

Geomagnetic Disturbances and the Transmission Grid

David A. Wojtczak,
American Transmission Co.
Asset Management
Pewaukee, WI
dwojtczak@atcllc.com

Michael B. Marz,
American Transmission Co.
Transmission Planning
Pewaukee, WI
mwarz@atcllc.com

***Abstract* — The threat of Geomagnetic Disturbances on the transmission grid cannot be dismissed or ignored. The effects of a major solar storm can significantly impact real time grid operations and possibly cause long term damage to transmission system components. This paper addresses the threat of geomagnetic disturbances to the transmission system and the efforts underway at the American Transmission Company (ATC) to understand and mitigate the effects of such a potentially catastrophic event.**

***Index Terms* — Geomagnetic Disturbances, Transformer Saturation, Harmonics, Voltage Collapse**

I. THE GEOMAGNETIC THREAT

SOLAR storms have occurred as long as there has been a solar system. In the last fifty years the exponential build out of the transmission system has evolved to interconnect distant supplies of electric power to load centers over large regions of North America. This has made the transmission system a “superhighway” for electricity and increased its vulnerability to large scale disturbances. The August 14, 2003 blackout, although not related to any geomagnetic disturbance, caught the attention of policy makers and resulted in the development of mandatory reliability standards for electric utilities connected to the North American Bulk Electric System. These mandatory reliability standards will soon include requirements designed to mitigate the effects of geomagnetic disturbances. The intent of these reliability standards is to prevent another wide-scale blackout that could leave tens of millions of people without power for more than a day.

In response to a 2010 study on High Impact Low Frequency events, the North American Electric Reliability Corporation (NERC) convened the Geomagnetic Disturbance (GMD) Task Force to assess the threat of a solar storm to the power grid

and to provide interim recommendations prior to the development of GMD reliability standards. The NERC GMD interim report issued in February of 2012 concluded that the greatest threat of a major solar storm hitting the earth would be an uncontrolled voltage collapse of the transmission system. [1] This conclusion was reached largely based on examination of anecdotal evidence from past GMD events and the input of industry experts. Much debate has raged regarding whether hundreds of large power transformers would be damaged during a cataclysmic solar storm, but the threat of GMD to grid stability is real, whether or not major equipment damage occurs. No one who lived through the August 2003 blackout would care to experience a similar event caused by a GMD event.

In May 2013, the Federal Energy Regulatory Commission (FERC) issued an order requiring NERC to create reliability standards to address the GMD threat. [2] These standards were scheduled to be created within 6 and 18 months of the order’s effective date (60 days following publication in the Federal register). The first set of standards will require transmission system operators to create operating procedures to address GMD events. The second set of standards will require transmission system owners and operators to conduct assessments of their systems for susceptibility to GMDs and require appropriate measures be taken to prevent system collapse. NERC and its members are committed to creating and implementing these reliability standards in a timely manner to effectively address this threat.

The concern regarding GMDs on the electric system is multifaceted. Figure 1 shows a simplified electrical circuit representing the interaction of GMDs with the grid. When a solar storm creates a Coronal Mass Ejection (CME) that intersects the earth’s magnetosphere, quasi-dc Geomagnetically Induced Currents (GICs) will flow on high voltage transmission lines that do not include a series

capacitance. Depending on their magnitude at a specific location, these GICs may cause half cycle transformer saturation resulting in additional heating, harmonics and increased transformer var loading. Increased heating may damage transformers. Harmonics may cause incorrect operation of protective relays, in particular on capacitors and Static Var Compensators (SVCs) which may cause them to trip, thereby reducing reactive power margins. In severe cases, increased transformer var could result in voltage instability on the transmission system resulting in regional power outages.

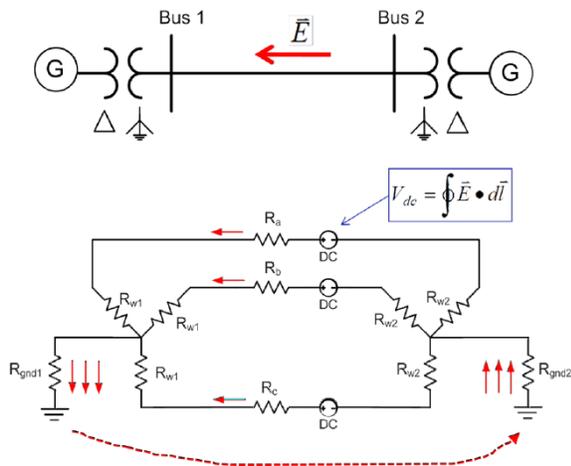
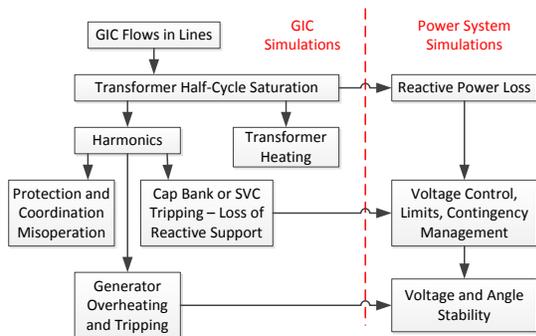


Fig. 1. Circuit Diagram of Geomagnetically Induced Currents (GIC) [3]

NERC’s 2012 GMD Special Reliability Assessment found the loss of reactive power to be the most likely outcome of a severe GIC event. This loss of reactive power could lead to system voltage collapse if it is not identified and managed properly. The NERC report showed how several different effects of GIC combine to negatively impact system voltage and angular stability (Figure 2).



From NERC 2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System (February 2012)

Fig. 2. Effects of GIC in a High Voltage Transmission Network [1]

When the GIC flowing in a transmission line causes a transformer to enter half cycle saturation the transformer’s effective magnetizing reactance is reduced and the transformer absorbs more reactive power than during normal operation. The amount of reactive power absorbed by the transformer is related to the flux linkages produced by the GIC and the transformer core form. Like the quasi-DC GIC currents, which have a frequency in the minutes range, transformer reactive power absorption and system voltage varies with a frequency in the minutes range.

Although shunt capacitors are essentially open circuits to the quasi-DC GIC currents, the harmonics produced by transformers driven into saturation by GICs see capacitors as low impedances to ground. An increase in shunt capacitor harmonic currents due to GIC can cause RMS current and voltage overloads as well as neutral currents high enough to cause a capacitor’s protection scheme to take it out of service. The likelihood of a capacitor tripping out of service for a GIC event depends on its grounding, protective relaying configuration and its resonance at a harmonic frequency produced by transformer saturation. These factors need to be evaluated on a case-by-case basis.

Generators, which can provide critical vars during GMD events, can also be affected by GIC currents. These effects include additional heating, damage to rotor components, increased mechanical vibrations and torsional stress due to oscillating rotor flux caused by increased negative sequence harmonic currents. The harmonic content of negative sequence currents can also cause relay alarming, erratic behavior or generator tripping.

All three of these effects, increased transformer reactive power consumption, loss of capacitors and SVCs due to protection operation or misoperation, and tripping generators due to negative sequence harmonics reduce the capability of the network to maintain voltage stability. The 1989 Hydro Quebec GMD related outage was due to voltage collapse caused by the improper tripping of SVCs and increased transformer var consumption. Damage to equipment during this event was due to over voltages that occurred during network splitting and were not due to the direct effects of GIC.

Actions system operator can take to mitigate the effects of GIC on voltage stability include reducing system var demand and increasing the available vars. This can be accomplished by, among other

procedures, minimizing power transfers to minimize line loading and var consumption and by increasing the number of generators on line that are generating below their maximum power outputs to increase available vars and reduce generator heating. These problems and the need for operator action to minimize them could also be addressed if the system were more effectively designed to monitor and mitigate the effects of GICs.

II. ATC'S STRATEGY TO ADDRESS GMDs

To proactively address GMD threats to its system, American Transmission Company (ATC) formed an internal GMD Working Group in early 2012 with executive sponsorship and a plan for implementing several of the NERC GMD Task Force interim report recommendations. These initiatives fall into three broad categories; measuring, modeling and mitigating GIC and its effects. Mitigation should be based on models, measurements and operational history.

Measuring GIC – In order to understand the effects of GMD events on its transmission system, ATC initiated an effort to install additional GIC measurement devices on its larger extra high voltage (EHV) autotransformers. The transformers were identified based on a GIC assessment conducted in 2005. At the time when this project was initiated, there were few if any commercially available packages for GIC monitoring, so ATC's SCADA Engineering group custom designed a GIC measurement system using commercially available components. This system consists of two cabinets housing the sensing equipment with a fiber communication link to the SCADA RTU.



Fig. 3 Sensor Cabinet Installation on an Autotransformer

A sensor cabinet housing a split-core, hall-effect current sensor is mounted on the neutral lead of the transformer before this lead is connected to ground. A 600 volt cable is used to isolate the transformer neutral from the ground bus until the current is measured by the transducer. The design of the cable matches the existing conductor attached to the H0X0 bushing. The sensor and transducer are enclosed in a NEMA 3R weather tight enclosure. This enclosure is mounted as close as possible to the neutral bushing at a safe distance below the top of the transformer to allow the sensor to be removed and tested while the transformer is in service. This design allows for retrofitting on a variety of neutral to ground connections on existing transformers (Figure 3).

A second cabinet houses a voltage to current transducer, a power supply for the sensor and the fiber optic converter. The transducer is arranged such that the signal indicates positive flow when DC current is entering the transformer from the ground per EPRI recommended practice. The second enclosure meets NEMA 3R weather tight standards as well and is installed on or next to the monitored transformer at a convenient height for access from the substation gravel surface next to the autotransformer.

New fiber optic cable was installed from the transformer to the control house RTU. Several sites had existing six strand fiber optic cable installed with adequate spare fibers available for connecting to the GIC monitor. At these sites the design was adjusted to accommodate existing fiber optic communication assets.

In addition to measuring the GICs directly, ATC is also measuring the harmonics associated with GIC related autotransformer saturation. To do this we used the existing capabilities of our electronic relays to measure lower order harmonics and report them over the SCADA system to our system operators. With this information our operators can determine when a transformer is beginning to saturate and when it has gone well into the non-linear region of operation.

One of the clearest markers of transformer core saturation is second order harmonics, which are not typically seen on transmission systems other than briefly during transformer energization. These harmonics are usually the result of half-wave rectification which is analogous to transformer half-cycle saturation. The GIC flowing through an autotransformer causes a DC shift which can cause

non-linear operation during the half cycle commensurate with the direction of the GIC/DC current flow. Thus, if GICs are flowing into a transformer, using our convention, they will cause a positive DC shift and saturation during the positive half of the cycle. It only takes a little GIC flow to cause significant half-cycle saturation currents to flow (Figure 4). [1]

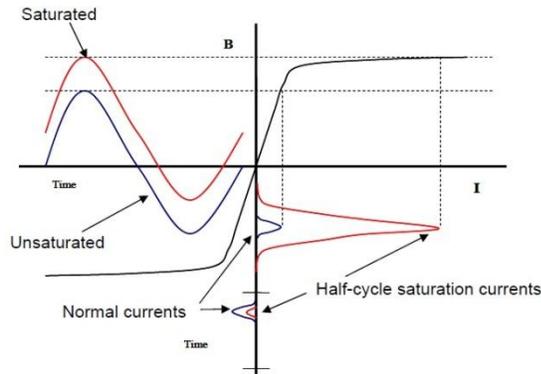


Fig. 4 Effects of GIC on Transformer Operation [1]

Modeling GIC – Prior to 2012, commercial software for modeling GIC was not readily available. The efforts of the NERC GMD Task Force encouraged software development with the result that toward the end of 2011 commercial software started to emerge with development continuing.

ATC collaborated with Power World to have its transmission system modeled using a newly developed module for predicting the impact of various solar storm fields at various directions on the grid. Simulations indicated possible voltage collapse on the ATC system for electric fields of about 20 volts/kilometer. Such fields are certainly plausible in ATC’s territory given a high magnitude solar storm such as the Carrington Event of 1859. Degradation effects on the transformers were not studied, but will be assessed in future system studies as more information becomes available.

These simulations were then used to test the effectiveness of GIC blocking devices. It was demonstrated that approximately two dozen GIC blocking devices installed at strategic locations on the ATC system would increase the system withstand from 20 volts/kilometer to approximately 27 volts/kilometer. This is a considerable increase in resiliency for a relatively small investment.

A major concern coming from this modeling effort is that its predictions do not closely match ATC’s operating experience. For over ten years, twelve GIC measuring devices on the ATC system have tracked

GIC flows during every solar storm. One substation in the northeastern portion of ATC’s system has historically seen higher measured GIC flows than the other monitored transformers during virtually every GIC event. However, this substation showed lower simulated flows than other substations. These results have prompted an investigation as to why there is such a big discrepancy between the measurements and simulation results.

A major source of the discrepancy between system measurements and simulations lies in the unique geology of Wisconsin and a critical simulation assumption. Southern Wisconsin has soils with relatively high conductivities while northern Wisconsin and Upper Michigan have soils with much lower conductivities (see circled area in Figure 5). The huge disparity in conductivity between these regions makes the software’s assumption of a uniform electric field grossly inaccurate, which skews simulation results. Work is underway to model a variety of soil conductivities to better match what occurs on the real system. Until modeling tools can better deal with these discontinuities, their effectiveness will be limited in areas where these conditions exist.

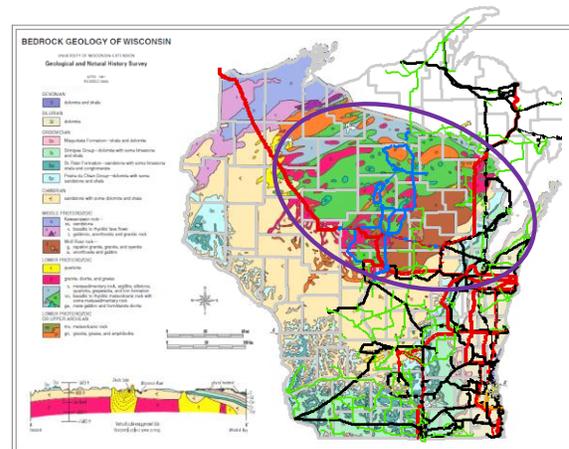


Fig. 5 ATC Transmission System with Soil Conditions

Additional factors that include uncertainties affecting model accuracy include: substation grounding resistance, electrical component DC resistance, and autotransformer var consumption as a function of GIC flow.

Mitigating GIC – The ultimate goal of measuring and modeling GICs is to mitigate their effects to manageable proportions. The uncontrolled loss of the grid due to voltage collapse has many undesirable

consequences. Although all NERC operating regions have black start plans to restore power after a major outage, it is never a good thing to have to resort to these strategies. Even if studies and research show that hundreds of transformers will not be damaged during a solar storm, an uncontrolled widespread outage of the transmission system would still cause untold hardship for millions of people and likely result in several deaths.

The Northeast blackout of 2003 caused electric service outages to 50 million people for up to two days. The event also contributed to at least 11 deaths and cost an estimated \$6 billion in lost economic activities and other damage. Since electricity is the lifeblood of every advanced society, it is unacceptable to allow the grid to operate at risk of an even wider spread outage due to a major solar storm. FERC recognized this in its order to the electric utility industry [2] and directed NERC to develop standards to deal with the GMD threat to the grid. It is becoming increasingly apparent that not mitigating the effects of a major solar storm is no longer acceptable.

There are basically two ways to mitigate the effects of a major GMD event. The first is to adopt operating procedures to manage the issue in real time. The second is to block GICs. Until recently most operating procedures had very little specificity due to a lack of relevant information on solar storm severity and system vulnerability. In the past the typical grid operator may have seen voltages decrease somewhat and may have heard reports of transformers “growling” during a solar storm, but little other information was available.

Without accurate modeling capabilities, operators cannot take action based on predicted results. In other words, they have no way of knowing exactly what to do for a given scenario. As models become more accurate and are calibrated against real-time data, better system studies can be done that will help predetermine operating steps to help minimize outages and limit damage to critical equipment.

One of the benefits of increased GIC monitoring on the ATC system is an increased understanding of what actually happens during a solar storm. As a result, operating procedures have been revised within the last year to call for dissolved gas analysis (DGA) after a transformer has clearly been in saturation during a GMD storm. This proactive measure will

help ATC determine whether solar storms are causing concerns with the affected transformers in its fleet. While DGA does not tell the whole story of a transformer’s health, it can give a signal that something is happening that may need further inspection, perhaps even an internal visual inspection.

In some parts of the grid operating procedures alone may still not be sufficient to prevent large scale blackouts or damage to transformers. In these instances other solutions may be needed.

In October of 2012, ATC began pursuing the purchase and installation of one of the first commercially available neutral blocking devices on its transmission system. The neutral blocking technology chosen uses a capacitor in series with a resistor to block GIC flow during large magnitude GMD events (Figure 6).

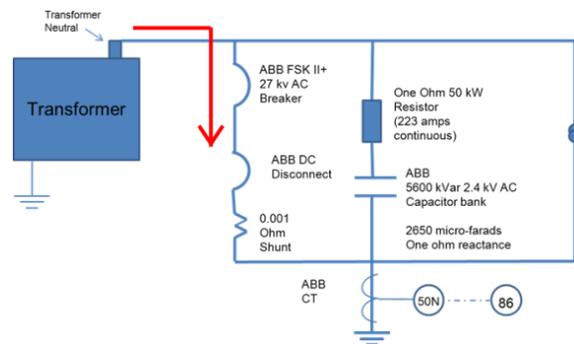


Fig. 6. Neutral Blocking Device One-line

During normal system conditions the device operates in bypass mode with a direct connection to ground through an AC breaker in series with a DC breaker and a DC shunt (leftmost leg in Figure 6). The shunt is used to measure neutral to ground current flow during normal operations. When GIC flow is detected a relay operates to open the breakers and force the current flow into the capacitor leg of the circuit. Since GIC is effectively DC it is blocked from flowing while AC current can still flow through the capacitor and resistor combination. A surge arrester in parallel provides surge protection for the transformer and for the components of the blocking device during a ground fault. This surge arrester is housed in a protective enclosure to limit exposure to equipment and personnel should the arrester fail. In this design, the arrester is a consumable device which will need to be replaced should it fail. The downside of this design is that GIC protection would be lost

until the arrester is replaced. The manufacturer is addressing this concern by installing a spark gap in parallel with the arrester to take the bulk of the fault current and mitigate the possibility of arrester failure.

ATC assembled a project team to determine where to install the neutral blocking device on its system. Since simulation results have not been entirely accurate, the team decided to choose a site based on historic measurements, system configuration and participation of the site transformer during GMD events. The site chosen has one large 345/138-kV autotransformer that is connected to a long 345 kV transmission line that links the Green Bay area with Upper Michigan. This site is an excellent location for a prototype installation since it is remote from any generators and has only one transformer. The low conductivity region that the line traverses makes this site ideal for blocking device testing. The expectation is that blocking GIC flow at this transformer will not adversely affect other transformers on the ATC system.

ATC plans on installing the neutral blocking device before the end of 2013 and is looking forward to gaining operating experience in subsequent years. This operating and performance history should provide valuable insights to the electric utility industry as efforts to address GMDs expand across North America and the rest of the world.

III. CONCLUSIONS

The threat to the transmission system posed by GMD events is real and of significant concern. The electric utility industry is taking steps to address these concerns via NERC standards development and individual efforts. Related work by NERC GMD Task Force is helping to move this effort ahead with the considerable research and development efforts of its participants.

ATC has been proactively addressing GMD concerns for several years and has cooperated with the electric utility industry via various forums and its own internal efforts. Much work still remains in the areas of model development, measurement technology development and development of mitigation technologies to deal with GMDs. ATC is committed to pursuing future opportunities in all these areas to benefit its customers and the rest of the electric utility industry.

REFERENCES

- [1] North American Electric Reliability Corporation (NERC) Geomagnetic Disturbance Task Force (GMDTF) Interim Report, "Effects of Geomagnetic Disturbances on the Bulk Power System," February 2012. <http://www.nerc.com/files/2012GMD.pdf>
- [2] Federal Energy Regulatory Commission (FERC), Docket No. RM12-22-000, Order No. 779, "Reliability Standards for Geomagnetic Disturbances," Issued May 16, 2013. http://www.nerc.com/FilingsOrders/us/FERCOrders/Rules/Order779_GMD_RM12-22_20130516.pdf
- [3] Overbye, T. J., "Integration of Geomagnetic Disturbances (GMDs) Modeling into the Power Flow," Power Systems Engineering Research Center (PSERC) Webinar, March 13, 2012. http://www.pserc.wisc.edu/documents/general_information/presentations/pserc_seminars/psercwebinars2012/Overbye_PSERC_March2012.ppt