Journal of Electrical Engineering, Vol. 75, No. 3, 2024, pp. 224-228

sciendo
PAPERS

Contribution to the determination of the effect of magnetic storms on the electric power transmission system

[1]Daniel Mayer, [2]Milan Stork

When a magnetic storm hits a power transmission system, quasi-stationary geomagnetically induced currents (GIC) are generated in the high-voltage part of the system. These currents cause semi-saturation of the magnetic circuits of power transformers, which induces current overload in their high-voltage windings and subsequently thermal overload, which can lead to system failures. This rather complex phenomenon was described in [11] by a system of nonlinear differential equations and subsequently solved. This very challenging method is replaced in the present work by a simple approach. It allows not only predicting the imminent danger of system collapse, but gives transformer designers valuable information on how they can counteract this danger.

Keywords: geomagnetic field, coronal mass ejection, geomagnetically induced currents, magnetic semi-saturation, current overload, thermal overload

1 Introduction

The idea of the physical nature of terrestrial magnetism, that the Earth is a magnetic dipole formed by a permanent magnet (W. Gilbert, around 1600), was replaced by a model known as a geodynamo. Since the Earth's liquid core is electrically conductive, its flow in the weak magnetic field that is present in interplanetary space induces strong electric currents in it that generate the geomagnetic field. The geomagnetic field forms the Earth's magnetosphere. The distribution of the Earth's geomagnetic field changes over time, but only very slowly. Changes are detected on a scale of decades. In our latitudes, the geomagnetic induction has a value of about 44 μT. This internal geomagnetic field has practically no effect on the electrical system.

In addition to the internal one, there is also an external geomagnetic field that originates in solar eruptions [1, 2]. Massive explosions on the Sun are associated with intense electromagnetic radiation in a wide range of the spectrum and with the ejection of coronal matter, formed by electrically charged particles with high energies. The coronal mass cloud, known as CME (Coronal Mass Ejection), spreads at a high speed (about 450 km/s) through interplanetary space and is called the solar wind. If the solar wind hits the Earth's surroundings, its magnetosphere largely shields the Earth from the solar wind and thus protects the Earth's biosphere. However, the solar wind partially penetrates the upper layers of the Earth's atmosphere, and the flow of electrically charged particles (i.e., the electric current) induces the Earth's external magnetic field. The interaction of the solar wind with air molecules in the upper layers of the Earth's atmosphere results in the emission of electromagnetic radiation in the visible spectrum – we are talking about the aurora borealis. The external magnetic field changes relatively quickly, on the order of tens of seconds – we are talking about geomagnetic field variations. At times of a relatively calm magnetic field, these variations have a magnitude of around 20 to 30 nT. If they reach hundreds of nT, we are talking about a magnetic storm. Magnetic storms occur more often in places close to the magnetic poles and threaten satellite telecommunications and navigation systems that move above the Earth's magnetosphere and are therefore not protected by it.

2 Geomagnetic induced currents in power transformers

The effect of the geomagnetic field on the electrical insulation system takes place according to the law of electromagnetic induction (M. Faraday). In the very high voltage (VHV) line, due to variations in the geomagnetic induction $B(t)$, thus due to the derivative of the geomagnetic induction $\partial B(t)/\partial t$, a voltage is induced, which causes geomagnetically induced currents (GIC). These GIC currents have a temporally random course. Compared to currents with an industrial frequency of 50 Hz, their changes are very slow, on the order of nT/min. Thus, GIC currents are quasi-stationary and we

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

https://doi.org/10.2478/jee-2024-0027, Print (till 2015) ISSN 1335-3632, On-line ISSN 1339-309X

will not make a big mistake if we count them as direct currents. Their distribution in the VHV transmission network is thus determined only by the ohmic resistance of the conductors, while the inductances and capacitances of the lines do not apply.

The emergence of GIC in the power line of the system can be predicted. Solar activity is permanently monitored by means of satellites, e.g., within the NASA project (called Solar Shield) by the SOHO and STEREO satellites. If the satellite detects a coronal mass heading towards the earth, they will measure the parameters of the solar wind and communicate the results to the laboratory in Greenbelt (Maryland, USA), where they will develop a forecast and send it to the operators of the energy systems. We can therefore predict the time course of the geomagnetic induction $B(t)$ in a certain area of the Earth's surface. If a magnetic storm then arrives in the area of the transmission system, we can measure the GIC directly on the VHV conductors [3, 4]. For example, works [5-11] deal with the calculation of the size of the GIC in the VHV line. Measurements on 400 kV lines showed that in England the GIC reached a value of 10 to 15 A, while in the Nordic countries up to 200 A, with a duration of up to several tens of minutes [12, 13].

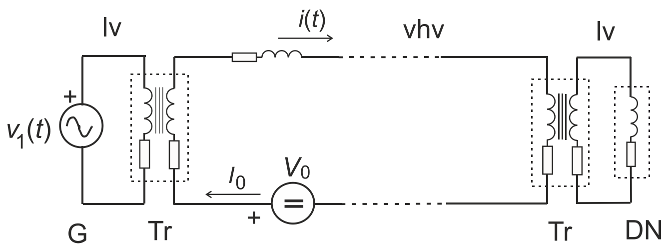

Fig. 1. Single-phase transmission system: generator (G), power transformer (Tr), VHV line into which GICs are induced, power transformer (Tr), distribution network (DN)

3 Current overload due to GIC

Since the function $B(t)$ has a random nature, these are approximate solutions and we can therefore afford certain simplifications. In [11], we started from a simple single-phase transmission system consisting of a generator, transformer, VHV line, transformer and distribution network (Fig. 1). The electric energy transmission current passes through the VHV line

$$i_1(t) = I_1 \sin(\omega t) \tag{1}$$

and the current I_0 (GIC), hence the total current is

$$i(t) = i_1(t) + I_0 = I_1 \sin(\omega t) + I_0\,. \tag{2}$$

In [11], a system of nonlinear differential equations was formulated for the transmission system according to Fig. 1, which was then solved numerically. From the found course of the current $i(t)$, it was possible to determine the current overload of the VHV line due to the current I_0. This way of solving is very complex and unclear. In the presented work, we will determine the current overload using a method (approach), which is much simpler. From the entire transmission system, we will limit ourselves to the high-voltage coil of the transformer, Figs. 2 and 3. Its magnetic circuit is made of transformer sheets with magnetization curve $B(H)$. From the curve $B(H)$, Fig. 4, we determine the dependence of the magnetic flux on the current $\Phi(i)$ and the dependence of the dynamic inductance, Fig. 5.

$$L_d = \frac{d\Phi}{di} \tag{3}$$

$\Phi(i)$ is practically linear for $i(t) \leq \pm I_p$, and for $|i(t)| > +I_p$ it grows more slowly. This corresponds to the values of the dynamic inductance L_d, which are initially constant, $L_d = {}^aL_d$=const., but then decrease with the saturation of the magnetic circuit to the value, see ${}^bL_d$.

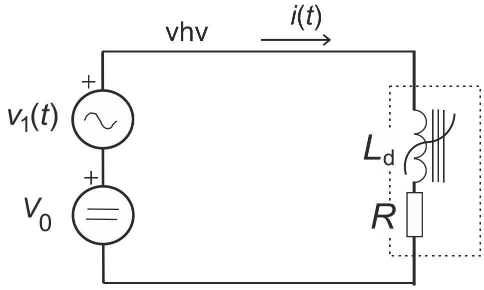

Fig. 2. Nonlinear coil with inductance $L_d(i)$ and ohmic resistance R

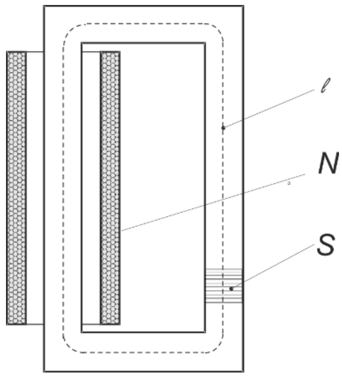

Fig. 3. Magnetic circuit of high voltage transformer coil

Consider two operating states of the coil:

a) The magnetic storm does not act, thus the GIC current I_0=0. The transformer works in the normal mode, a current $i_1(t)$ with amplitude $\pm I_1$ passes through the coil. If $|I_1|<I_p$, only the linear part of the curve $\Phi(i)$ is applied, the dynamic inductance L_d is constant, the circuit according to Fig. 2 is linear, the current $i(t)$ varies harmonically.

b) A magnetic storm works. A current (GIC) $I_0 \neq 0$ is induced, which is superimposed on current $i_1(t)$. If the current $|i(t)| > I_p$, the non-linear part of the characteristic $\Phi(i)$ applies, the dynamic inductance L_d decreases and therefore the current $i(t)$ increases. Oversaturation of the magnetic circuit (semi-saturation) occurs, which leads to an increase in the effective value of the current $i(t)$. The current overload of the coil can be assessed according to the quantity, which we define as an overload coefficient:

$$\alpha = \frac{^{b}I_{ef}}{^{a}I_{ef}} \tag{4}$$

where

$^{a}I_{ef}$ is the effective value of the current when the GIC current I_0=0, thus $^{a}I_{ef}=\sqrt{2}\,.\,I_1$,
$^{b}I_{ef}$ is the effective current value when GIC $I_o > 0$.

The overload coefficient indicates how many times the current – and subsequently also the temperature overload – of the high-voltage winding is greater, compared to normal operation, i.e. when I_0=0.

The overload coefficient α can be calculated according to the following algorithm.

- We determine the shape of the curve $\Phi(i)$, Fig. 3, using relations

$$\Phi(i) = B(i)\,.\,S \qquad H(i)\cdot l = N\cdot i \tag{5}$$

where S is the cross section of the magnetic circuit, N is the number of coil turns and l is the mean length of the magnetic induction line, Fig. 3.

- We determine the course of the dynamic inductance $L_d(i)$.
- We determine the current $i(t)$ by solving the non-linear differential equation of the circuit (Fig. 2).

$$L_d(i)\frac{di(t)}{dt} + Ri(i) = v(t) \tag{6}$$

where

$$v(t) = V_1 \sin(\omega t) + V_0 \tag{7}$$

Here, V_1 is the amplitude of the nominal voltage on the coil and V_0 is the voltage induced into the transmission system (Fig. 1) by the magnetic storm. It is related to the GIC current I_0 by the simple relation $V_0 = R\cdot I_0$, where R is the resistance of the line conductors, including both coils of the transformers.

- We determine the effective value of the current $i(t)$:

$$^{b}I_{ef} = \sqrt{\frac{1}{T}\int_0^T i(t)^2 dt} \qquad T = \frac{1}{f} \tag{8}$$

- We determine the overload coefficient from the definition relation (4).

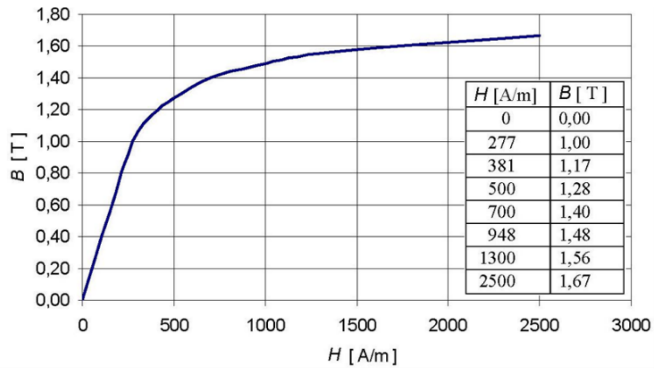

Fig. 4. Magnetization curve of 0.25 mm thick transformer sheets

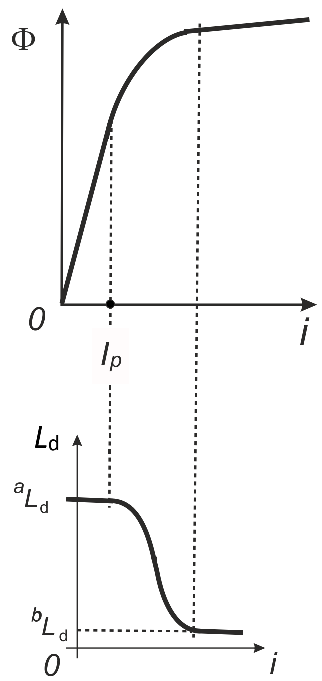

Fig. 5. Characteristics $\Phi(i)$ and dynamic inductance $L_d(i)$ of the coil

4 Example

1) We determine the overload coefficient α for the coil (Figs. 2 and 3), R=0.5 Ω, N=1125, l=1.1 m, S=0.005 m^2 whose magnetic circuit is made of transformer sheets (Fig. 4). A harmonic current of amplitude I_1=0.3 A passes through the coil at I_0=0.

- We determine the shape of the magnetic flux $\Phi(i)$ from the magnetization curve $B(H)$. Both curves differ only by changing the scale according to Eqns. (5). We approximate the dependence $\Phi(i)$, for example, by a polynomial.
- The derivative of this polynomial determines the dependence of the dynamic inductance $L_d(i)$ and approximates it, for example, by a polynomial, Fig. 6.
- By solving the differential Eqn. (6) we determine the shape of the magnetizing current $i(t)$, for different values of I_0. At I_0=0, V_0=0, a harmonic current of amplitude I_1=0.3 A, passes through the coil if the voltage amplitude is V_1=0.38 V. In Fig. 7 this current waveform is shown at time t (0; 0.10) s. At time t=0.1 s, the GIC is caused by the induced voltage V_0=0.06 V. From the transient plotted in Fig. 7, we are interested in the steady state current $i(t)$ and subsequently its effective value $^bI_{ef}$ calculated according to Eqn. (8).
- At the points marked in Fig. 8, they are calculated according to Eqn. (4) values of the coefficient α and these were approximated by a polynomial of the 4th degree:

$$\alpha = 91.6\,x^4 - 69\,x^3 + 20.1\,x^2 - 1.33\,x + 1.01 \quad (9)$$

where $x \in \langle 0 \div 0.6 \rangle$, $x = I_0/I_1$.

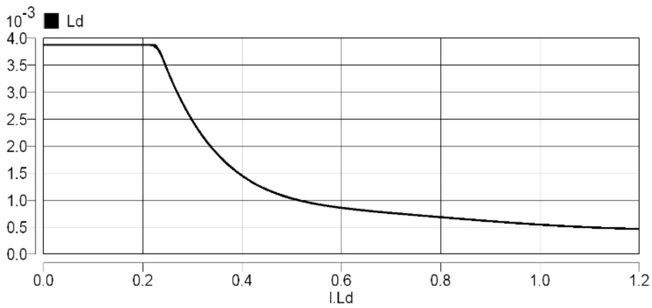

Fig. 6. Dynamic inductance, $L_d(i)$ (Henry), of the coil

2) Demonstrate the effect of semi-saturation phenomenon by directly measuring the shape of the current curve of a high-voltage coil of an (unspecified) transformer.

In Fig. 9, there is an oscillogram, which is the result of measurements on a model with 2 transformers according to Fig. 1, where the upper waveform is the voltage and the lower waveform is the current distorted by the influence of the GIC component.

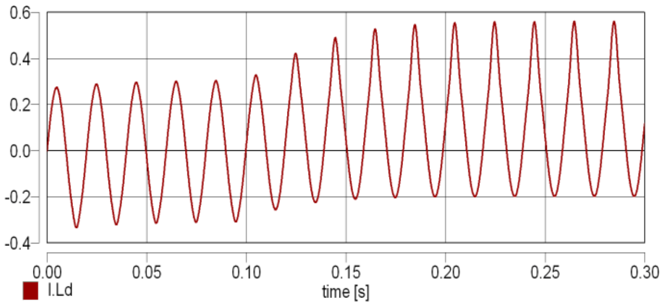

Fig. 7. Time evolution of current $i(t)$ (according Fig. 2) in the absence of GIC (I_0=0, left part) and in the presence of GIC ($I_0 \neq 0$, right part). At time t=0.1 s current I_0 is applied, we are interested in the steady state of the current.

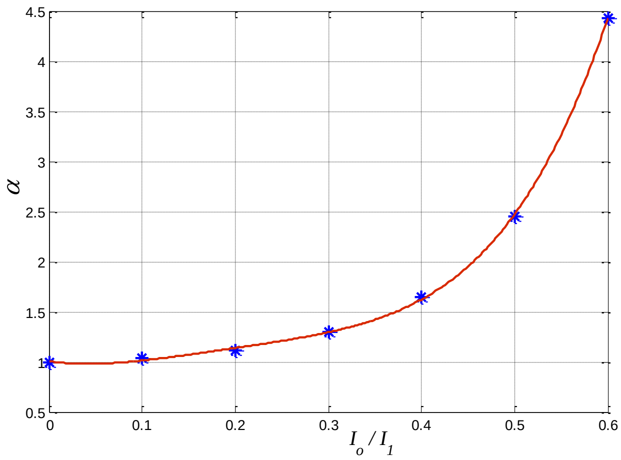

Fig. 8. Dependence of the overload coefficient α on the relative value of the currents I_0/I_1

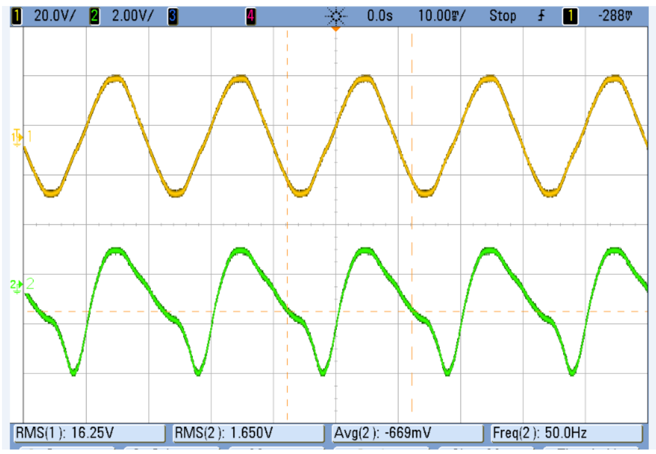

Fig. 9. Result of measurements on a model, where the upper waveform is the voltage and the lower waveform is the current distorted by the influence of the GIC component.

5 Conclusion

We have developed a method that allows us to determine with great accuracy the extent to which the VHV winding of a transformer is at risk due to a magnetic storm. A similar current and temperature overload occur in the VHV line conductors, but due to the more abundant cooling of the conductors, the risk of their failure recedes into the background. It is evident from the above that one of the most effective ways to counteract accidents due to magnetic storms is a robust design of the magnetic circuit of transformers, where the operating point is mainly in the unsaturated part of the magnetisation characteristic. However, this is at the expense of higher investment costs. Other methods of safeguarding the high-voltage segment of the transmission system against overload are presented in the papers [14-16].

Acknowledgments

This work was supported by the Department of Electrical and Computational Engineering and the Department of Electronics and Information Technology/RICE, University of West Bohemia, Plzen, Czech Republic and by the Ministry of Education, Youth and Sports of the Czech Republic under 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 the University of West Bohemia in Plzen, project SGS-2024-005.

References

[1] R. E. Benestand: *Solar activity and Earth´s climate*. Berlin, Springer-Verlag, 2003.

[2] L. J. Lanzerotti: *Space weather effects on technologies*. In: Song P. et al (eds.): Space Wheater. American Geophysical Union, Geophys. Monograph., 2001, 125, pp. 11-25.

[3] D. Mayer, M. Stork: “Indicator of the influence of a geomagnetic storm on transmission electric system”. *Journal of Electrical Engineering*, vol. 74, no. 1, pp. 32-39, 2023.

[4] D. Mayer, M. Stork: *Device for indicating the effect of magnetic storms on the power transmission systems*. Czech Patent No. 309 504, granted 19. 01. 2023.

[5] R. Nishiura, S. Yamashita, S. Kano: *Simulation analysis of geomagnetically-induced currents (GIC) effects on shell-form transformers*. Power and Energy Society General Meeting (PES), 2013 IEEE, 21- 25 July 2013.

[6] R. Girgis: *Effects of geomagnetically induced currents on power transformers and power systems*. CIGRE, 21, rue d´Artois, F-75008 Paris, A2-304, pp. 1-8.

[7] K. J. Patel: *An analytic review of geomagnetically induced current effects in power system.* Internet. Conf. on Electrical, Electronics and Optimization Techniques (ICEEOT), Issue Data 3-5 March 2016.

[8] J. Ramírez-Niňo: “Core saturation effect of geomagnetic induced currents in power transformers”. *Journal of Applied Research and Technology*, vol. 14, pp. 87-92, 2016.

[9] D. Mayer: “Contribution to investigation of influence of geomagnetic storms on electrification system”. *Acta Technica*, vol. 58, pp. 351-365, 2013.

[10] D. Mayer: *The effect of geomagnetic storms on the electrification system*. In: Cyclonic and Geomagnetic Storms. Editor: Victoria P. Banks, Nova Science Publishers, Inc., New York 2015, pp. 1-18. ISBN 978-1-63482-360-9

[11] M. Stork, D. Mayer: “Direct currents in power transformers”. *Journal of Electrical Engineering*, vol. 70, no. 1, pp. 68-72, 2019.

[12] R. Price: “Geomagnetically induced currents effects on transformers”. *IEEE Transactions on Power Delivery*, vol. 17, no. 4, pp. 1002-1008, October 2003.

[13] M. Lahtinen, J. Elovaara: “GIC occurrences and GIC test for 400 kV system transformer”. *IEEE Transactions on Power Delivery*, vol. 17, no. 2, pp. 555-561, 2002.

[14] D. Mayer: “Protection of power transformers against the effect of magnetic storms”. *Journal of Electrical Engineering*, vol. 72, no. 4, pp. 249-255, 2021.

[15] M. Stork, D. Mayer: “Simulation of electrical system protection against the effects of magnetic storm”. *Journal of Electrical Engineering*, vol. 74, pp. 321-327, 2023.

[16] L. Bolduc et al.: “Development of DC current-blocking device for transformer neutrals”. *IEEE Trans. on Power Delivery*, vol. 20, no. 1, pp. 163-168, 1995.

Daniel Mayer 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. 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.

Milan 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 on University of West Bohemia in Plzen, Czech Republic and full professor in 2007. He has numerous journal and conference publications. He is member of editorial board magazine "Physician and Technology". His research interests include analog/digital systems, signal processing and biomedical engineering, especially cardiopulmonary exercise tests systems.

Received 10 April 2024