Journal of Electrical Engineering, Vol. 76, No. 4, 2025, pp. 386-390

Protecting power transmission systems from magnetic storms – rational approach

Daniel Mayer

"There are more things in heaven and earth, Horatio,
than are dreamt of in your philosophy."
William Shakespeare: Hamlet

This paper concludes the research studies [1-11] on the effect of magnetic storms on the electrical transmission system. A brief overview of the physical nature of geomagnetism, space weather, and ways to monitor it is given. Furthermore, the mechanism of the solar wind on the magnetosphere and subsequently on the electrical transmission system is recalled. The focus of this paper is a rational view of the implementation of power transformer protection of the transmission system. It is shown that the introduction of protective devices is not only a technical matter, but their deployment must be decided on the basis of economic, social, and political considerations.

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

1 The geophysical basis of magnetic storms

1.1 Space weather

The geomagnetic field is generated by both internal sources and external sources.

Internal source of geomagnetic field. The first significant observation was made by William Gilbert (†1603), personal physician to Elizabeth I and her successor James I. Using a model of the Earth with a magnet, he found that the Earth acts as a permanent magnetic dipole in its surroundings. It was also found that the axis of this dipole is deviated from the Earth's axis of rotation by an angle of about 20°, called *declination*, which changes slowly with time (on the order of years), called *slow secular variation*. The magnetic field around the Earth is called the *Earth's magnetosphere.*

The idea that the Earth is a permanent magnetic dipole was accepted for nearly 300 years and was abandoned after the discovery that the temperature inside the Earth greatly exceeds the Curie point. This idea was replaced by the Irish physicist Joseph Larmor (1919) with a model called *the geodynamo*. According to him, the geomagnetic field is generated by the axisymmetric, laminar, rotational flow of the outer (liquid) core. However, even this model did not stand up to criticism (e.g., it does not explain the cause of the slow secular variations), and was therefore replaced by an improved, magnetohydrodynamic model by the British physicist H. K. Moffatt, the Swedish physicist H. Alfén and others in the 1960s. This is the turbulent flow of liquid iron in the Earth's outer core. It is mathematically described by the equations of magnetohydrodynamics, together with the Stokes equations, respecting the Coriolis forces due to the rotation of the Earth and the flow due to thermal convection.

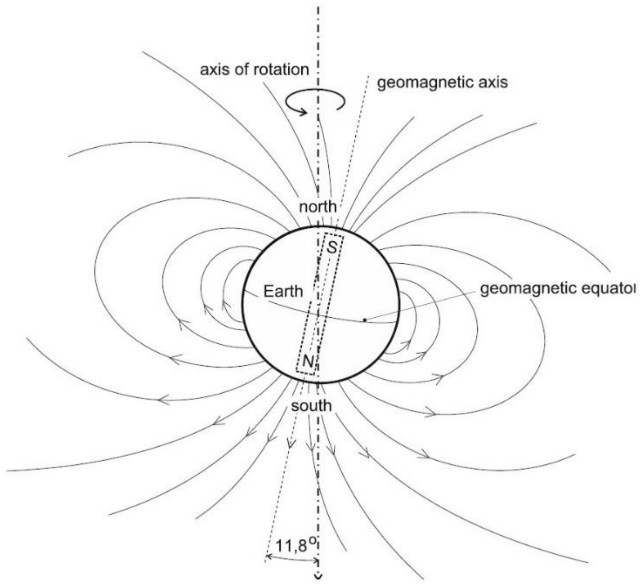

Fig. 1. Earth's internal magnetic field. Geomagnetic field undisturbed by solar wind.

Figure 1 shows the Earth's magnetosphere generated by the indicated physical processes within the Earth. The magnitude of the magnetic induction vector of the geomagnetic field at the Earth's surface is at the poles $B \sim 60$ μT, at the magnetic equator $B \sim 30$ μT and in the Czech Republic it is around 44 μT.

Department of Electrical and Computational Engineering, University of West Bohemia, Pilsen, Czech Republic
mayer@fel.zcu.cz

https://doi.org/10.2478/jee-2025-0040, Print (till 2015) ISSN 1335-3632, On-line ISSN 1339-309X

The external source of the geomagnetic field is solar activity. During solar flares, i.e. huge explosions on the surface of the Sun, coronal mass ejections of high-energy particles (electrons and protons) occur – this phenomenon is referred to as CMA (Coronal Mass Ejection). The particles propagate through interplanetary space at speeds of 400 to 700 km/s and are referred to as the *solar wind*. The process of solar wind propagation through interplanetary space has been termed *space weather*. The entry of electrically charged particles into the Earth's neighbourhood is prevented by the geo-magnetic field. The interaction of the solar wind with the magnetosphere results in electrically charged particles moving in the direction of the magnetic lines of force and circumnavigating the magnetosphere by the action of the Lorentz force.

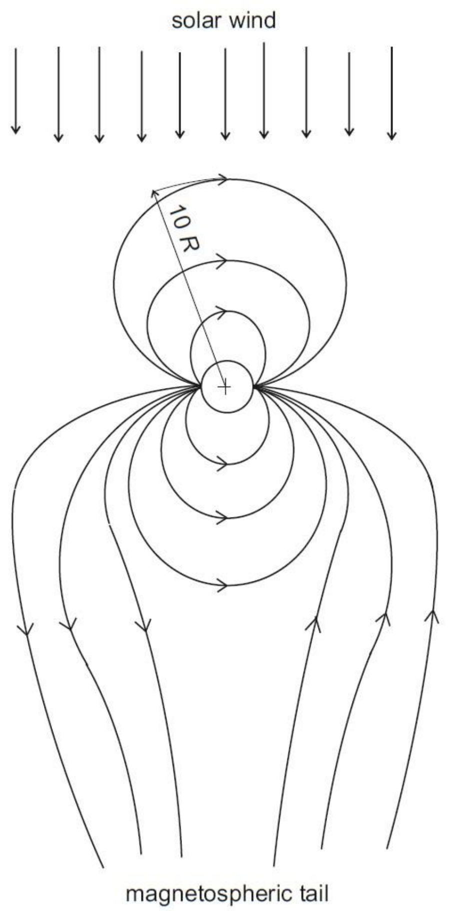

Fig. 2. Earth's magnetosphere deformed by the solar wind.

The solar wind thus distorts the shape of the magnetosphere (Fig. 2): on the front (day, windward) side the magnetosphere is compressed to about ten Earth diameters, and on the reverse (night, leeward) side it is extended into a long tail of magnetosphere, extending far beyond the orbit of the Moon. Geomagnetism thus shields the Earth from the solar wind and thus protects the Earth's biosphere. Without geomagnetism, there would be no existing life forms on our planet. It is only around the geomagnetic poles, where the magnetic induction vector is nearly perpendicular to the Earth's surface, that channels are created through which solar wind particles can partially penetrate into the deeper layers of the magnetosphere and endanger passengers and crews on transoceanic flights. Astronauts are in serious risk of radiation hazards on their mission to the Moon or even to Mars.

If a CMA hits the Earth's magnetosphere, it will cause geomagnetic activity in the magnetosphere, resulting in rapid variations in the magnetic field. These vary in intensity from small disturbances that occur several times a day to strong disturbances that are like solar wind shock waves – called *magnetic storms*. The small daily variations during times of "calm" geomagnetic field are 20 to 30 nT, with magnetic storms reaching hundreds of nT. The magnitude of the geomagnetic field is classified on a ten-point scale and is referred to as K0 to K9. For example, in the K0 group the magnetic induction is $B \in <0, 5>$ nT, in the K3 group it is $B \in <20, 40>$ nT and at K9 is $B > 500$ nT. The largest magnetic storm was registered by the British astronomer R. Carrington in 1859. As the introduction of electricity was then in its infancy, a magnetic storm of K9 ($B \sim 3000$ nT), although it knocked out the telegraph network throughout the northern hemisphere, could not have caused much damage. In the present days, when the whole of human civilization is dependent on electrical and electronic engineering, a similar storm could cause immeasurable damage.

1.2 Space weather monitoring

Solar activity is continuously monitored both by solar chromospheric telescopes and by satellites such as SOHO and STEREO. If the satellites detect a coronal mass ejection (CMA) heading towards the Earth, they measure the relevant solar wind parameters and report the results to the laboratory in Greenbelt (Maryland, USA), where they produce a three-day forecast and distribute the results to power system operators [1].

The geomagnetic field is continuously monitored by a worldwide network of geomagnetic observatories. For example, in the Czech Republic, the Institute of Geo-physics of the Academy of Sciences operates a low-noise industrial site in the village of Budkov in the Prachatice region. Here, the rapid variations of all three components of the geomagnetic induction vector are measured continuously at 1-min intervals, or at 1-second intervals, with an accuracy of 0.1 nT. The results are continuously published on the internet [12] and are transmitted to worldwide agencies.

The immediate effect of a magnetic storm on the transmission system can also be monitored. For this purpose, an indicator [4, 5, 8] is used, which is implemented in the vhv line and wirelessly sends information to the operators' workstation for controlling the system carriage.

2 Effects of magnetic storms on the transmission system

The power transmission system has the following parts:

- *generators* (usually 24 kV) connected to power transformers that supply,
- *very high voltage transmission lines* (usually 400 kV) terminating at the power transformers which supply electricity to the
- *distribution network* and to consumers.

We will focus on the long-distance vhv line. The geomagnetic field $B(t)$ induces a voltage in this line, which causes currents in the conductors; these are called *GIC* (Geomagnetically Induced Currents). The time course of the geomagnetic field $B(t)$ is random. Although we are talking about its rapid variations, it changes quite slowly with time, and we monitor its changes at one-second intervals. Its variations are very slow compared to the industrial frequency of 50 Hz, so we refer to the GIC currents as *quasi-stationary*. To this we note:

- Since GICs have their origin in Faraday's law of induction, their magnitude does not depend on the magnitude of the geomagnetic induction $|B(t)|$ but on its derivative $\mathrm{d}B/\mathrm{d}t$.
- Since GICs are quasi-stationary (i.e., they behave like DC currents), their magnitude is limited only by the ohmic resistances of the path through which they pass, i. e., the conductors of long-distance vhv lines and the high-voltage windings of transformers; the corresponding capacitances and inductances do not apply.

The GIC current (let us call it I_0) is superimposed with the working current $I_1 \sin \omega t$, hence through the line flows the current

$$i(t) = I_1 \sin \omega t + I_0$$

a) If there is no magnetic storm, GIC does not occur ($I_0 = 0$) and the transformers operate in the normal mode, i. e., in the linear part of their magnetization characteristics $B_\mathrm{t}(i)$ [11]. The circuit formed by the transmission line and the high voltage windings of the transformers is linear, the currents and voltages vary harmonically, Fig. 3a.

b) When a magnetic storm induces a GIC ($I_0 \neq 0$) into the vhv line, the operating point on the $B_\mathrm{t}(i)$ characteristic shifts by I_0 and causes a dc pre-magnetization of the magnetic circuit of the transformers, called *semi-saturation*, Fig. 3b.

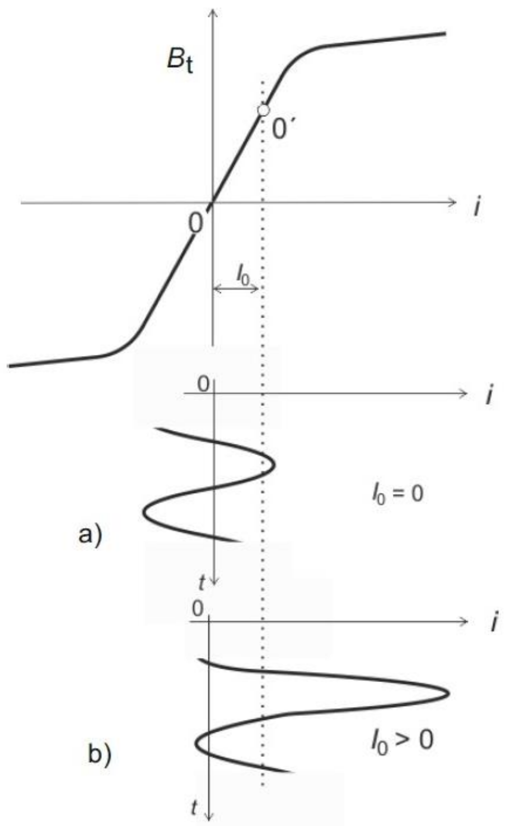

Fig. 3. Effect of oversaturation of the transformer magnetic circuit on the occurrence of current overload: (a) without oversaturation, (b) with oversaturation.

- ✓ In the half-period when $i(t) > I_0$, the working point goes into the saturated part of the magnetization curve. This reduces the inductance of the transformer windings (the circuit becomes nonlinear) and the current $i(t)$ increases strongly above the normal value.
- ✓ In the half-period when $i(t) < I_0$, the operating point is in the linear part of the magnetization curve, the circuit behaves as a linear circuit and no current overload occurs.

The current dependence of the winding inductance of the vhv winding of transformer $L_\mathrm{t}(i)$ can be easily determined from the magnetization curve $B_\mathrm{t}(i)$, Fig. 4, [10].

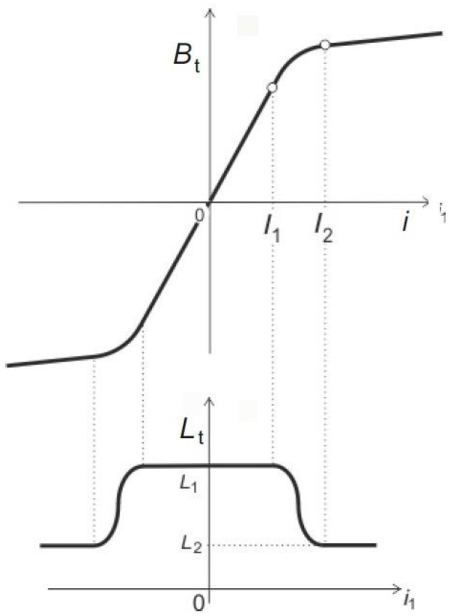

Fig. 4. Inductance waveform of a transformer vhv winding with oversaturation of its magnetic circuit.

If we denote the effective value of the current $i(t)$ without magnetic storm action as $I_{\mathrm{ef}0}$ and with magnetic storm action as I_{efGIC}, then obviously

$$I_{\mathrm{efGIC}} = n\, I_{\mathrm{ef0}},$$

where $n > 1$, n is a positive integer number.

According to Joule's law, the dissipated energy in the resistance vhv of the winding is n^2-times greater than in the normal regime, which can cause thermal damage to the winding and collapse of the system. The conductors of the vhv line are equally affected, but they resist higher temperatures and therefore the collapse of the vhv line is not imminent.

3 How to protect the transmission system from magnetic storm?

3.1 Technical possibilities of protection

In papers [1 to 11] we have described various technical measures that can protect or at least reduce the risk of damage to the vhv windings of transformers. Let us recall the most important ones.

Controlled blackout. Before a predicted magnetic storm, the transmission system is shut down and after the storm subsides, it is put back into operation. From a technical point of view, this method is primitive, it only reduces but does not eliminate serious economic losses, and besides, it damages the credibility of the operator**.**

Use of superconducting filters. Superconducting filters are connected in parallel to the high voltage windings of transformers in case of danger [3, 8, 9]. This will perfectly protect these transformers from the thermal effects of quasi-stationary currents (GIC) but at the cost of having to introduce expensive cryotechnical equipment. These costs can be reduced by using filters that are not superconducting but are less efficient in their protective action. The limiting case of this method is the oversizing of the cross section of the copper conductors of the high voltage transformer coils.

By suppressing the magnetic circuit nonlinearity of transformers [6, 11]. This is achieved by oversizing the magnetic circuit. The magnetic induction in the magnetic circuit will then be lower so that quasi-stationary currents (GIC) will not cause semisaturation of the magnetic circuit.

Install robust transformers. This uses the above-mentioned ideas based on the parallel filter approach (*robustness in copper*), or nonlinearity suppression (*robustness in iron*), or both.

Robust transformers have a significant bonus. This is because they represent a significant power reserve, which will certainly be appreciated by every system operator. Another bonus of robust transformers in iron is the reduction of their noise level. This is significant from an environmental point of view and a valuable asset for transformer manufacturers in terms of marketability. The sources of noise in transformers are the vibration of the winding coils and magnetostriction, i. e., the change in the magnetic circuit volume in alternating magnetization. Both of these noise sources are more prevalent the greater the magnetic induction in the magnetic circuit. The disadvantage of robust transformers is their higher manufacturing cost.

3.2 Economic and socio-political criteria for deciding how to protect

A number of other dangers to citizens must be taken into account when deciding on the protection of the transmission system. None of the energy professionals from Central Europe have experienced such a magnetic storm that would cause a collapse of the transmission system. It is therefore a legitimate question whether devastating magnetic storms are a reality or just a literary fiction. However, energy experts from the Nordic countries have a clear answer to the danger of magnetic storms. Magnetic storms here have caused severe blackouts in recent years, affecting areas with several million inhabitants and causing great economic damage.

In addition to magnetic storms, many other natural phenomena and social excesses threaten human society, such as floods, meteorological phenomena, disease epidemics, as well as terrorism, wars and many others. Each of these hazards can be countered (sometimes with greater, sometimes with lesser and often with little effectiveness), but at a financial cost. Since the economic possibilities of each society are limited, it is up to the legislative bodies of each country to decide on the amount of money to build the appropriate protection, based on an assessment of the severity and probability of a real threat. The decision on how to protect the transmission system should therefore be based on a comparison of the risk of system collapse due to a magnetic storm with the risks of many other phenomena threatening the population, the limiting factor being the economic capacity of the society. Table 1 outlines one possible solution.

Table 1. Example of a solution for protecting the transmission system

	risk	type of protection system
mid-Earth area	low	without protection?
north-Earth area	high	robust transformers

References

[1] D. Mayer: Contribution to investigation of influence of geomagnetic storms on electrification systems. Acta Technica, Vol. 58, No. 1, 2013, pp. 351-365.

[2] M. Stork, D. Mayer: Direct currents in power transformers. Journal of Electrical Engineering, Vol. 70, No. 1, 2019, pp. 68-72.

[3] D. Mayer: Protection of power transformers against the effect of magnetic storms. Journal of Electrical Engineering, Vol. 72, No. 4, 2021, pp. 249-255.

[4] D. Mayer, M. Stork: Indicator of the influence of a geomagnetic storm on transmission electric system. Journal of Electrical Engineering, Vol. 74, No. 1, 2023, pp. 32-39.

[5] D. Mayer, M. Stork: Device for indicating the effect of magnetic storms on the power transmission systems. Czech Patent No. 309 504, granted 19. 1. 2023.

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

[7] D. Mayer, M. Stork: Contribution to the determination of the effect of magnetic storms on the electric power transmission system. Journal of Electrical Engineering, Vol. 75, No. 3, 2024, pp. 224-238.

[8] D. Mayer: A new way of protection of the transmission power system against the effects of magnetic storms. Journal of Geography and Natural Disasters, Vol. 12, Issue 3 No. 1000251, pp. 1-4.

[9] D. Mayer: An approaching for protecting electrical system power transformers against the effects of rapid geomagnetic field variations. Czech Patent No. 309 130, type of document: B6, granted 06.01.2022.

[10] D. Mayer, M. Stork: Contribution to the determination of the effect of magnetic storms. Journal of Electrical Engineering, Vol. 75, No. 3, 2024, pp. 224-228.

[11] D. Mayer, B. Ulrych: The effects of magnetic storms on power system transformers. Elektro, No. 3, 2018, pp. 62-65 (in Czech).

[12] http://bdv.ig.cas.cz/inex.html

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.

Received 23 June 2025