

## Protection of Power Transformers Against Geomagnetically Induced Currents

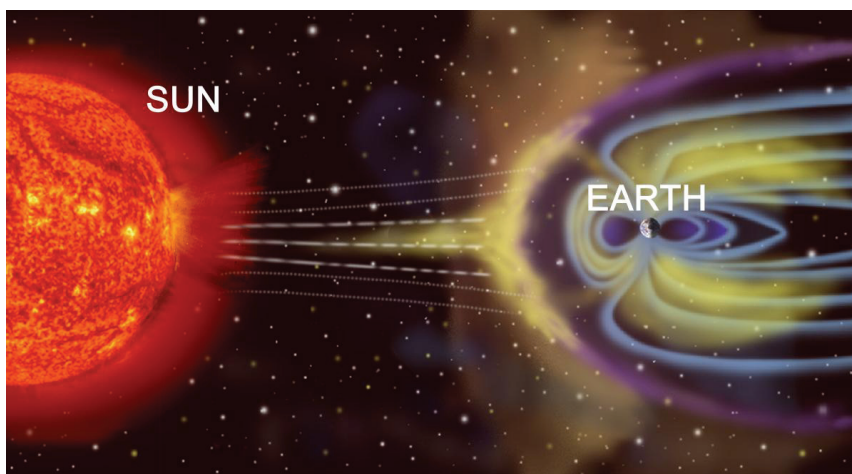
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**Abstract:** The article examines the problem of saturation and failure of power transformers under geomagnetically induced currents and currents of the E3 component of high-altitude nuclear explosions. It also describes a special protective relay reacting on DC component in the transformer neutral current.

**Keywords:** Solar storm, Magnetosphere, Geomagnetic induced current, Ionosphere, Transformer saturation, Relay protection.

### 1 Introduction

Geomagnetic induced currents are the ground currents generated by the geomagnetic disturbances in the Earth's magnetosphere. These currents are also induced in long buried metal objects, such as pipelines, railroad rails or cables. Severe disturbances in the magnetosphere of the Earth arise during solar storms and the resultant emission of huge amount of ionized plasma (the so-called "solar wind") striking the Earth, see Fig. 1.



**Fig. 1** – *The distortion of the Earth's magnetic field under the solar plasma ejection.*

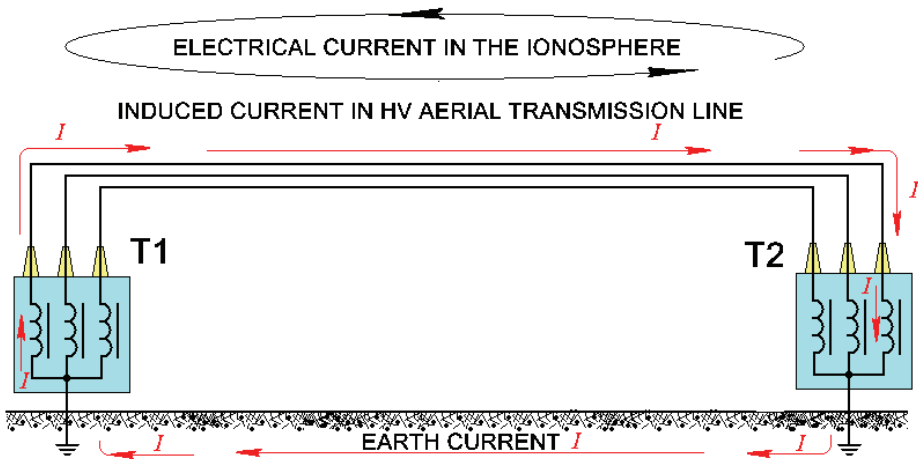
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The magnetic field of Earth and its rotation around its axis generate continuous electric currents in the Earth's ionosphere surrounding the planet a few hundreds kilometers above the Earth's surface.

The currents are maintained by the persistent generation of a large number of charged particles – ions, and free electrons radiating from the molecules of atmospheric gases broken down by solar radiation. These electrical currents have a significant influence on the Earth's magnetic field generation.

During the solar storms, extremely powerful streams of protons and electrons from the solar plasma sharply increase the electrical currents flowing in the ionosphere. Aside from the rapid changes in Earth's magnetic field, such abrupt current changes generate geomagnetically induced currents and induce high currents in long power transmission lines. These induced currents are looped through the grounded neutrals of power transformers, see Fig. 2.

Since such currents are of a very low frequency, their flow through the windings of power transformers saturates the magnetic cores of transformers and leads to the sharp decrease in transformers impedance. As is known, the constant component of the power transformer current also appears at the power transformer switching-on, so the protective relays of power transformers are usually offset from the current constant component and do not react to it.



**Fig. 2** – Diagram of currents in electric mains and ground induced by ionosphere electric currents.

In addition, a constant current (or a current of a very low frequency) is practically non-transmissible through the current transformers. Thus, the traditional protective relay will not respond to the induced currents saturating

the transformer and the transformer will just burn out. In the past there have been many cases of power transformers burnt out under the geomagnetic currents induced during solar storms. For example, in 1989 a moderate solar storm made the ultrahigh voltage power transformers inoperative and benighted the Canadian province of Quebec for 9 hours. The same storm disabled an ultrahigh voltage power transformer at the Salem nuclear power plant in New Jersey, USA. On April 29, 1994, shortly after the beginning of the impact of the solar wind, the strong geomagnetic storm completely deactivated the ultrahigh voltage power transformer at the Yankee nuclear power plant in Maine. On March 24, 1940, a major geomagnetic storm temporarily disrupted the electric power supply in some regions of states of New England, New York, Pennsylvania, Minnesota, Quebec and Ontario, and incapacitated 80% of all telephone lines in Minneapolis, Minnesota [1].

The scientists of NASA expect unusually strong solar storms in 2012 (or in 2013 according to some forecasts). According to these forecasts [1] strong magnetic storms causing failures of the power systems all over the world are expected in coming years. Such failures could last from several hours to several months (due to a lack of backup power transformers in many power systems). It can result in major collapse for the humanity since we are too dependent on modern technologies and too vulnerable to disasters of this kind.

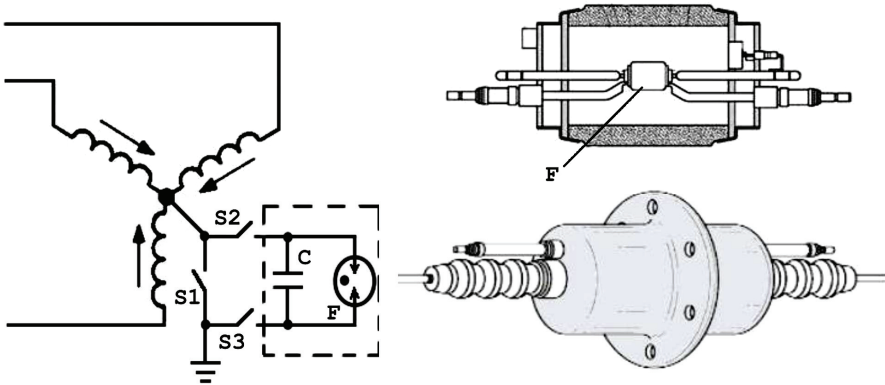
The E3 component of high-altitude nuclear explosion [2, 3] has a similar physical affect on power transformers and is considered by the militaries of many countries as the so-called "non-lethal weapon" aimed at destroying the infrastructure rather than killing people which makes it particularly attractive.

## **2 Power Transformer Protection**

The power transformers differ from the electronic devices, also exposed to damage under such impacts, in their impossibility of quick change in case of failure [4, 5, 6]. In the context of the foregoing, it becomes clear that it is important to protect power transformers against damage under geomagnetically induced currents of low frequency.

One of the solutions proposed by Western scientists is to include a current limiting capacitance (i.e., powerful capacitor) in the transformer's neutral. Elements of this type transmit alternating current of the mains' frequency (generated by asymmetry of the phase current) under normal operation but block the flow of the low-frequency geomagnetically induced currents. Some Western sources even give the cost of such current limiting elements (it is about 40,000 USD) and comment that presently the Congress is considering the question of investing 150 million USD in the installation of such elements on the most important power transformers. The major problem of this solution is

the generation of the extremely high voltages on such elements under short-circuits in the mains (we are speaking of power transformers of 110 kV and higher).



**Fig. 3** – Protection of the power transformer against the low-frequency induced currents based on the power elements included in the neutral, proposed by Western specialists [7].

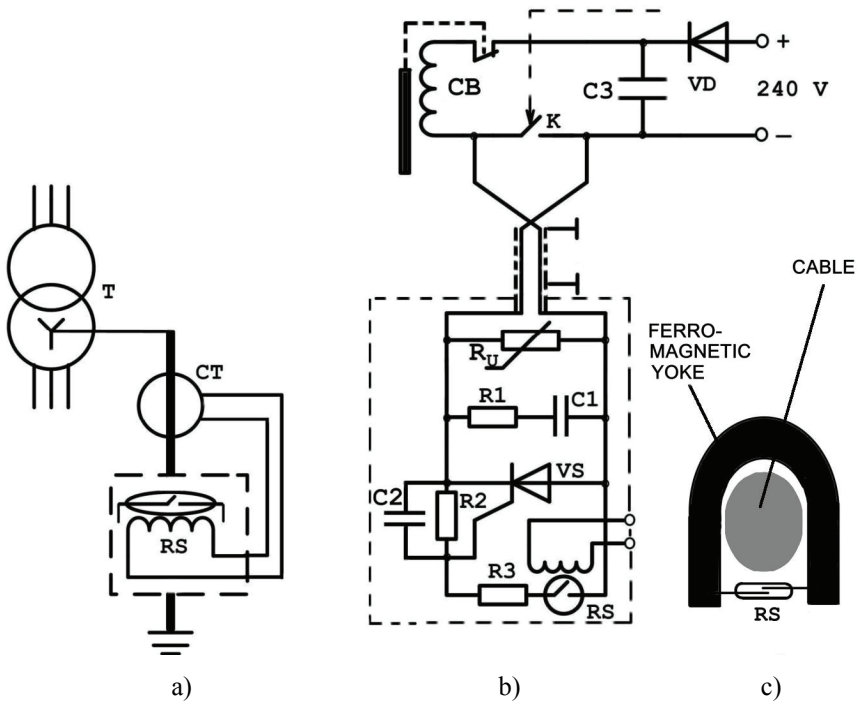
### 3 High Power Protective Installation

To solve the problem the [7] proposes using special super high-power cold cathode electron tubes, short-circuiting the capacitor under voltage buildup and allowing the short-circuit currents of dozens of kA, see Fig. 3.

The installation of a powerful capacitor with super high power electron tube (type 4275 Bi-Tron™, 30 kV, up to 75 kA) also requires using additional switching devices S1, S2, S3, needed to connect the unit to or disconnect it from the neutral of the power transformer. Generally, it appears to be a quite massive and very expensive device which will unlikely be widely used due to its high cost.

### 4 Special Protective Relay

We, on the other hand, propose another type of the protection of high-power transformers against the low-frequency geomagnetically induced currents using a special relay containing no microelectronic components and based on discrete high-voltage elements [8] resistant to electromagnetic interferences and surge overvoltage, see Fig. 4.



**Fig. 4** – Relay protecting the power transformer against the low-frequency geomagnetically induced currents in the neutral circuit.

Fig. 4a shows the operational principle of the relay sensitive to the DC component in the power transformer neutral and insensitive to the widely varying AC component.

The relay consists of a reed switch, RS, with a coil placed on the cable (bus) that connects the transformer neutral to the grounding point perpendicular to the axis of the cable, and a conventional toroidal current transformer, CT, installed on the same cable.

If there is no DC current in the neutral the magnetic field of the cable (bus) acting directly on the reed switch, this is fully compensated by the magnetic field of the coil put on the reed switch and powered by the current transformer. AC current changes in the neutral lead proportionally to the changes in both magnetic fields acting on the reed switch, and to their compensation. Under high DC currents in the neutral (over 10–20A), the balance of the magnetic fields acting on the reed switch is offset: the magnetic field of the cable (bus) still acts while the compensating magnetic field of the coil energized by the

current transformer is disabled as the DC component of the current is not transformed by the current transformer. This leads to reed switch activation. The real relay circuit includes an additional output amplifier installed on VS thyristor, varistor  $R_U$  and the R1C1 all protecting the thyristor from interferences and voltage surges, see Fig. 4b. The relay is equipped with a continuous electrostatic shield and a ferromagnetic shield with the only window on the cable side next to the reed switch and is connected to the circuit of the CB switch trip coil through a special twisted-pair control cable with the combined multi-layer shielding grounded at both ends [4, 5, 6] and resistant to the electromagnetic pulses [2, 3]. The relay can be constructed on miniature high-voltage vacuum reed switches, for example, of type KSK-1A85 (manufactured by Meder Electronics), with the electric strength of insulation between the contacts of 4000V and the bulb having a diameter of 2.75 mm and length of 21 mm. This reed switch is capable of switching loads up to 100W (the maximum switching voltage is 1000V, the maximum switching current is 1A) with the response time of 1 ms and a maximum sensitivity of 20A. Additional ferromagnetic elements (magnetic field concentrators) located next to the reed switch can be used to increase the sensitivity. To get a relay with lower sensitivity and a higher pickup, the longitudinal axis of the reed switch should form a non-perpendicular angle to the axis of the cable on which it is installed.

The thyristor should also be miniature and of high-voltage, e.g., of type SKT50/18E (manufactured by Semicron), with a maximum voltage of 1800V and maximum continuous current of 75A, and must withstand high rates of voltage rise (1000V/ $\mu$ s) under a wide operating temperature range (-40, +130°C). The power circuit of the trip coil is equipped with storage capacitor C3 enabling switch activation even under the loss of operating voltage. The R2C2 in series is designed to further enhance the immunity of the device. Capacitor C2 provides a certain delay of the thyristor switch-on, preventing it from unlocking under the powerful impulse noise.

Application of the discrete high-voltage components instead of conventional microelectronics in the relay ensures its high reliability under powerful electromagnetic interferences and surge voltages specific to solar storms and electromagnetic pulses.

The purpose of this article was to identify the problem and present a simple solution. For this end we have described a relay design to demonstrate its general concept only. It is obvious that the described device can be supplemented by signal relay (blinker) registering the response, time delay device, reed switch sensitivity control unit, reinforced insulation [9], etc. We believe that the proposed solution is more than adequate and far cheaper to implement than other proposed solutions.

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