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Review Article

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A New Way of Protection of The Transmission Power System Against The Effects of Magnetic Storms

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Abstract

Severe collapses caused by anomalies in the Earth's magnetosphere, known as geomagnetic storms, have been reported in the operation of transmission power systems. A semi-saturating phenomenon occurs in which geomagnetic induced currents (GIC) are induced in high voltage lines, which cause the power transformers of the system to be overloaded with current and subsequently also thermally. The presented article describes a device that will either completely eliminate or at least significantly reduce the possibility of a power transformer accident. The essence of this device are frequency filters, which are automatically connected in parallel to the high-voltage windings of the power transformers at the beginning of the magnetic storm and are disconnected after the storm subsides. The online information about the effect of the magnetic storm on the system is provided by the indicator to the control workplace. The proposed equipment can be easily implemented into existing transmission systems.

Keywords: Geomagnetic Field, Coronal Mass Ejection, Geomagnetically Indukced Currents, Magnetic Semi-Saturation, Frequency Filter.

Introduction

At present, when human civilization is heavily dependent on electrical engineering and electronics, magnetic storms can severely disrupt the functioning of various electrical engineering systems. The more advanced technology a person uses, the more vulnerable this technique is, and thus the threat of dangerous magnetic storms becomes relevant. In addition to various advanced technical devices (eg satellite of telecommunications networks, navigation systems, etc.), magnetic storms can damage electrical systems for the transmission of electricity, especially power transformers, and cause large power outages.

Geomagnetism and Geomagnetic Storms

The geomagnetic field forms the Earth's magnetosphere [1] – [3]. The source of the geomagnetic field are both physical processes inside the Earth and physical processes in the heliosphere of the Sun. Thus, according to the source, we distinguish between internal and external geomagnetic fields; both magnetic fields are superimposed.

Internal Geomagnetic Field

The idea of the Earth as a permanent magnetic dipole (William Gilbert, 1600) was abandoned after the discovery that the Earth's core had a temperature above Curie's temperature. For example, at a depth of 100 km below the surface, the temperature is of the order of 1.000 ° C, i.e. substantially higher than the Curie temperature. Since 1919, a model called *geodynamo* has physically explained geomagnetism. According to this idea, the internal geomagnetic field is induced by the rotational flow of the Earth's liquid core around the magnetic axis. Since it is a moving electrically conductive medium that is exposed to a magnetic field (very weak, such as the Sun's magnetic field), very strong electric currents are induced in it, which generate a geomagnetic field. This relatively simple model was initially designed as stationary. However, he did not explain the well-known fact that the internal geomagnetic field changes with time - there is talk of secular variations. *Secular variations* are very slow, being detected on a scale of tens to thousands of years. Therefore, the original idea that the geomagnetic field is induced by axially symmetrical, stationary flow was abandoned and the geodynamic model was gradually improved. Modern geodynamic theory envisages a very complex model, respecting turbulent and non-stationary magnetohydrodynamic flow. This model has not yet been solved mathematically even with the help of powerful computers. However, an approximate solution was found, which well explains the secular variations and the possibilities of polarity reversal of the Earth's magnetic poles.

The intensity of the internal magnetic field varies with place on Earth. In our latitudes, the magnetic induction has a value of about 44 μT, at the poles around 60 μT and at the magnetic equator around 30 μT. Due to the very slow time course of secular variations, the influence of the internal geomagnetic field on the electrical systems is completely insignificant.

External Geomagnetic Field

There are relatively fast variations of the geomagnetic field, which have their origin in solar activity[1] – [4]. One of the manifestations of solar activity are solar flares, Fig. 1. These massive explosions produce intense electromagnetic radiation in a wide range of spectra and create jets of solar matter. Solar matter containing electrically charged particles, especially electrons, protons and high-energy alpha particles, can be torn off.They spread at high speed through interplanetary space and are referred to as *Coronal Mass Ejection* (CMA).Their flow is called the solar wind.For the process of *solar wind* flow through interplanetary space, the designation Space weather has been adopted. If a wave of the solar wind comes close to the Earth, its internal geomagnetic field - the *Earth's magnetosphere* - prevents electrically charged particles from hitting the Earth. Under the action of the Lorentz force, the electrically charged particles of the solar wind move in the direction of the magnetic field lines of the magnetosphere, bypass the Earth, deform the original symmetrical shape of the internal geomagnetic field and flow further into interplanetary space. The Earth's magnetic envelope thus shields the Earth from the solar wind, thus protecting the Earth's biosphere.Without internal geomagnetism, there would be no existing forms of life on our planet. Some of the electrically charged particles of the solar wind penetrate into the higher layers of the Earth's atmosphere, ionosphere, turn to the Earth's magnetic poles and cause ionization of the Earth's atmosphere. The movement of electrically charged particles in the ionosphere represents an electric current that induces an external magnetic field in its vicinity. The waves of the solar wind then manifest on the Earth by rapid variations of the external magnetic field.

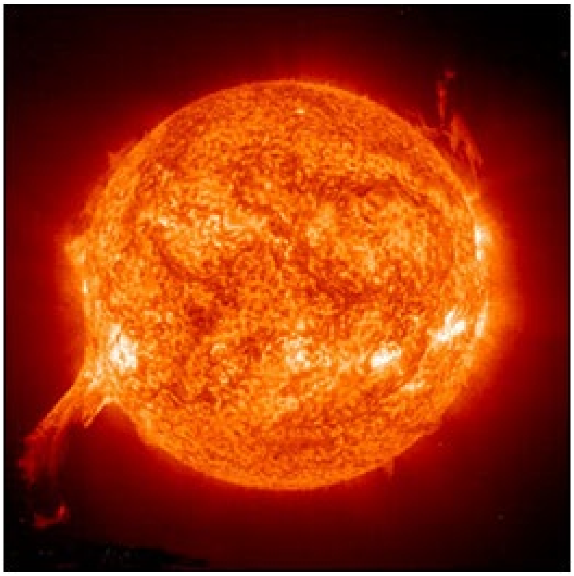

Figure 1: Eruption at the edge of the solar disk observed by the solar cosmic space probe SOHO (Solar and Heliosphere Observatory) [4].

The intensity of the external magnetic field changes in the order of seconds or tens of seconds. Their amplitude varies:from small disturbances of 20 to 30 nT and occurring several times a day, to strong variations whose amplitudes can reach up to hundreds of nT –then there is talk of a *geomagnetic storm*. It usually takes two to four days between a solar flare and a magnetic storm on Earth. The frequency and intensity of magnetic storms depends on the earth's position; they are higher near the earth's magnetic poles, ie in the Nordic countries. A geomagnetic storms cannot be influenced or even averted by human possibilities, but a few hours before it affects the Earth, its intensity can be predicted and the area on Earth affected by the storm can be determined approximately.

Geomagnetic Field Monitoring

A worldwide network of geomagnetic observatories monitors the geomagnetic field. All three components of the geomagnetic induction vector $B(B_x, B_y, B_z)$ are measured continuously here and the results are recorded, at 1 min intervals or at second intervals, respectively, with an accuracy of 0.1 nT. The results are then passed on to the *World Data Center in Boulder* (USA) and the *Edinbourgh Geomagnetic Information Node* (Scotland). The *Space Weather Prediction Center*(SWPC) publishes a three-day space weather forecast. The results are freely available on the Internet.

In addition to continuous monitoring of the geomagnetic field, solar activity is constantly monitored[3], [5]. In addition to observing solar flares with solar telescopes, these phenomena are continuously monitored by satellite (for example, SOHO and STEREO satellites) by the US *National Oceanic and Atmospheric Admin-*

istration (NOAA), *Boulder and the European Space Agency*(ESA),*Paris*. At the moment of detection of coronary matter heading to Earth, a mathematical calculation is performed at the Goddard Space Flight Center (GSCF) to determine the density at which it will hit the Earth's magnetosphere and then predict the intensity and location of the magnetic storm on Earth. This information is then passed on to the power system operators.

Geomagnetically Induced Currents (Gic)

The geomagnetic field B(t) acts on the earth's crust and on metal structures placed above the earth's surface, eg on outdoor power lines. In this environment, an electric field E is induced, and because it is an electrically conductive environment (with conductivity $\gamma \neq 0$), *Geomagnetically Induced Currents* (GIC) of density J flow through it. According to the law of electromagnetic induction and Ohm's law is valid

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

During magnetic storms, GICs reach high values and cause accidents of power transformers. From (1) it follows an important finding that the magnitude of GIC depends on the derivation of the geomagnetic induction vector $\boldsymbol{B}(t)$, *ie* on the rate of variation of the external geomagnetic field, not on its magnitude, as is often mistakenly stated.

The magnetic induction $\boldsymbol{B}(t)$ and thus also the GIC have a random time course, and although there is talk of rapid variations in the external magnetic field, it changes relatively slowly, compared to alternating electrical quantities of industrial frequency. Magnetic storms are changes in units of nT/min. Depending on the time, GICs essentially behave as direct currents, we call them quasi-stationary. Only their ohmic resistances determine the distribution of GIC in the conductors of the transmission system. Inductances and capacitances of the electrical network do not affect the GIC. In works [10], [11] a method of determining the distribution of GIC in a general transmission system is formulated, which can be topologically arbitrarily complex.

Effect of Magnetic Storm on Unprotected Transmission System

The essence of the destructive effect of a magnetic storm on the transmission system is explained using a simple single-phase model of the system according to Fig. 2. A source of harmonic voltage (generator) *u(t)* of frequency f supplies electrical power to the system a long line of vhv to the place of consumption, where vhv/lv is transformed and supplies the distribution network, from which electricity is taken by individual consumers. In Fig. 2, a load consisting of a resistor and an inductance represents the distribution network. A magnetic storm characterized by magnetic induction ***B(t)*** acts on this transmission system. Vector **B** is a superposition of the internal magnetic field (it does not change with time) and the external magnetic field (itchanges "slowly" with time, it is quasi-stationary). Only its vertical component Bz(t) is applied, ie the component perpendicular to the drawing in Fig. 2. In the loop formed by the hv line, which is connected at its beginning and end to the hv windings of the power transformers is induced (according to the law of induction) a voltage

$$V_0(t) = \frac{\mathrm{d}\Phi}{\mathrm{d}t} = S\frac{\mathrm{d}B_z}{\mathrm{d}t} \tag{2}$$

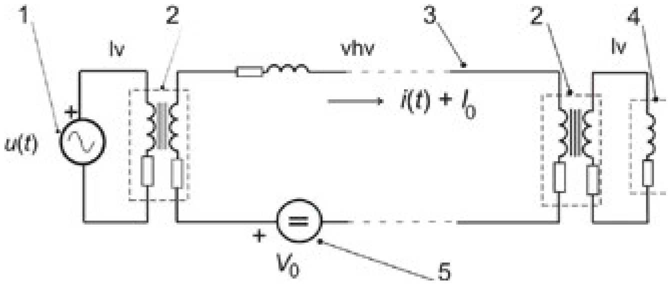

Figure 2: *Simple model of transmission systém: 1 – generator, 2 –power transformer, 3 – vhv transmission line, 4 – distribution network, 5 – source quasi-variable voltage induced by magnetic strom.*

This equation holds under the assumption that induction of the geomagnetic fieldis equally distributed along the hv line. In (2), the magnetic induction flux Φis linked with a loop whose area is $S=a\,l$, wherel is the length of the hv line and a is the distance between the conductors of the hv line.

The induced voltage V_0 in the loop results in an induced GIC I_0. The internal geomagnetic field is stationary, ie according to (2) it does not contribute to the magnitude of the induced voltage V_0 (*ie not even to GIC*I_0). In contrast, the external geomagnetic field changes over time, but "slowly" (compared to the current supplied by the generator *i(t)*, whose frequency is 50 Hz), is quasi-stationary. Only the resistances in this loop limit the magnitude of the current I_0 in the loop, formed by the vhv line and the high-voltage windings of both transformers. Measurements on real systems have shown that the induced voltage V_0 reaches in the order of up to hundreds of V during magnetic storms and the subsequent current I_0 in the vhv line up to tens of A [6], [15].

Geomagnetically induced current I_0 is superimposed to the working current *i(t)* supplied by the source, the current $I_0 + i(t)$ passes in the vhv line. Its rms value is a measure of dissipated thermal energy. (According to Joule's law, the electrical energy dissipated into thermal energy is proportional to the square of the rms current value.)This energy thermally endangers the conductors of the vhv line, but above all the high-voltage windings of both transformers. The vhv line is designed as a bundle conductors and is dimensioned in such a way that there is no risk of thermal damage. It is more complicated with transformers. Let us observe the current *i(t)* in a high voltage line.

- If there is no magnetic storm, GIC $I_0 = 0$ and both transformers operate in normal mode. The operating point moves in the linear part of their magnetization characteristic, ie below the knee of this curve. The transmission system according to Fig. 2 is linear, all currents and voltages in the circuit change harmoniously, Fig. 3a.
- During a magnetic storm, a quasi-stationary voltage V_0 is induced in the high-voltage line and a quasi-stationary GIC I_0 passes through the line. Let us observe the current flowing through the vhv line. The operating point on the magnetization curve of the transformers is shifted by the value I0, the zero position of the operating point is 0´, Fig. 3b. In the half-period, when $|i(t)| < I_0$ the operating point moves in the linear part of the magnetization curve (ie below the knee), the system is linear and current overload of the transformers does not occur. However, in the half-period, when $|i(t)| > I_0$ the operating point passes to the nonlinear part of the magnetization curve (ie at and above the knee) and the current *i(t)* supersaturates the magnetic circuits of the transformers. The permeability of magnetic circuits ($\mu = B/H$) has decreased and thus the inductance of the transformer windings will also decrease, the system is nonlinear, Fig. 4. Due to the quasi-stationary current I0, the magnetizing current curve has changed its shape, its effective value is considerably higher than when the geomagnetic field did not affect the system, ie when it was $I_0 = 0$, the high-voltage windings of both transformers become overheated. This phenomenon is called *semisaturation of magnetic circuits*. The theoretical solution [13] and the investigation of faults in practice [7] to [16] show that the current overload can range from 2.5 times to three times the nominal value.

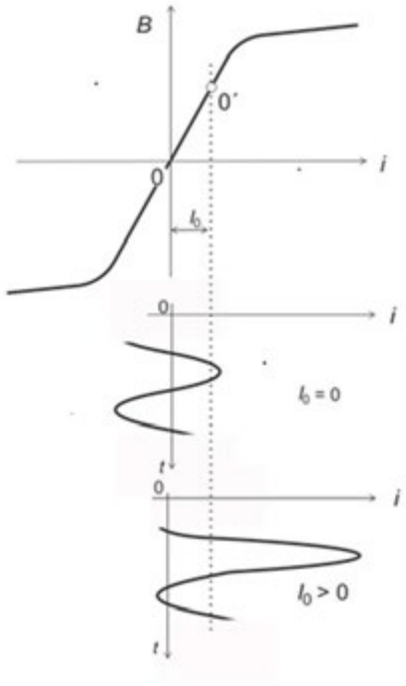

Figure 3: Influence of supersaturation of the magnetic circuit of the power transformer on the occurrence of current overload the phenomenon of semisaturation of the magnetic circuit of the power transformer: (a) – without supersaturation, (b) – with supersaturation.

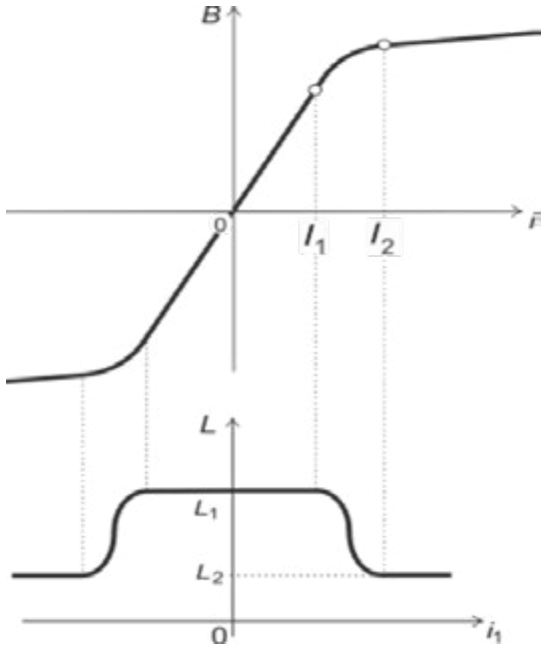

Figure 4: The course of inductance of the power transformer winding during supersaturation of its magnetic circuit.

Example. Fig. 5 shows a model of a very simple single-phase transmission system: generator –step-up transformer - vhv line – step-down transformer - distribution network. The vhv line itself represents a nonlinear circuit RL (Fig. 6), where current *i(t)* is expressed by the equation

$$R\,i + \frac{\mathrm{d}\Phi}{\mathrm{d}t} = u_0 + U_0\,, \qquad i(0) = 0$$

where for the induction flux Φ and the inductance *L* is

$$\frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left[L(i)\,i\right] = \left[i\frac{\mathrm{d}L}{\mathrm{d}t} + L(i)\right]\frac{\mathrm{d}i}{\mathrm{d}t}$$

By numerical interaction for parameters $L_1 = 0{,}03$ H, $L_2 = 0{,}002$ H, $I_1 = 25$ A, $I_2 = 60$ A, $U_0 = 500 \sin \omega t$, $\omega = 2\pi f, f = 50$ Hz,
R = 4 Ωa pro tϵ<0,38; 0,40> (we are interested in steady state only) we find: compared to the state without magnetic storm ($U_0 = 0$), due to the magnetic storm, the current overload is doubled (at $U_0 = 100$ V), resp. by three times (at $U_0 = 150$ V).

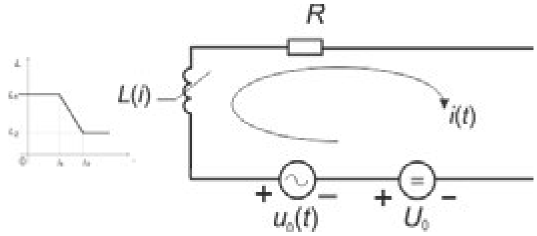

Figure 5: Simplified vhv line model.

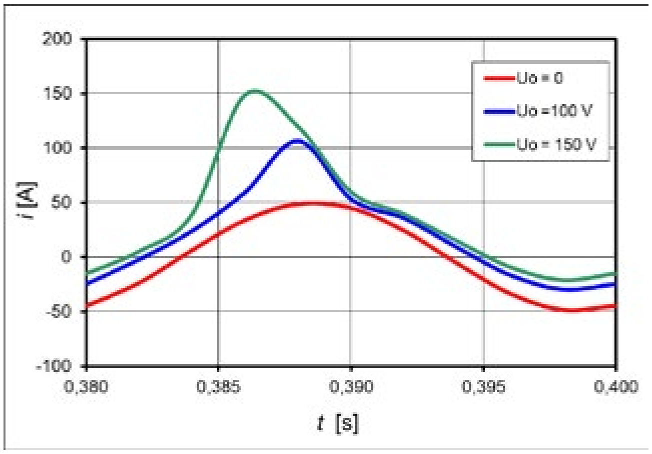

Figure 6: The Time Course of the Current at Different Degrees of Involvement of The Hv Line By A Magnetic Storm.

A New Way of Protecting Transformer Windings from Magnetic Storms

A new method of protecting the transformer windings consists in connecting a frequency filter in parallel with the high-voltage winding of both transformers during a geomagnetic storm. The frequency filter consists of a coil wound on a ferromagnetic core. It can be modeled by series connection of resistance Rf and inductance Lf, Fig. 7. The current I0 induced in the vhv line is divided into the current If passing through the frequency filter and the current It in the high-voltage winding of the transformer (Fig. 8):

$$I_f = \frac{R_t}{R_f + R_t} I_0\,, \qquad I_t = \frac{R_f}{R_f + R_t} I_0 \qquad (3)$$

All three currents are quasi-stationary, so only by resistances are limited.

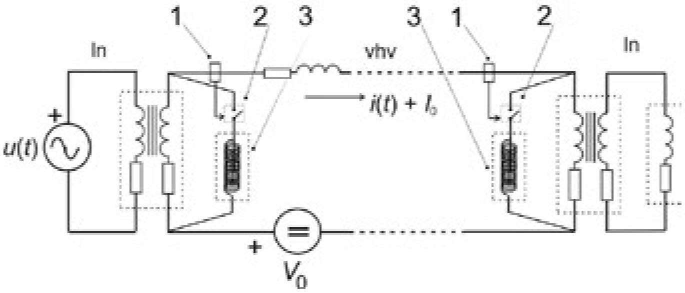

Figure 7: A simple model of a single-phase transmission system, whose power transformators are protected by superconducting reactors: 1 – indicator of the quasi-stationar current I0 (GIC) in the vhv line, 2 – a switch that connects/disconnects the superconducting reactor to the high voltage winding of the power transformer, 3 – single-phase superconducting reactor.

- A frequency filter with zero resistance($R_f \rightarrow 0$) will provide perfect protectionfor the transformer. According to (3), all currentI0 then flows through the frequency filter ($I_f = I_0$), while no GIC passes through the windings of the transformers ($I_t = 0$). Such a frequency filter can be realized by a coil (with a ferromagnetic core), made of a high-temperature superconductor, brought into a superconducting state. It is a *superconducting reactor*, which includes a cryotechnical device that produces liquid nitrogen, which cools the frequency filter coil to a critical temperature at which the coil resistance is $R_f \rightarrow 0$. The advantage of this frequency filter is perfect protection of the transformer winding, the disadvantage is the need cryotechnical equipment.

Note thatsuperconducting coils are usually used to generate extremely strong magnetic fields, using extremely high magnetizing currents. Thus, non-ferrous ("air") superconducting coils are used for strong magnetic fields. In our case, however, the superconductor of the frequency filter coil only serves to reach Rf = 0, so the coil can have a magnetic circuit made of ferromagnetic material, which is of course advantageous.

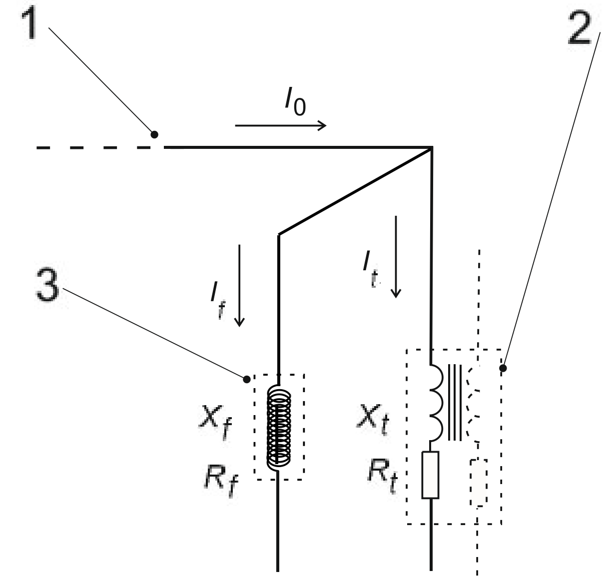

Figure 8: Distribution of the current I0 (GIC) in vhv line 1 into the current If passing through the frequency filter 3 and into the current It in the high- voltage winding of the transformer 2.

- If the coil of the frequency filter is made of a common (not superconducting) material, for example from copper, $R_f \neq 0$. The filter provides only partial protection. (For example, when $R_f = R_t$, then It = 0.5 I0.) For partial protection of the transformers, a frequency filter can be implemented with a conventional iron reactor. The sharper the inequality $R_f < R_t$, the more efficient the protection by the frequency filter, but the greater the weight and dimensions of the reactor. The advantage of this method of transformer protection is that it does not require cryotechnical equipment,the disadvantage is only partial protection. As an example, consider a frequency filter whose resistance is $R_f = R_t/4$, ie the cross-section of its coil is four times larger than the cross-section of the high voltagewinding of the transformer. Then, according to (3), a quasi-stationary current in hv winding of the transformer is $I_t = 0.2\ I_0$, ie only 20 percent of current I_0 in the hv winding of the transformer in comparison with the current in the unprotected winding. Forever, at the cost of the frequency filter having approximately four times the weight of the transformer´s hv winding. Due to the rare occurrence of magnetic storms, this solution seems uneconomical.

The connection/disconnection of the frequency filters to the transmission system can be automated. If a geomagnetic storm $B_z(t)$ acts on the system, a quasi-stationary voltage V_0 and then a current I_0 is induced in the vhv line. Its magnitude is monitored by sensor 1, Fig. 7. As soon as the current I_0 reaches a preselected (adjustable) value, it activates both switches 2 at the beginning and end of the transmission path and connects frequency filters in parallel to the high-voltage windings of both transformers. The current I0, in whole or in part (depending on the type of frequency filter), does not flow through the high-voltage windings of both transformers, but through frequency filters. As soon as the geomagnetic storm stops, the current I0 drops and the sensor 1 activates both switches 2, which disconnect both frequency filters from the transformer windings.

In addition to the quasi-stationary current I_0, an alternating current *i(t)* also flows through the frequency filters, which has an inductive character and the impedance of the filter coil determines its magnitude. If this current increases the reactive power in the system and thus reduce the power factor (cos φ) to undesirable values, it can be compensated in the usual way, *ie* by connecting a compensator in parallel, which is most often a static capacitor.

Figure 9 shows a three-phase network with transformer protection by frequency filters at the point of connection to the distribution network. The three-phase superconducting reactor in connection Y is here connected to the high-voltage winding of a step-down power three-phase transformer, connected between the high-voltage transmission line and the distribution network. The transformer winding is connected to the grounded Y-D node. Similarly, at the point of connection of the generator to the step-up transformer, a superconducting reactor is connected in parallel to the high-voltage winding of the transformer.

The essence of the new method of protection of transformers against the effects of magnetic storms was described here on an elementary models of the transmission system. However, frequency filters for complete or partial protection of transformers can be used in cooperation with transformers that are part of any topologically complex transmission system.

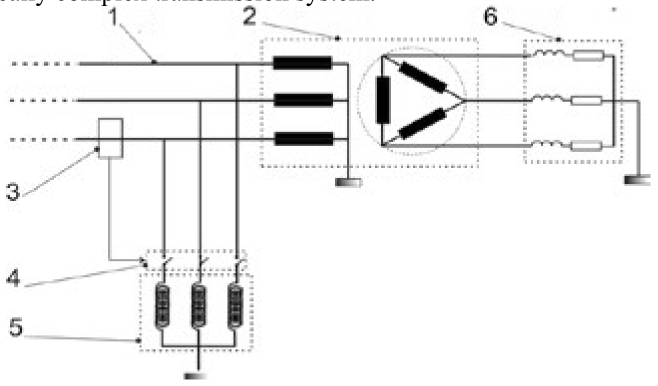

Figure 9: Connection of a three-phase superconducting reactor to the high-voltage side of a power transformer in a Y-D connection, convering electrical power into the distribution network: 1 – high voltage transmission line, 2 – three-phase step-down power transformer in Y-D connection with zero output, 3 – indicator of quasi-stationar current I0 (GIC) in high voltage transmission line, 4 –switch that connects/disconnects superconducting reactor in the transmission system, 5 –three-phase superconducting reactor in connection Y with output zero, 6 – three-phase distribution network simulated by three-phase impedance in connection Y with ground.

Indicator of Direct Action of A Magnetic Storm on The Transmission System

The danger of the Earth's magnetosphere being hit by a magnetic storm is predicted both by direct observation of the Sun's surface and by processing data from satellite networks (see Chapter 2.4). Much more accurate (and at the same time incomparably lower costs) information is provided by the described indicator. The indicator is located in the immediate vicinity of one of the vhv bundle conductors through which the current I_1 sin ωt + I_0 flows, where the current I1 sin ωt is supplied by the power plant and the quasi-stationary current I_0 is generated by a magnetic storm. The indicator measures the current I_0. It has the following parts (Fig. 10):

- The source of the indicator's energy, ie the converter of energy from the vhv conductor to the next part of the indicator. The magnetic field *B(t)* of current *i(t)* is closed by a magnetic circuit with a coil into which a voltage is induced, which is then further adjusted: rectified, stabilized and filtered.

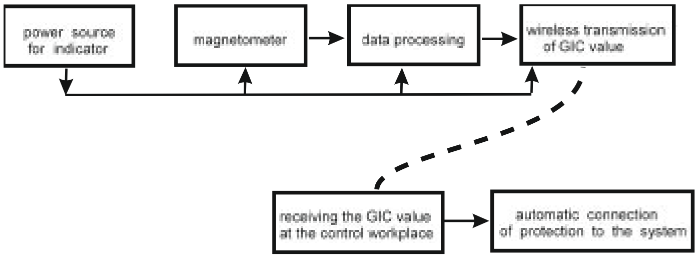

Figure 10: Indicator operation scheme.

- A magnetometer with a Hall probe, ie a magnetic field sensor B(t), which is proportional to the current I1 sin ωt + I_0.
- Circuits for data processing from a magnetometer, containing a digital low-pass filter, which suppresses the harmonic component in the current I_1 sin ωt + I_0 and passes the current $I'_0 \approx I_0$.
- Wireless transmission of current value I_0.
- Receipt of current values I_0 in the control workplace. When this current reaches a certain critical value, it automatically activates the connection of frequency filters to the transmission system.

The indicator is designed in such a way (Fig. 11) that it only "hangs" on the vhv line conductor during installation and its position is then automatically locked. Its implementation in the transmission system can be performed on the line in full operation (ie under voltage) using a drone. The indicator can be dismantled in a similar way. The indicator requires no maintenance or service, it works automatically.

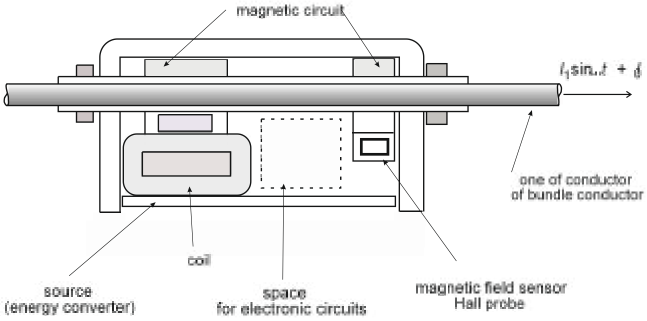

Figure 11: Longitudinal section of the indicator arrangement.

Older Proposals on How To Protect The Energy System From Magnetic Storms

The methods of protection of transformers against magnetic storms proposed so far are generally imperfect. For completeness, we will remind them here.

- Due to the predicted geomagnetic storm, a smaller or larger part of the system is switched off, which leads to a controlled collapse of the system. After the storm subsides, the system is restored to its original state. The disadvantage of this method of protection is the breach of supplier-customer relations between the provider and the consumer and, as a rule, the resulting need to compensate for economic losses caused by a power outage.
- The phenomenon of semisaturation, which is the cause of thermal overload and subsequent damage to transformers, develops only to a lesser extent in power transformers whose magnetic circuit is strongly oversized. In such robust transformers, the working area of the transformer lies in the linear part of its magnetization characteristic during DC pre-magnetization. The disadvantage is that the oversized, robust transformer is magnetically unused in normal operation. The robust transformer has more weight and dimensions, more losses in iron and more noise. Due to the rare occurrence of magnetic storms, its positive properties are used only sporadically and it is significantly uneconomical in terms of investment and operation.

Conclusion

The collapse of the electricity system is a serious technical event, which, especially in densely populated areas, can lead to huge economic losses.The presented work describes a new method of transformer protection, which uses frequency filters. Two types of frequency filters are described: filters with superconductor coils for complete protection, and filters with coils of common materials for partial protection.It is characterized by reliable exclusion, resp. limiting the occurrence of current overload of transformers, low purchase price, the possibility of easy adaptation to existing electrical systems and then automatic, unattended operation. The device is relatively simple and robust, which virtually eliminates its failure rate.

Acknowledgement

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References

1. Parker E. N (1979) Cosmical magnetic fields. Oxford, Clarendon Press.
2. Priest E (1984) Solar magnetohydrodynamics. Dordecht, D. Reidel Publia. Co.
3. Benestand R. E (2003) Solar aktivity and Earth´s climate. Berlin, Springer-Verlag, 2003.
4. https://www.abicko.cz/clanek/precti-si-priroda/3433/
5. Lanzerotti, L. J. (2001). Space weather effects on technologies. Washington DC American Geophysical Union Geophysical Monograph Series, 125, 11-22.
6. Nishiura, R., Yamashita, S., & Kano, S. (2013, July). Simulation analysis of geomagnetically-induced currents (GIC) effects on shell-form transformers. In 2013 IEEE Power & Energy Society General Meeting (pp. 1-5). IEEE.
7. Stork, M., & Mayer, D. (2019). Direct currents in power transformers. Journal of Electrical Engineering, 70(1), 69-73.
8. Patel, K. J., Patel, J. A., Mehta, R. S., Rathod, S. B., Rajput, V. N., & Pandya, K. S. (2016, March). An analytic review of geomagnetically induced current effects in power system. In 2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT) (pp. 3906-3908). IEEE.
9. Ramírez-Niño, J., Haro-Hernández, C., Rodriguez-Rodriguez, J. H., & Mijarez, R. (2016). Core saturation effects of geomagnetic induced currents in power transformers. Journal of applied research and technology, 14(2), 87-92.
10. Mayer, D. (2013). Contribution to investigation of influence of geomagnetic stroms on electrification system. Acta Technica, 58, 351-365.
11. Mayer, D. (2015). The effect of geomagnetic storms on the electrification system. Cyclonic and Geomagnetic Storms, Predicting factors, formation and enviromental impacts, Editor, Victoria P. Banks, Nova Science Publishers, Inc., New York, 1-18.
12. Bachinger, F., Hackl, A., Hamberger, P., Leikermoser, A., Leber, G., Passath, H., & Stoessl, M. (2013). Direct current in transformers: effects and compensation. e & i Elektrotechnik und Informationstechnik, 1-5.
13. Mayer, D. (2021). Protection of power transformers against the effect of magnetic storms.
14. Ramírez-Niño, J., Haro-Hernández, C., Rodriguez-Rodriguez, J. H., & Mijarez, R. (2016). Core saturation effects of geomagnetic induced currents in power transformers. Journal of applied research and technology, 14(2), 87-92.
15. Price, P. R. (2002). Geomagnetically induced current effects on transformers. IEEE transactions on power delivery, 17(4), 1002-1008.
16. Bolduc, L., Granger, M., Pare, G., Saintonge, J., & Brophy, L. (2005). Development of a DC current-blocking device for transformer neutrals. IEEE Transactions on power delivery, 20(1), 163-168.