West Bohemia in Plzen, Czech Republic, and full professor in 2007. He has numerous journal and conference publications. He is member of the editorial board in "Physician and Technology". His research interests include analog/digital systems, signal processing and biomedical engineering, especially cardiopulmonary exercise tests systems.

D. Mayer, Prof, Ing, DrSc received the Ing, PhD and DrSc degrees in electrical engineering from Technical University in Prague, Czech Republic. In 1959 Associate Professor at the University of West Bohemia in Pilsen, in 1968 full Professor of the Theory of Electrical Engineering. For many years he was head of the Department of Theory of Electrical Engineering. Research interests: circuit theory, electromagnetic field theory, electrical machines and apparatus, history of electrical engineering. He published 9 books, more than 350 scientific papers and 15 patents. He is a member of editorial boards of several international journals and leader of many grant projects.

Received 3 July 2023