The Effect of Geomagnetic Disturbances on the Electric Grid and Appropriate Mitigation Strategies

Trevor R. Hutchins and Thomas J. Overbye
Department of Electrical and Computer Engineering
University of Illinois – Urbana-Champaign
Urbana, IL, 61801-2918
Email: {hutchns2, overbye} AT illinois DOT edu

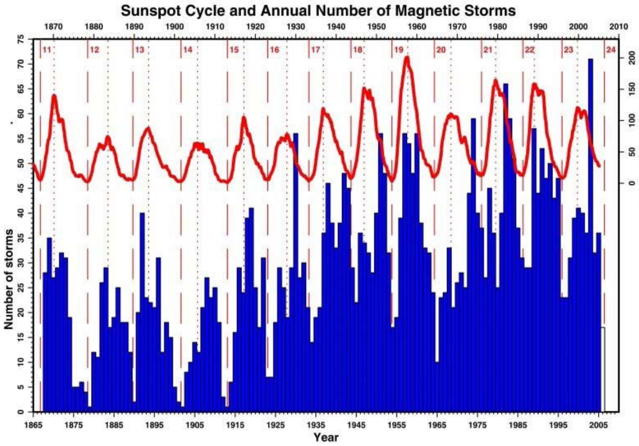
***Abstract*— Geomagnetic induced currents (GICs) generated by space weather, such as solar storms, currently pose a threat to North American electric grids. GICs enter the power grid through the neutral connection of high voltage transformers causing unusual megawatt and megavar flows, voltage fluctuation, frequency shifts, undesired relay operations, high third harmonic currents, and telemetry and supervisory alarm failures in the power grid. A storm on the order of 5000 nT/min is believed to occur in the not too distant future. Once this storm occurs, widespread damage to the power grid of unprecedented proportions will take place. Mitigation strategies must be considered. Systems involved in restoration and reinstitution of the power grid need to be prioritized, and the effectiveness of existing black-start procedures need to be evaluated. This paper explores the effects of GICs on high voltage power transformers and presents a 37-bus critical infrastructure case. In the event of a geomagnetic disturbance, it is not plausible to protect all the high voltage transformers in the power grid, but by protecting critical transformers, and bypassing others, the grid's integrity can be maintained.**

I. INTRODUCTION

High impact low frequency (HILF) events currently pose a threat to the United States electric grid. Two HILF events of popular discussion include high-altitude electromagnetic pulse detonation (HEMP) and geomagnetic disturbances due to space weather. This paper concentrates on the effect of geomagnetic disturbances on the electric grid.

A. Background

The geomagnetic disturbances of concern are solar storms, or solar flares. Associated with solar flares are coronal mass ejections. The ejection is plasma consisting mainly of protons and neutrons. The Earth's magnetic field captures the charged particles approximately 20-40 hours after a flare occurs [1]. A violent change in the Earth's magnetic field results from the capture of the energized solar plasma. The magnetic field of the Earth changes over a time period of approximately 5 minutes when it is disturbed by a solar event. Auroral currents are induced in the atmosphere due to the changing magnetic field. An opposing dc current is then induced in the ground of approximately 100A in the severe case [1]. The current is said to be dc when compared to the electric grid's 60 Hz waveforms. The intensity of the geomagnetic induced currents (GICs) depends on the intensity of the solar flare. The more intense the flare is, the larger the GICs are because there is a larger change in the Earth's magnetic field. The sun goes through 11 year solar cycles. Historically, the end of the cycle is more violent than the beginning of the cycle. The current solar cycle is 24, ending in 2012-2013. The number of storms per year has also been increasing, as seen in Fig. 1.



Graph taken from Fig. 9 of [2]

Figure 1. The annual number of magnetic storms is represented by each bar of the histogram. Superimposed is the smoothed sunspot number. The dashed lines indicate solar minima; the dotted lines indicate solar maxima [2].

The histogram, of Fig. 1, represents the number of magnetic storms per year. The trend, between solar cycles, is the magnetic activity increases over time. Also, note the correlation of magnetic activity with solar activity. The magnetic and solar activity experience maximums every 11 years, in accordance with the 11 year solar cycle.

The scale used to categorize the intensity of geomagnetic storms is the K-Index. Geomagnetic disturbances are measured with the units of nT/min. The K-Index is severely outdated. It was created in 1932 using the instrumentation for detecting geomagnetic storms of that era [3]. The index ranges

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from zero to nine, zero being the minimal geomagnetic disturbance. The K-Index suffers from insufficiencies, which are discussed later in this paper.

Geographically, the regions of North America that are at the most risk to geomagnetic disturbance are Canada and the Northeast United States. Not only are these regions close to the poles of Earth's magnetic field, the regions' soils are very rocky, i.e. they suffer from high resistivity. The GICs will seek an easier path than the rocky soil, e.g. electric grid neutral connections.

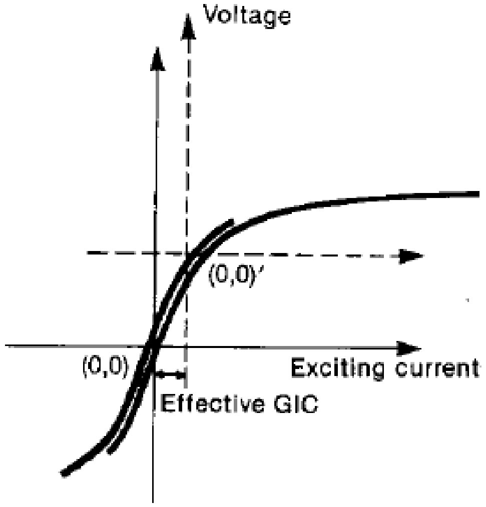
II. EFFECTS OF GROUND INDUCED CURRENTS

A. How Ground Induced Currents Enter the Electric Grid

The easiest point of entry for GICs into the electric grid is through the neutral wire of wye connected power transformers. These wires are dug into the rocky soil. These low resistivity wires are the path of least resistance for the GICs. The high voltage neutral connections are of even easier entry for GICs since their resistivity is less than that of the lower voltage transmission lines (approximately 10 times lower). Coincidentally, the higher voltage transformers are damaged easier by excess current flow. The transformers' combination of most at risk and most easily damaged, is not ideal for the North American bulk power system.

B. The Effects of GICs on Power Transformers

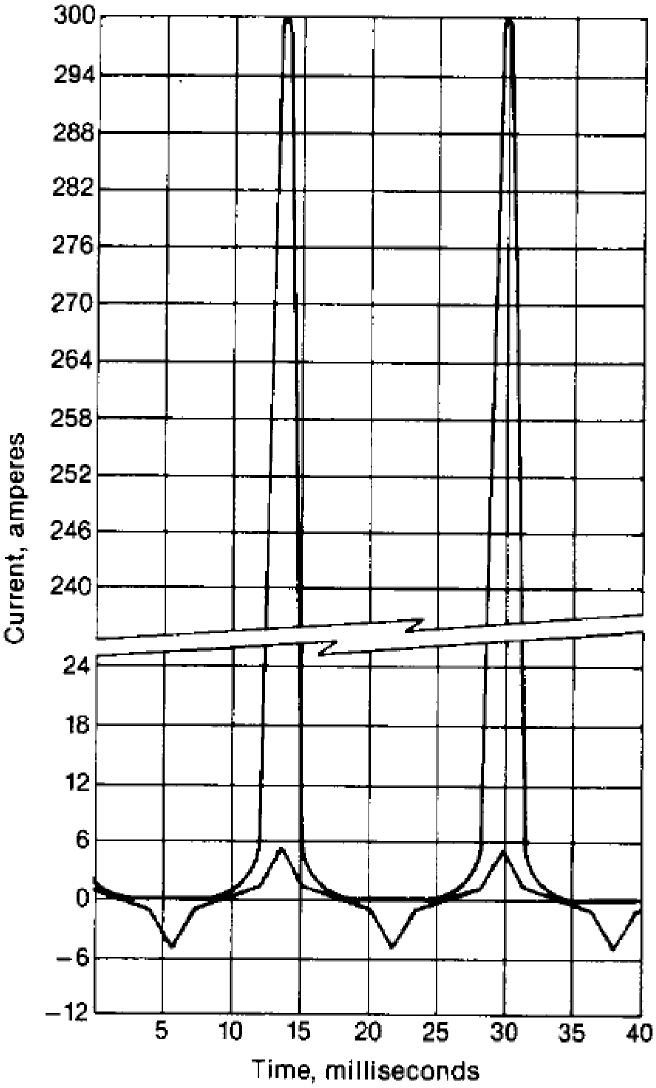
Present day power transformers have been optimized to only require a few amps of ac exciting current. The voltage transformation requires magnetic flux, generated by the ac exciting current. The core of the power transformers is made of steel. The steel core's performance is non-linear [4].



Graph taken from [4]

Figure 2. The steel core performance characteristics of a power transformer.

At the voltage peeks, saturation is seen in the transformer's voltage-current characteristics. As the magnitude of the voltage increases past the linear region, as seen in Fig. 2, the voltage begins to saturate. With GICs entering the transformers, the exciting current increases significantly. Positive GIC flow into the transformer severely saturates the positive cycle of the ac starting current. Field test from a 600 MVA transformer, with 75 A of GIC entering the neutral connection, show a starting current of approximately 300 A, as seen below in Fig. 3 [4].



Plot taken from [4]

Figure 3. Half cycle saturation in a 600 MVA transformer with 75 A of GIC flow [4].

The waveform peaking at about 6 A represents a typical excitation current for the transformer. The current after GICs have been introduced into the transformer increased asymmetrically to nearly 300A. The operating point of the transformer is no longer in the linear region. It has been pushed far into the positive saturation region. The core is saturated and the flux begins to leak and couple to everything near it. This damages the transformer's physical and electrical integrity. According to spectrum analysis, the asymmetric starting current contains several even and odd harmonics [4]. These harmonics are capable of improperly triggering the power line's relays. The distorted excitation current produces severe reactive power losses in the transformer. The 600 MVA transformer suffers a reactive power loss of 50,000 KVA with the excitation current of Fig. 3 [4]. This translates into a voltage drop in the system that is of serious concern. Design of a transformer immune to GIC effects has been considered. The design is cumbersome and the transformer's core size is impractical [4].

C. The Effects of GIC on Capacitor Banks and Static Var Compensators

GICs have a significant effect on high voltage transmission lines as well as power transformers. By observing the transmission line equivalent π circuit, as the load increases, the reactive power consumed by the line increases with the square of the line's current [5].These long lines require support devices such as static var compensators (SVCs) and capacitor banks in an effort to keep the line at the rated voltage. With GIC present, the system is overloaded with reactive power. The voltage of the line drops, and the capacitor banks are switched into the system, as an effort to boost the voltage back to the rated value. The capacitor banks are charged and discharged by the power lines they are connected to through a system of breakers and relays. As mentioned before, the transformer generates unusual even and odd harmonics under GIC conditions [1]. These harmonics are capable of improperly triggering the relays, which results in the improper operation of the system's breakers controlling the SVCs and capacitor banks [1]. During a GMD event, the capacitor banks and SVCs are unreliable and are likely to be destroyed from overcharging [1]. Without devices in the system to help recover from a voltage drop, the voltage may continue to drop, resulting in the collapse of the transmission line. With a high voltage transmission line instantly removed from the system, a 1000 MW loss is instantly seen in the system [4]. This is equivalent to the largest generating plant in the system going down. A domino effect of power outages can result from the large power loss [4].

III. PREVIOUS GEOMAGNETIC DISASTER

A. Hydro Québec System Collapse, 1989

On March 13-14 of 1989, the Earth experienced a geomagnetic storm with a magnitude of 500 nT/min. This storm resulted in the collapse of the Québec Interconnection, and ultimately the entire Québec grid. The grid collapsed in a total of 25 seconds. The seven static var compensators on line tripped, resulting in voltage drop of 0.2 p.u. Through loss of synchronism, the five lines to Montréal tripped, and the entire network separated [3]. The power outage did not extend beyond the Québec Interconnection to the rest of North America. However, power system anomalies were recorded around the globe during the next 24 hour period.

83% of the people affected by the storm in Québec had power restored in nine hours [3]. 21,500 MW of load and generation was lost in total [4]. After nine hours, 17% of the load was still out of service [4]. One generator step-up transformer was damaged from overheating due to GICs. If several of these key transformers are damaged, long term outages would be expected. The lead time of a high voltage step up transformers is 12-24 months. In 1921, a geomagnetic disturbance of approximately 5000 nT/min was believed to have occurred. This is ten times the magnitude of the 1989 storm. If a storm of this magnitude were to occur today, widespread damage to the electric grid of unprecedented proportions would occur.

IV. FUTURE STORMS AND MITIGATION STRATEGIES

Unfortunately, it took the Québec disaster for the scientific community to begin taking the effects of geomagnetic storms on the electric grid seriously. The Hydro Québec incident has been called a "case in point" by the North American Electric Reliability Corporation. With even more high voltage lines installed today, the power grid is at more risk than ever to geomagnetic disturbances. Stemming from the Québec disaster, K9 storms are now handled with special operation procedures.

A. K-Index Classification Insufficiencies

The K-Index suffers from a few key insufficiencies. As mentioned earlier, the scale was created in 1932. The instruments used at that time are inferior to those used today. As a result, the scales bandwidth is not wide enough. Any storm greater than 500 nT/min is classified as a K9 storm. This can be confusing to someone not familiar with the field. A scale that covers a larger range would benefit society as a whole when it comes to precautionary procedures. Storms of different magnitudes greater than 500 nT/min need to be handled differently. As the end of this solar cycle approaches, the storms are expected to become more frequent and violent.

B. Research Directions

- Editing and/or creating a scale to forecast geomagnetic disturbance conditions – Special operating conditions need to be performed when storms of great magnitude occur.

- Critical infrastructure – By protecting critical electric grid components and bypassing others after an event occurs, power can be maintained and restored as soon as possible to the consumers in a cost and time effective manner.

- Blocking capacitors or resistors in the neutral connections of vulnerable wye-connected high-power transformers

- Automatic load shedding scheme – If the load can be reduced when a geomagnetic disturbance has been detected, load shedding can counter the slow voltage collapse.

- Real-time asymmetry monitoring – By monitoring the in-rush asymmetric excitation current during GIC flow in high voltage transformers, preventative measures can be used to help protect the transformers from further damage.

- Effectiveness of existing black-start procedures – The current black-start procedures need to be evaluated and adapted to be fit for the response of a geomagnetic storm. The systems involved in restoration and reinstitution of the grid need to be evaluated.

C. *Cost of Protecting Transformers from GIC*

There are two major issues with protecting every high voltage transformer in the electric grid from GIC, time and money. In order to protect all the high voltage transformers, a standard of protection must first be established across all utilities. Next, all of the transformers must be retrofitted with the GIC protection device. With the next major geomagnetic storm immanent, the time required in order to protect the transformers is too large. It has been suggested that these devices be installed during existing maintenance periods [6]. This is a viable solution to the long term problem, but the near term threat is still present.

The cost of protecting the high voltage transformers in the grid is non-trivial. The quickest, and most cost effective, way to protect the transformers is by adding a blocking capacitor or a switchable resistor to the neutral connection of the wye-connected transformers [6]. There are several thousand high value transformers in the United States electric grid [6]. After cost-benefit analysis, the Electromagnetic Pulse Committee believes that switchable ground resistors are the best option to limit the GIC flow in transformers. The committee estimates the cost of the resistors to be between \$75 million and \$150 million [6]. This does not include the cost of labor, the sensors used to detect the GIC, or the breakers used to switch in the ground resistors. Since the labor is to be scheduled at the same time of existing maintenance, it is substantially reduced from new maintenance orders. In total, the end cost of the units protected is \$250 million to \$500 million [6].

V. CRITICAL INFRASTRUCTURE

Explained above, in the event of a near term geomagnetic disturbance, it is not plausible to protect all the high voltage transformers in the power grid. However, if critical transformers are protected, and others bypassed, the grid's integrity can be maintained. The power system of Fig. 4 contains one high voltage generator step-up transformer and one high voltage step-down transformer. Each is connected between a bus at 138 kV and a bus at 768 kV. The top figure of Fig. 4 shows the nominal ideal voltages of the transmission system. In order to bypass the transformer, a transmission line is connected in parallel with the transformer. The power flows around the transformer, and now, all transmission lines connected to the transformers terminals are operating at 138 kV. Bypassing the transformers in this manner, allows for the use of the original transmission topology. The only downtime the load sees is the time it takes the utility to install the patch transmission line. The bottom figure of Fig. 4 shows the system's voltages after the transformers have been bypassed with transmission line.

Bypassing the critical high voltage transformers in the power grid after damage from a geomagnetic storm has occurred is a cost effective solution to the power system's vulnerability. Utilities may be reluctant to spend hundreds millions of dollars to protect their system from a one in 100 year storm. When the storm occurs, the damage to the transformers cannot be undone. Bypassing the damaged transformers with patch transmission line is a viable solution to restoring power to the grid. Since the transformers are being bypassed, the voltage is not transformed. The transmission lines will be operating at the pre-transformed voltage and current. There is concern that the current may be too high for the higher voltage lines, this concern is addressed in the 37 bus case-study.

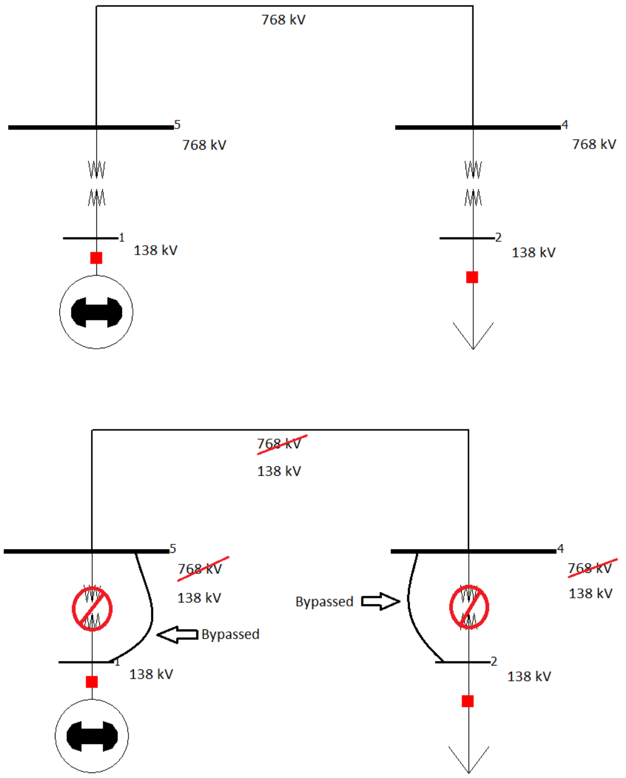


Figure 4. Simplified transmission system to illustrate the bypassing of high voltage transformers. (top) before transformer bypass, (bottom) after transformer bypass

The 37 bus case study explores the grid's integrity if only critical transformers are protected, and if critical transformers are protected and others bypassed.

A. *Strategically Protected Transformers*

Critical infrastructure analysis can be performed in order to determine the critical high voltage transformers in the grid. In the 37 bus case, there are six high voltage transformers. By inserting contingencies in Power World Simulator, each of the transformers can be disabled. Since there are only six high voltage transformers in this study, it is simple to determine which transformers are crucial to the system. By trial and error, it was determined as few as two transformers are required to maintain the full integrity of the system. If any two of the transformers were protected, the system suffered no outages.

B. *Bypassing Destroyed Transformers*

This study focuses on the scenario that a geomagnetic storm has occurred, and with no preventative measures in place, all six high voltage transformers in the 37 case system were destroyed, Fig. 5. In an effort to restore power to the system, two of the blown transformers were bypassed with transmission line.

In the simulation, the transformers are bypassed by replacing them in the one-line diagram with a transmission line. The impedance of the transmission line is that of the pre-transformed voltage line impedance. The high voltage lines are now operated at a lower voltage so their impedance must be modeled with the impedance of the operated voltage. In reality, the generator step-up transformer would be damaged. Utilities would bypass the transformer with transmission line. Now, the high voltage line would be operated at the pre-transformed voltage since the transformer was bypassed. It is of notable concern that the current will be higher since the line is operated at lower voltage. The simulations account for the higher current by modeling the lines impedance as the impedance of the lower voltage lines.

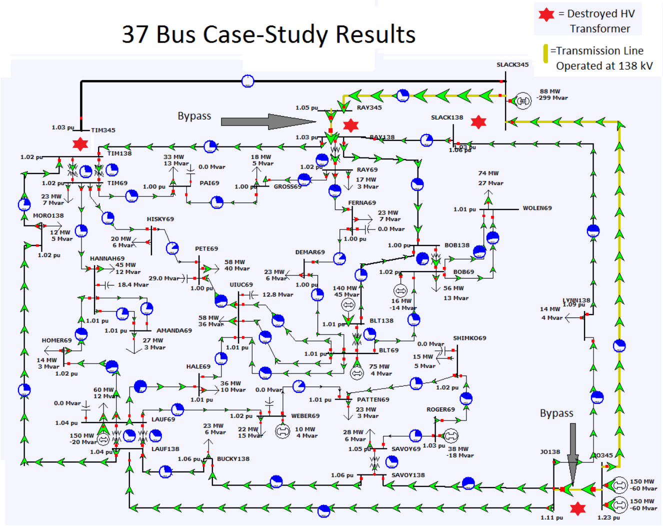


Figure 5. 37 bus case-study with two bypassed transformers. The star denotes transformers destroyed by the geomagnetic disturbance. The highlighted transmission lines denote lines operating at 138 kV.

It is important to notice that all six of the high voltage transformers have been removed from the system. Transmission lines have been installed to bypass two of the critical transformers. The highlighted transmission lines have the equivalent impedance of comparable 138 kV lines. The power flow solution to the one-line diagram shows the system is fully operational and operating under the limits of each component.

VI. CONCLUSION

In conclusion, a history of geomagnetic disturbances and the effects of GICs on the electric grid have been presented. Also, a variety of research directions have been suggested. A critical infrastructure case study of a 37 bus system was analyzed. It was determined that critical transformers can be protected, and the grids integrity can be maintained during a geomagnetic event. After the damage from a geomagnetic event has occurred, bypassing blown transformers allows the portions of the grid without power to be brought back on line in the quickest manner. In the near-term, bypassing the damaged transformers is the best cost effective, and time effective solution.

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