

High altitude electromagnetic pulse: Power transformers also need to be protected



ABSTRACT

This article addresses the issue of geomagnetically induced currents (GIC) produced by electromagnetic pulse at a high-altitude nuclear explosion (HEMP) and its influence on power transformers. The article contains a description of the set of devices developed by the author that consists of a reliable electronic protective relay and a portable tester for its periodical testing, which are meant to resolve the problem. These devices, based on a standard electronic component, are suitable for mass production and can be widely used in power grids.

KEYWORDS:

HEMP, electromagnetic pulse, geomagnetically induced currents, GIC, power transformer

The protection of a power system’s electrical equipment against the impact of electromagnetic pulses produced by high-altitude (30 – 400 km) nuclear explosions (HEMP) is a challenging issue

Introduction

The protection of a power system’s electrical equipment against the impact

of electromagnetic pulses produced by high-altitude (30 – 400 km) nuclear explosions (HEMP) is a challenging issue,

which until recently has not received proper attention. More precisely, attention was paid only to theoretical issues, as well as to the discussion in public media of the dangers and consequences of the impact of HEMP on the electrical power system (especially in the United States), while in practice, all electrical power systems in the world remain unprotected. Why? Because for decades there has been an erroneous paradigm that in order to protect civilian critical infrastructure, it is necessary to use well-known and commercially available

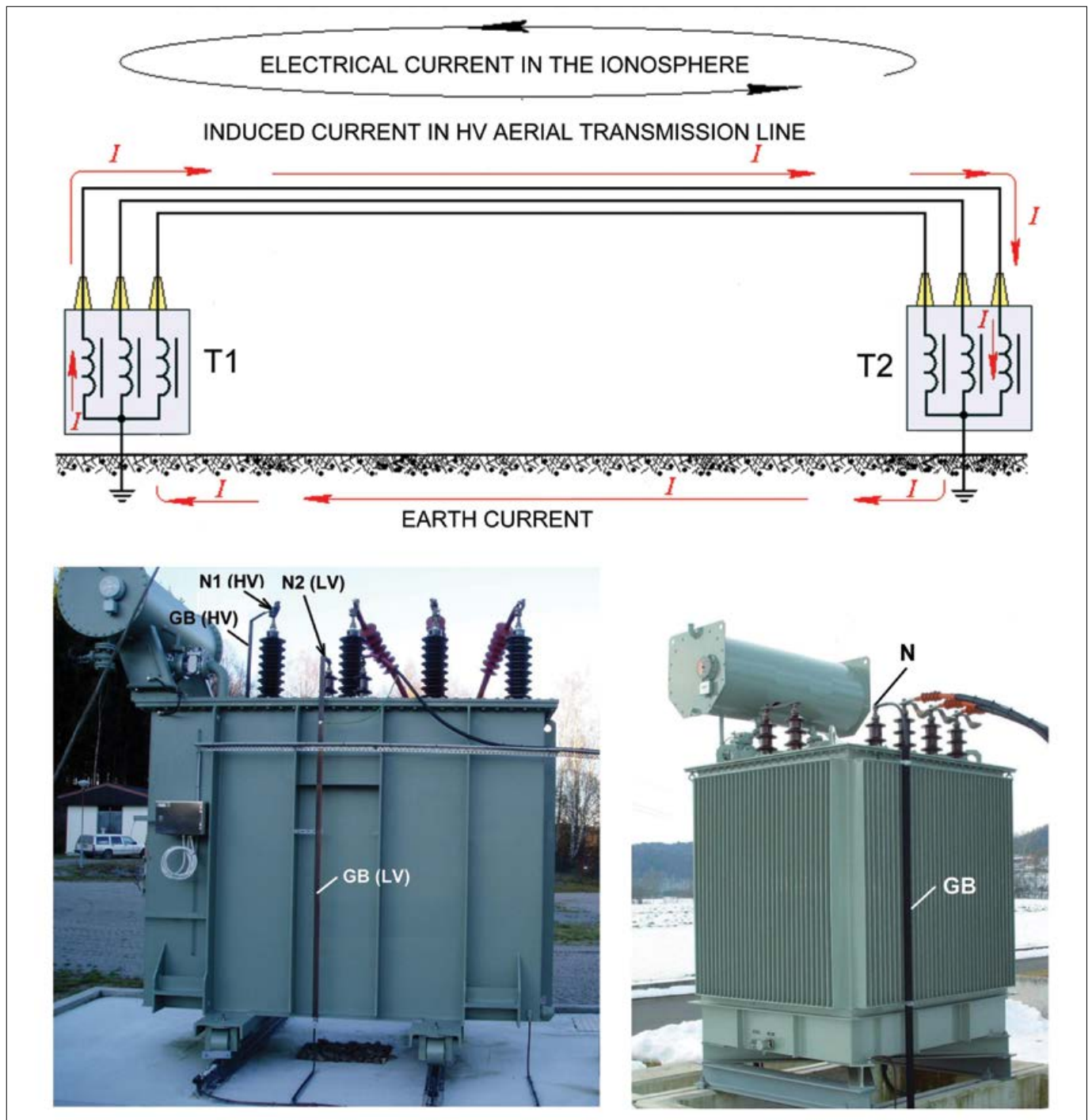


Figure 1. Geomagnetically induced currents (GIC) passing through neutral conductors (grounding bus – GB) of power transformers T1 and T2

means of protection designed to protect military equipment [1].

The fact is that HEMP does not affect people directly, but it is a powerful, devastating factor for the power grid's electronic and power supply equipment.

Geomagnetically induced quasi-DC currents (GIC) with an amplitude of dozens and hundreds of Amps may pass through neutral conductors of power transformers.



Figure 2a. Transportation of a high-power transformer



Figure 2b. Transportation of a high-power transformer

The SolidGround™ device promoted by ABB is meant for blocking GIC in neutral conductors of power transformers

Since the electrical power industry is the foundation of any country's infrastructure, such a feature of HEMP is very attractive for the military [2].

HEMP is known to consist of three components: E1, E2, and E3. These are significantly different from each other in terms of their properties and specifications, due to a full set of complex physical effects occurring in the ionosphere upon nuclear explosion. For example, while the E1 component represents a short single pulse (2.5/25 ns) creating very high electrical field strength at the ground surface (50 kV/m), the E3 component is inversely a very slow oscillating process with a frequency of less than 0.1 Hz and low electrical field strength (up to 85 V/km) [3], which lasts several minutes. The E2 component is very similar to

lightning in terms of its impact, and thus protection of this equipment has been envisaged.

This article discusses the protection of the electrical grid's power transformers from HEMP's E3 component.

E3's impact on electrical power equipment

It may seem that the issue of protection from slow electromagnetic oscillations with such a low electrical field strength as 85 Volts per kilometer is exaggerated. Nevertheless, this is true at the first glance only. Indeed, these electromagnetic oscillations are induced in many kilometer-long *overhead power transmission lines* and closed through a very low impedance loop, e.g., a grounding

system (Fig. 1). As a result, geomagnetically induced quasi-DC currents (GIC) with an amplitude of dozens and hundreds of Amps may pass through neutral conductors of power transformers. This leads to quick saturation of the transformer's core and consequently reduction of its impedance. Concurrently, operational current flowing through its windings will increase, resulting in the transformer's excessive heating. A similar impact of geomagnetically induced currents caused by solar storms in the Northern Hemisphere (Canada and the USA) resulted in coils blowing on powerful power transformers that cost several million dollars. Apart from the high cost of such transformers, other problems would include long-term manufacturing of such equipment and complicated transportation of it to the point of use, Fig. 2.

That is why the malfunction of such transformers represents an emergency situation for power systems, requiring costly efforts to prevent them in the future.



Figure 3. SolidGround™ [4] by ABB (left) is meant for blocking GIC in a neutral conductor of a power transformer (right)

The SolidGround™ device promoted by ABB is meant for blocking GIC in neutral conductors of power transformers (Fig. 3).

Fig. 3 shows that this device is an expensive (more than USD 300,000 in 2012 [5]) high-voltage unit, which requires ample space to be mounted at a substation site. Initially, this device was developed to block GIC during severe solar storms, which may last for many hours. Later on, it was promoted as a main remedy to block the E3 component of HEMP [4, 6] (which lasts several minutes only!). However, this difference has never been mentioned in technical literature (except for books and articles by the author). Alternatively, the developers (in order to promote this expensive piece of equipment) suggest that there is almost no difference between a solar storm's GIC and that induced by HEMP, e.g. [7]:

"... mitigation options against GIC in power systems are also suitable for mitigation against nuclear EMP E3 events".

"The 2008 EMP commission report states, "steps taken to mitigate the E3 threat also would simultaneously mitigate this threat from the natural environment".

"An EMP model of the SolidGround™ neutral blocking device (NBD) which is capable of protection against higher EMP E3 levels ... has been designed, tested, and is available".

Field strength of the E3 component: 85 V/km is a value close to maximum, which depends on multiple external factors (geographical location of transformers and overhead power transmission lines, grounding system resistance, soil properties, design of the transformers' core, etc.), and thus GIC in the transformer's neutral conductor will not necessarily be equal to hundreds of Amperes. With the current of several dozen Amperes passing through, several minutes are not sufficient for a very big power transformer containing tons of steel, copper, and oil to heat up to dangerous temperatures (although such currents are quite sufficient to dangerously heat smaller transformers, Fig. 4).

Does it mean that the problem does not exist and that we can neglect GIC occurring as affected by the E3 component in

Field strength of the E3 component: 85 V/km is a value close to maximum, which depends on multiple external factors, and thus GIC in the transformer's neutral conductor will not necessarily be equal to hundreds of Amperes

most cases? This conclusion was made by the authors of the renowned Electrical Power Research Institute (EPRI) [8]. Nevertheless, it should be admitted that the conclusion of EPRI regarding HEMP impact on the power grid's electrical equipment faced severe criticism from corresponding experts, Fig. 5.

1. <https://www.newsmax.com/peterpry/epri-grid-nuclear-scadas/2019/05/01/id/914108/> by Peter Pry, May 01, 2019, Newsmax
2. <https://securethegrid.com/epri-emp-report-selling-snake-oil-to-america/> by Michael Mabee, April 29, 2019, Secure the Grid

3. <https://securethegrid.com/epri-emp-study-frank-gaffney-and-michael-mabee-break-it-down/>

By Frank Gaffney, May 3, 2019, Secure the Grid

Yet, the feasibility of significant investments into HEMP protection of power transformers still needs to be addressed. It should be kept in mind that; (i) the probability of high-amplitude GIC occurrence still exists (under specific combination of external parameters and conditions); and (ii) a power transformer with a saturated core acts as a powerful source of harmonics generated into the power system (Fig. 6). These harmonics

The feasibility of significant investments into HEMP protection of power transformers still needs to be addressed

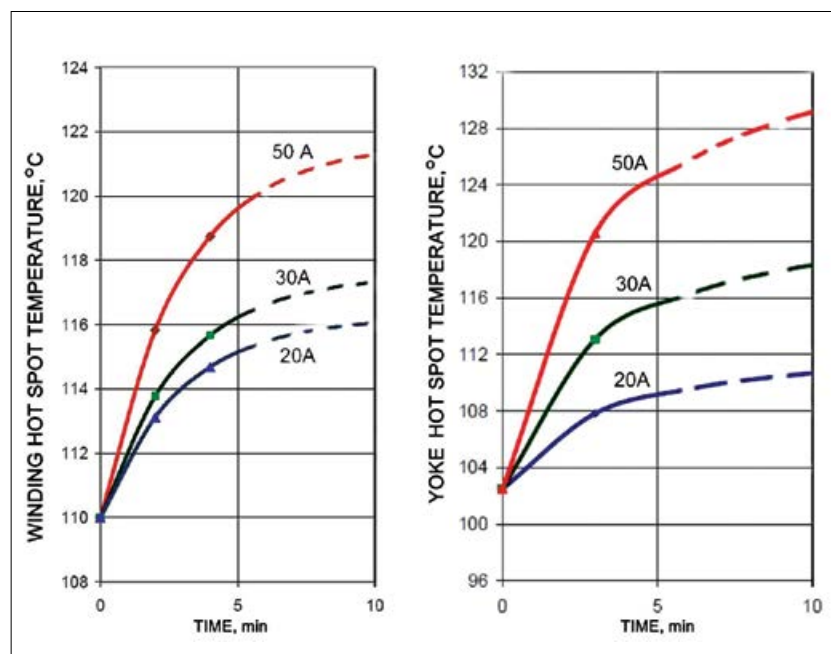


Figure 4. Examples of the power transformer's winding and core heating when 20, 30, and 50 A geomagnetic current flows through its neutral conductor, published in the technical literature

The idea is to perform a short-term automatic disconnection of the power transformer (achieved by HEMP-protected relay upon sensing GIC in the neutral conductor) with automatic return to operation after a several-minute pause

can negatively affect many types of electrical equipment in the power system, e.g., capacitor banks of longitudinal and transverse capacitive compensation, relay protection devices, etc.

While the first harmonic delivers active power, other harmonics demand extra current and heighten reactive power needs, i.e., harmonic currents increase reactive power demand, reducing avail-

able system capacity. Therefore, another issue is a sharp loss of available reactive power in the grid upon GIC impact on power transformers and a further sharp reduction of voltage. As a result, the power system's stability is compromised, potentially leading to its collapse. Yes, of course, the time it takes for this powerful set of harmonics to be generated into the electrical grid is only a few minutes upon GIC impact. But these minutes are quite

enough to cause instability of the power system and incorrect tripping of numerous protective relays that control (through the appropriate switching devices, of course) the configuration of the electrical grid with all the ensuing consequences.

It is very difficult to predict or assess the behavior of the specific power grid upon E3 impact. However, it is worth taking preventive measures when considering the possible damage. What are these measures? Are there any other solutions apart from extremely expensive and bulky installations to limit the DC component of the current in the neutral of a power transformer?

Suggested solution for the problem

The solution of the above-mentioned problem (protection of the power grid's

1 Institute's 'Junk Science' Report Misses on EMP Threat

2 EPRI EMP Report: Selling Snake Oil to America
© April 25, 2019 Secure the Grid
EPRI | ELECTRIC POWER RESEARCH INSTITUTE
 OLDE TYME SNAKE OIL

3 EPRI EMP Study: Frank Gaffney and Michael Mabee Break It Down
© May 3, 2019 Secure the Grid

The EPRI EMP Study is being billed in the press as an "independent" scientific study. However, it is not. Listen to the experts break this scam down
 EPRI is misleading the press and the nation on the danger to the U.S. Electric Grid

Figure 5. Harsh headlines of some critical publications regarding EPRI report in the US media.

electrical equipment from the E3 component of HEMP) is based on the difference between GIC occurring during solar storms and GIC occurring during high-altitude nuclear explosions. I offered this solution back in 2011 [11, 12]. The idea behind it involves a short-term automatic disconnection of the power transformer (achieved by HEMP-protected relay upon sensing GIC in the neutral conductor) with further automatic return to operation after a several-minute pause (i.e., when the E3 impact is over). I described this principle several times in various articles and books.

So, on the basis of my idea published 15 years ago, I developed an electronic relay for the transformer's protection, suitable for large-scale use and to be conveniently implemented in power systems. This protection relay includes the GIC sensor designed as a portable split-core current transformer to be put on the cable (without disconnection, of course), grounding the transformer neutral and a special electronic relay, which responds to a signal from the GIC sensor, Fig. 7. The equipment also includes a tester for periodical testing of protection relay serviceability directly

A high-altitude nuclear explosion will generate a direct current component (E3 component) in the cable, which produces voltage at the sensor output proportionate to that current at the GIC sensor's input

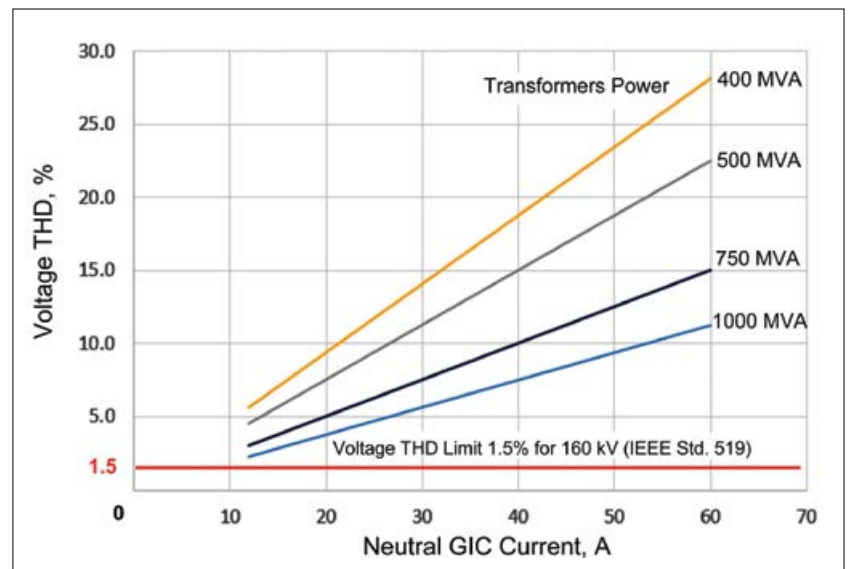


Figure 6. Total harmonic distortion (THD) generated by a transformer into a high-voltage circuit as a function of GIC value in the neutral conductor [9]. The maximum permissible value of THD for 160 kV overhead power transmission lines is 1.5% [10]



Figure 7. GIC protective relay for high-power transformers with grounded neutral

The disconnection and subsequent connection of a powerful transformer to the electrical network after a 2 - 3 minutes is always accompanied by corresponding transient processes that negatively affect the network

at the installation point by means of GIC simulation, Fig. 8.

Under the normal mode of the power grid's operation, it is only the alternating current that can pass through the cable, grounding the neutral of the power transformer's coil "wye" connected. A high-altitude nuclear explosion will generate a direct current component (E3 component) in the cable, which produces voltage at the sensor output proportionate to that current at the GIC sensor's input. If the current value exceeds 20 - 25A, the output voltage from the sensor will activate an electronic relay that energizes the trip coil of the high-voltage circuit breaker through the substation's auxiliary relay to disconnect the transformer. Of course, the threshold of the device can be adjusted within a wide range. However, we deliberately excluded the adjusting element (variable resistor)

from it and use only a constant resistor, which we can change at the request of the customer. This is done to increase the reliability of the device, since a variable resistor is always an element of reduced reliability compared to a constant unregulated resistor. It should be noted that all critical components in this device are duplicated in order to increase reliability. After all, one false alarm of this device and the shutdown of a powerful transformer is enough to cause extreme distrust in this device and to refuse to use it at all. After all, unlike standard protection relays, without which the transformer cannot be operated, this device is not at all mandatory for use.

Several minutes later (i.e., when the impact of the E3 component is over), the automatic reclosing system on the substation will return the transformer back to the operating mode. The same system

performs a short-term interruption of the power supply of the GIC protective relay through an auxiliary timer. This short-term power supply interruption is enough for the GIC protective relay to return to the initial condition, i.e., into a stand-by mode.

Of course, the disconnection and subsequent connection of a powerful transformer to the electrical network after a 2 - 3 minutes is always accompanied by corresponding transient processes that negatively affect the network. However, in this case, it should be borne in mind that the developed device will turn off the transformer only in one single emergency: a high-altitude nuclear explosion, and in this exceptional case, in an emergency, it is much better to turn off a transformer worth millions of dollars with a transient process occurring, than to allow it to be damaged without

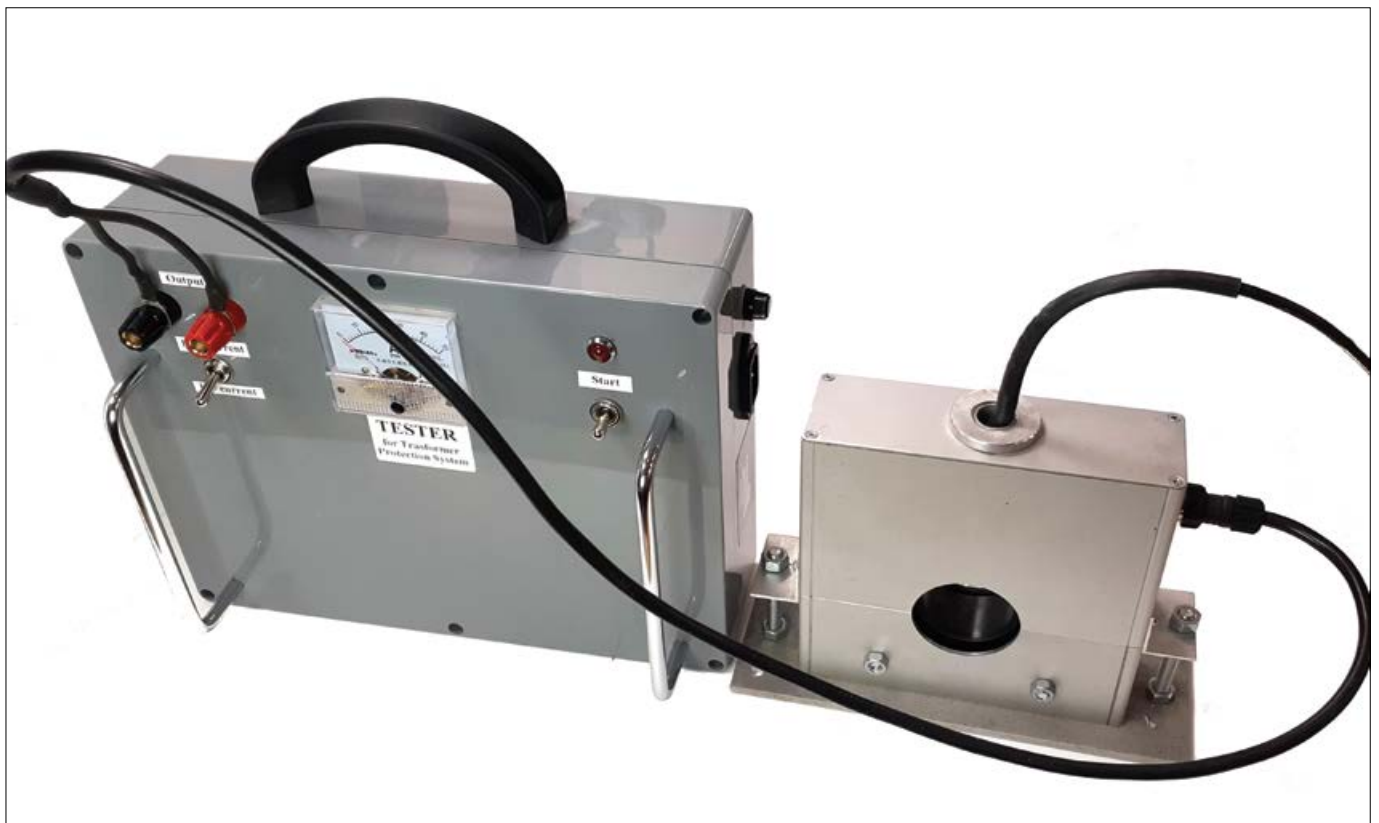


Figure 8. Portable tester for testing the GIC protective relay serviceability, designed and constructed by the author

the occurrence of a transient in the network.

The electronic relay is placed into a sealed aluminum container, which ensures the circuit's protection from the E1 component of HEMP. The sensor is also placed into a similar shielding container. The circuit is then connected to external circuits by means of a shielded cable. Inputs and outputs of the relay are protected by highly effective surge suppressors. The relay power supply circuit is protected by an additional high-efficiency electromagnetic filter.

This protective relay was installed in a pilot operation on a 161/22 kV transformer 5 years ago and is still in operation today and has been constantly connected to the main dispatch system of the energy system to check the absence of false trips. Every 6 months, the relay was activated using a tester to check its readiness to actuate when exposed to GIS. Over the past 5 years, this relay has never given an erroneous signal or failed to trip.

If the device for limiting direct current in the transformer neutral circuit only reduces the degree of influence of GIC on the transformer and on the power system, then the relay developed by us and described above completely eliminates the effect of GIC.

This relay is small in size and is installed directly on the wall of the transformer compartment or in a separate small cabinet on the rack. The cost of the entire set is about USD 5,000, or one and a half hundred times less than the cost of installation to limit the DC current in the neutral of the transformer.

Conclusion

The set of compact and not expensive devices described above solves the problem of protecting a power transformer (a major element of an electrical power supply system) against HEMP and from the consequences of its impact on the power grid altogether. These device designs are very simple, inexpensive, and suitable for mass production. With this set of equipment, the issue of HEMP's impact on a power supply transformer can be deemed completely resolved.

References

- [1] Gurevich V. EMP Protection of Critical Civilian Infrastructure. Problems and Solutions. – Lambert Academic Publishing, London, 2023, 216 p.
- [2] Gurevich V. Protecting Electrical Equipment: Good Practices for Preventing High Altitude Electromagnetic Pulse Impacts. – De Gruyter, Berlin, 2019. – 386 p.
- [3] Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures. – Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, 2017.
- [4] SolidGround™ neutral blocker is the most effective and economical solution to protect the electric power grid from stray DC, Solar Storms (GMD) and Nuclear EMP E3 - <http://www.emprimus.com/solidground>
- [5] Power World Grid Modeling with GIC and Neutral Blocking. - Presentation to 2013 Power World Client Conference January 22, 2013.
- [6] SolidGround™ Grid Stability System Geomagnetic Storm Induced Currents (GIC) and Electromagnetic Pulse (EMP) E3 Protection. - ABB Inc. High Voltage Products, 2012.
- [7] Faxvog F.R., Fuchs G., Jensen W., et al. HV Power Transformer Neutral Blocking Device (NBD) Operating Experience in Wisconsin. – 53-rd Annual Minnesota Power System Conference (MINPSYCON), University of the Minnesota, November 7 – 9, 2017.
- [8] Magneto-hydrodynamic Electromagnetic Pulse Assessment of the Continental U. S. Electric Grid. - Report EPRI No. 3002009001, February 2017.
- [9] Analysis of Geomagnetic Disturbance (GMD) Related Harmonics. – Report EPRI No. 3002002985, March 2014.
- [10] IEEE Std. 519 - 2014. IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, 2014.
- [11] Gurevich V. The Power Transformers are Also Affected by the Sun - Electrical Market, 2011, No. 5, pp. 48 – 51.
- [12] Gurevich V. Protection of Power Transformers Against Geomagnetically Induced Currents. – Serbian Journal of Electrical Engineering, 2011, Vol. 8, No. 2, pp. 333 – 339.



Author



Vladimir I. Gurevich was born in Kharkov, Ukraine, in 1956. He received an M.S.E.E. degree (1978) at the Kharkov Technical University, named after P. Vasilenko, and a Ph.D. degree (1986) at Kharkov National Polytechnic University. His employment experience includes: teacher, assistant professor and associate professor at Kharkov Technical University, and chief engineer and director of Inventor, Ltd. In the former USSR, before its collapse, he participated in many projects in the defense industry of the USSR. In 1994, he arrived in Israel and worked during 22 years at Israel Electric Corp. as a Senior specialist and Head of section of the Central Electric Laboratory. Now Dr. V. Gurevich is owner and CEO of "Industrial EMP Solutions" consulting company. He is the author of more than 200 professional papers and 16 books and holder of nearly 120 patents in the field of electrical engineering, power electronics, EMP protection of critical civilian infrastructures.