Geomagnetic Disturbances (GMD) Impacts on Protection Systems

IEEE PSRC Working Group on GMD Impacts on Protection Systems

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***Abstract*--This paper provides background and historical events of Geomagnetic Disturbances (GMD), and reviews GMD impacts on power systems equipment, and associated protection and control systems, mitigating measures, and Geomagnetic Induced Current (GIC) monitoring methods. This paper is a summary of the IEEE PES-TR72 report, titled, GMD Impacts on Protection Systems, prepared by the K17 Working Group of the IEEE Power System Relaying and Control committee.**

***Index Terms*--Geomagnetic Disturbances (GMD), Generator Protection, Capacitor Protection, Transformer Protection, Transmission Line Protection, Communication Aided Protection.**

I. INTRODUCTION

This paper discusses impacts of Geomagnetic Disturbance (GMD) phenomena on protection systems. GMD phenomenon and impact on our society have been monitored and studied for decades and warning systems are in place to provide level of intensity and approximate time of impact. One example is NOAA (National Oceanic Atmospheric Administration) GMD Planetary K-index in the United States [1]. In power system, GMD events create low frequency primary currents (quasi-DC) that circulate between transmission lines, high-side Y-grounded transformers and ground. GMD events may cause unanticipated damage to high voltage equipment such as transformer, generator, shunt capacitor and SVC, and may have impacts on radio or satellite communications used as timing source or for protection and control functions. Depending on the severity of GMD, they may also affect the performance of protection and control schemes. The low frequency current created by GMD events is referred to as Geomagnetically Induced Current (GIC). GIC may cause elevated levels of harmonics. GIC flow in Y-grounded transformers, for example, may cause high magnetic flux that could cause severe transformer damage through overheating. Protection system reliability (security and/or dependability) may also be affected depending on GMD severity. Many technical papers have been published regarding GMD and their impact on protection systems. This paper intends to summarize main findings of previous events and current practical experiences on protection systems.

This paper provides GMD background, followed by potential impacts to primary equipment. Finally, impact to power system protective relaying is discussed. This paper serves to raise the reader's awareness on issues with equipment specification, operation and maintenance practices, application, and setting of protection systems that may be impacted by GMD events.

II. IMPACTS ON POWER SYSTEMS

Space weather disturbances have been observed before the Common Era (BCE). A 2012 study [2] reports an assessment on the probability of occurrence of extreme solar particle events based on historical proxy data since 1485 BCE.

The "Solar Storm of 1859", known as the Carrington Event is the most severe GMD event recorded in history [3]. The range of magnetic strength have been observed from -800 to -1750 nT (nanotesla). Telegraph systems all over Europe and North America failed due to the severity of these GMDs. A 2013 study reported an estimated cost to the United States during this event to be about \$0.6 - \$2.6 trillion USD [3].

The IEEE PES-TR72 report [4] lists several notable GMD events since 1859. Solar storms causing GMDs on the Earth's magnetosphere may have substantial impacts on the Bulk Power System (BPS), telecommunications, navigation, and satellite systems. For example, during March 13, 1989 GMD event, tripping of harmonic filter banks and seven static var compensators led to a massive power (~21.5 GW) outage in Hydro Québec transmission grid. High harmonic levels caused misoperation of protection system, and collapsed entire Hydro Québec grid in less than a minute and left about six million people out of power for about nine hours. A report produced by NERC [5] addresses the system operation concerns on the BPS and concludes that loss of reactive power compensation could be the most likely outcome of a severe GMD event.

A. GMD background

A GMD event is caused by interaction between the cloud of charged particles produced by a Coronal Mass Ejection (CME) from a solar storm, and earth magnetic field. A solar storm's impact on transmission facilities depends on many factors, including solar storm intensity, whether the mass of particles ejected from a solar storm strikes Earth, proximity of affected system/equipment to Earth's poles and local geology, length and orientation of transmission lines, winding connection of connected transformers, and design of connected transformers and their connected load.

Most solar storms and CMEs occur during a 4 ~ 6 years interval, within the sunspot cycle that peaks predominantly every 11 years. GMD events typically appear on Earth 1 ~ 4 days after an earth-directed flare or eruption on the Sun takes place. CMEs interact with the Earth's magnetosphere and cause slow-varying electrojet currents about 100 km above earth. Fluctuations of electrojet currents result in changes on Earth's surface magnetic field (geomagnetic field). Geomagnetic field changes at Earth's surface layer induce GIC in transmission lines and associated equipment directly connected to the line (e.g., power line carrier) and other high voltage equipment terminated through bus coupling at Substation.

B. *Harmonics produced by GIC-induced saturation*

GIC may cause transformer core to saturate. Single-phase transformers, transformers with five leg cores, and shell type transformers are more susceptible to applied DC current [6]. These types of transformers can present the highest risk to system reliability should core saturation occur. Three-leg core form designs are less susceptible to saturation from GIC, but they too may saturate at high GIC levels.

Flow of GIC through transformers may cause asymmetric part-cycle saturation of transformers' cores. Transformers under half-cycle saturation absorb increased amounts of reactive power (var). In addition to causing reactive power losses that may threaten system voltage stability, large amounts of harmonic current can be injected into the power system if numerous transformers are simultaneously saturated during a severe GMD event. These harmonic currents can have a magnitude greater than that of the fundamental reactive current. Harmonic currents can directly affect power system equipment such as capacitors, harmonic filters, SVCs, and generators, and may interfere with proper operation of protection systems.

The magnetizing current of a saturated transformer, due to GIC, consists primarily of unipolar pulses with magnitude and pulse-width that are functions of the GIC magnitude. Fourier analysis of magnetizing current reveals a DC component that is equal to the GIC, a fundamental frequency reactive current component, and harmonic components.

Harmonic components of magnetizing current for single-phase transformers can be calculated based on per-unit fundamental voltage, slope of magnetization curve in fully saturated region (often called "air core reactance"), harmonic order, and saturation delay angle. Harmonics produced by GIC saturation of single-phase transformers fall into classic sequence component pattern: multiples of third harmonics are zero sequence, 3^{rd}, 6^{th}, etc.; 2^{nd}, 5^{th}, 8^{th}, etc. are negative sequence; and 4^{th}, 7^{th}, 10^{th}, etc. are positive sequence [6]. GIC saturation behavior of three-phase transformers is quite complex because of interaction of magnetic circuits of the phases. Appropriate time-domain magnetic circuit modeling technique such as duality-based modeling is required to determine harmonic currents [7].

C. *GMD impacts on power systems*

Historical GIC observations

After the Hydro Quebec blackout and other utilities' experiences during earlier geomagnetic disturbances, several utilities installed GIC monitoring systems on the neutrals of some vulnerable EHV transformers to assess transformer vulnerability to GIC during Solar Cycles. BC Hydro, for example, has observed GIC caused excitations in its 138 kV line, which has been mitigated by placing a GIC blocking capacitor in the neutral of the transformer at the receiving terminal of the line. This reduced harmonic excitation mitigated overvoltages due to harmonic resonance. In some cases, half cycle saturation of some 500 kV transformers caused increased reactive power absorption that reduced the voltage at the 500kV terminal. However, the voltage reduction was not severe and was mitigated by normal operating procedures. Refer to [4] for other examples.

Capacitor bank tripping

Capacitor banks are low impedance paths for harmonics. During the March 1989 solar storm, thirteen capacitor banks within the Dominion Energy Virginia Power (DVE) service territory tripped within two minutes due to a protection scheme susceptible to harmonic distortion. A neutral unbalance scheme that measured current at the neutral ground point to determine the failure of capacitor units would operate. Though the scheme was equipped with a parallel capacitor to provide immunity to third harmonics, the electromechanical relay was unable to distinguish excessive harmonics of other orders from fundamental frequency component during GIC, therefore, the relay misoperated. This event pointed out a vulnerability of the system that could increase when the system is under higher stress.

GIC impacts on transformers

Transformer Core saturation due to GIC is highly undesirable as the transformer will become incapable of delivering the required rated power to the load. In addition, localized heating and general overheating will occur due to stray magnetic flux that induces eddy currents in conductors and metal components within the transformer tank. A prolonged saturation condition can potentially lead to failure of the power transformer. Reducing the transformer load is one method to minimize thermal stress to the transformer structural parts, such as tie plates, yoke clamps, tank walls, tank cover, tank bottom, etc. Damage may not be immediate following only a single GIC instance. Failure may result as a cumulative or residual effect from a combination of multiple GIC occurrences, which may involve both over-excitation and GIC.

GIC impacts on generators

<u>Generator harmonics</u>

Generators are usually interconnected to transmission grid by grounded-wye delta step-up transformers, which do not allow any GIC flow into the generator itself. However, harmonic currents caused by transformer saturation can flow into a generator and pose a considerable risk to the machine if excessive. A detailed, and potentially extensive, system model may be needed to calculate generator harmonic currents during a GMD. Only positive and negative sequence harmonic current can flow into the generator, by virtue of the wye-delta Generation Step-up Unit (GSU) connection. Both positive and negative sequence harmonics create impacts similar to negative-sequence fundamental currents.

Rotor heating

Positive sequence harmonic currents flowing into the stator of a generator cause an air-gap magnetic field that rotates, in forward direction, at a rotational speed that is n times the synchronous speed. From the reference frame of the rotor, the apparent rotation is at n-1 times synchronous speed. Negative sequence harmonic current into the stator causes a magnetic field that rotates in reverse direction at n times the synchronous speed. In the rotor reference frame, the apparent speed is n+1 times synchronous speed [4].

Both positive and negative sequence harmonics result in a magnetic field that is rotating with respect to the rotor, and thus eddy currents will be induced in the rotor. IEEE Std C50.12-2005 and C50.13-2014 specify negative sequence current withstand capabilities for salient-pole and cylindrical-rotor 50 Hz and 60 Hz synchronous generators, respectively.

Mechanical resonance excitation

The interaction between rotating magnetic fields induced by synchronous generator stator harmonic currents and the DC magnetic field produced by the rotor causes mechanical torque pulsations. The frequency of this mechanical stimulus is the same as the frequency of the harmonics as seen in the rotor reference frame; stator harmonic order plus one for negative-sequence harmonics and stator harmonic order minus one for positive-sequence harmonics.

III. GMD Impacts on Protection Systems

A. CT Saturation due to GIC

Some impacts to protection have been described earlier, i.e. flux, excitation, excessive negative or ground current flows and harmonics. GIC levels have some effect on conventional instrument current transformer (CT) performance. Depending on the type and application purpose for a CT, and the CT tap selected, when it has multi-tap CT, the magnetic core may measure a small added magnetism during a GMD event compared with performance ratings in typical protection applications. Most often, the CTs are selected for short circuit currents with an expected voltage saturation for particular application over a life cycle, for example, transmission line and transformer protection. The GMD caused magnetic flux may not lead to a CT damage. The quasi-DC drives the flux linkage closer to the knee-point of the CT excitation curve. CT saturation due to GICs is of transient nature, and the saturation observed based on historical events is generally short-lived. The error is increased, compared with no DC present, but the differences observed in simulations show negligible impact. It may be worthwhile to check CT conditions of equipment, after a known GMD with measurable impact on nearby stations.

B. GMD Impacts on Protection & Control Schemes

Based on the transient nature of the GIC, impact of GIC-induced CT saturation on protective relays is often masked by the protective device settings, or the time delay applied for coordination. Protective relays may experience slightly degraded dependability (under-reaching, slower operation) due to GIC. This is similar to the performance degradation experienced during CT saturation caused by a number of other well-known factors. Also, in light of decades of enhanced protection system performance monitoring and analysis of captured recordings, several enhancements are built in many microprocessor-based protective devices and schemes, to address CT saturation. These well-recognized factors ensure security for CT errors due to GICs as well. Below is a short overview of some protection elements and their performance during a GIC-induced event.

Line distance and overcurrent elements may slightly underreach due to CT errors. For instantaneous elements, the relays are typically applied with a margin to cover more severe faults, hence, the low magnitude quasi-DCs may not have significant impact. Time-coordinated distance or overcurrent elements apply overreaching margins with time delay to operate, so they retain dependability, despite the GIC-induced CT magnetism. Line differential elements typically incorporate a means to address CT saturation, and they operate on principal of currents flowing towards a protected area, as opposed to current flow in opposing directions away from the protected area.

Transformer differential elements include percentage restraint to cope with CT errors, and they too remain secure for external faults even under GICs.

Distance and overcurrent relays would tend to underreach due to substantial CT saturation in the first half cycle of the fault current. As a result, protection might be slightly delayed for in-zone faults due to transient CT saturation caused by the GIC.

Fast line differential microprocessor relays may be affected by transient CT saturation, but these relays already guard against CT saturation, and when designed properly, do not face any problems. Slower line differential relays are secure because errors during transient CT saturation from GIC are short-lived.

Non-restraint elements of transformer differential protection function are similar to those in line differential relays. A similar analysis can be presented in terms of their performance during a GIC-induced electromagnetic impact.

Capacitor Bank Protection and GIC Impact

Capacitor banks are low impedance paths for harmonics. Transmission capacitor banks are composed of many individual capacitor units that are connected in series and parallel based on equipment specification. Capacitor banks are often wye, double wye or delta connected and grounded or ungrounded. Four types of capacitor units and their respective connections are widely used:

- Externally fused, with individual fuses for each capacitor unit
- Internally fused, with each element fused inside the capacitor unit

- Fuseless, with capacitor units connected in a variety of series and parallel arrangements
- Fuseless, with capacitor units connected in series strings between line and neutral (or between line terminals)

Capacitor bank protection schemes are described in IEEE Std C37.99-2012. Varieties of sensitive protection schemes are available to measure unbalanced currents or voltages between various parts of the bank and identify possible failures of individual capacitor units that could cause unacceptable overvoltage across good capacitor units in other parts of the bank. When applying sensitive unbalance protection schemes to capacitor banks, it is important to be aware of the possibility of high proportions of harmonic currents flowing into these banks under various power system conditions (including GICs).

In terms of protective schemes performance, in general, digital relays are designed to measure fundamental frequency currents, and filter out other frequencies for protection purposes while having the feature to identify and record presence of a significant proportion of harmonics.

Electromechanical and solid-state protective relays, on the other hand, may be susceptible to undefined performance in the presence of harmonics. Some severe geomagnetic storm events have led to tripping of multiple shunt capacitor banks deployed throughout one utility service territory [11] in a relatively short period due to a protection scheme susceptible to harmonic distortion.

Most microprocessor-based relays have filters that will protect the capacitor bank and associated components from damage due to excessive harmonic current flow. Therefore, in some cases, protection or monitoring systems that measure total rms currents may be advantageous to measuring total phase currents into a capacitor bank exposed to harmonic absorption.

Transformer Protection and GIC Impact

Transformer protection consists of electrical and some mechanical detection functions. For the electrical protection, basic functions include differential and overcurrent protection. Mechanical protection often includes a sudden pressure and low oil detections. The impact of GIC on the electrical protection elements is a combination of CT saturation and harmonics. The GIC impact on the primary side of the CT and the protection performance are minimal for reasons explained earlier. Furthermore, the primary side of the CT acts as a high pass filter, basically filtering out low frequency component (including quasi-DC) and allow for nominal frequency component to be correctly utilized without much loss of signal integrity.

Figure 1 shows current distribution in transformer windings for a two-winding transformer with magnetizing current appearing as a differential or operating current (I_{OP}). Magnetizing or excitation current (I_{ET}) distribution on primary and secondary windings are presented feeding towards the magnetic core while load flow (I_{LOAD}) is from primary towards secondary windings of the transformer.

The magnetizing current (I_{ET}) magnitude is dependent on the GIC strength as is the magnitude of the harmonics generated by the magnetizing branch of the transformer. In general, the quasi-DC is not large enough to generate sufficient operating current in the differential measuring element to jeopardize security of the element, i.e., this I_{OP} current is below pickup current to operate differential element. As shown in Figure 1, the GIC current is only part of the transformer excitation, and does not flow in the CT circuit used for overcurrent element protection. However, GIC current will result in transformer drawing a larger magnetizing current than under normal operating conditions.

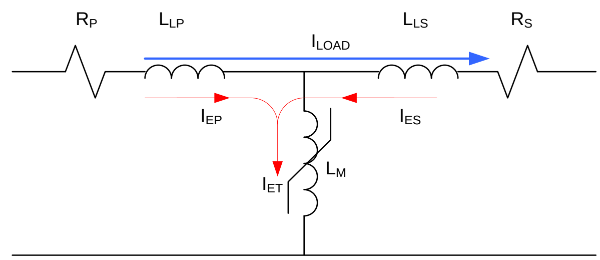

Fig. 1 Electrical equivalent diagram for a two-winding transformer

The vector sum of transformer nominal load current and magnetizing current, even under GIC conditions, is unlikely to drive the operating current above threshold of the overcurrent element set point. This is true for operating quantities for the overcurrent element that are rms or fundamental frequency current. However, if a transformer is overloaded during a GIC event, the higher magnetizing current may reduce the security margin of the overcurrent element. Under external fault conditions, there may be a concern that a GIC condition could jeopardize security of transformer protection elements. Investigation of behavior of these elements under an external fault condition in the presence of GIC may help resolve this concern.

The increased GIC may lead the power transformer to draw above average magnetizing current, which can result in elevated differential current (I_{OP}). When a fault occurs on the power system, the voltage across power system will decrease resulting in a drop in the voltage across the magnetizing branch. This voltage drop reduces magnetizing current of the power transformer. This will result in the differential element becoming more secure since the percentage of differential current versus restraint current decreases. However, due to GIC current, the primary CT tap windings are more susceptible to saturation. (GIC current behaves similarly to a residual current). By taking GIC into account when selecting a primary CT tap, it could minimize the GIC impact on the protection for external faults. In addition, many modern differential relays employ logic to secure the differential element during external faults.

Operation of overcurrent element during an external fault depends on the performance of CT.

Generator Protection

Harmonics may cause heating of generator rotors due to circulation of eddy currents. However, the capability of generators to withstand specific levels of harmonics is not an industry standard. This means that it is not yet possible to define an acceptable level of harmonics that will not damage a particular generator. Given the unknown harmonic-withstand capability of generators, protection relays available today are not designed to protect the generators from the harmonic impacts present during a GMD. Many modern digital relays are designed to operate exclusively on fundamental frequency currents, and filter out harmonic currents. Legacy electromechanical and static generator protection negative sequence overcurrent relays use phase shifting circuits intended to calculate negative sequence component of fundamental current. These phase shifting circuits do not provide proper phase shift to identify negative sequence currents at harmonic frequencies. Therefore, these legacy relays may over or under protect a generator. Reference [4] describes one case of undesirable tripping of a generator during a GMD event, and several cases of alarms. The alarms may or may not have been desirable, because of the unknown harmonic withstand capability of the generators. Note that negative sequence overcurrent protection is not intended to protect a generator from harmonic currents. The impacts from harmonic currents are not limited to negative sequence current. Thermal protection may protect generators against damages during GMD events.

Transmission Line Protection

Series compensated lines are generally not vulnerable to impact of GMD events as the compensation blocks the GIC current flow. When a line is designed to support compensation, the compensation can be switched on when a GMD event is expected.

For uncompensated lines, or lines without series capacitors, the protection systems, particularly legacy protection systems, may misoperate due to their unknown response to harmonic currents flowing in the lines during a GMD. Latest generation of microprocessor-based relays and phasor-based transmission line protective devices are not particularly susceptible to harmonics, as these protective devices respond primarily to fundamental frequency components. Some utilities have reported line relay operation [12] by sensitive unbalance (negative and zero sequence) overcurrent protection during a GMD. Another relay misoperation is attributed to the ground time overcurrent relay undesirably responding to harmonic distortion. It was replaced with a numerical ground overcurrent relay that had high harmonic rejection.

C. *GMD Impacts on Communications*

Loss of GPS Signals

The availability of an accurate time reference, such as GPS signal, allows Intelligent Electronic Devices (IEDs), such as protective digital relays, to synchronize the system data for precise event report alignment. This facilitates sequence of events, off-line event analysis and troubleshooting of a possible misoperation following a GMD occurrence.

Many Substations today have GPS clocks that allow utilities to date and time stamp fault records to the microsecond. Loss of these clocks during a large GMD event would hamper troubleshooting suspected misoperations. Although the internal clocks in the relays may drift a little bit over time, they would remain accurate enough for at least some time without a GPS signal, so the temporary loss of the GPS signal (lasting from a few minutes to possibly a few hours) will not severely impact reliable operation of the power system [5].

A minor solar storm in October-November 2003 disabled the USA Federal Aviation Administration's new GPS system for nearly 30 hours and damaged electrical systems from Scandinavia to South Africa, covering primary and secondary affects [8]. These storms interfered with satellite communications and produced a brief power outage in Sweden.

As utilities expand the use of IEC 61850 and synchrophasor-based wide-area control schemes, there will be more exposure to system operational issues associated with loss of a GPS clock. Utilities should plan for loss of a GPS clock when implementing any feasible wide-area control schemes.

Power line carrier

Power line carrier (PLC) is a protective relaying communications system that couples high frequency radio signals (typically in the 50 kHz to 300 kHz range) onto the power line itself for terminal relay to relay communications. PLC components include line traps, coupling capacitors, drain coils, line tuners, coaxial cable and transceivers. By and large, protective relays key the signal on or off for blocking purposes, or use frequency shift keying to transfer trip remote breakers.

The GIC is most likely to emerge into power system where grounded power transformers exist at the terminals of transmission lines. It is difficult to conclude that an induced GIC would couple into a carrier communications system due to its low frequency characteristics, but the relatively higher frequency harmonics generated at the half-cycle saturated transformers may introduce some noise that can interfere with carrier signal. Figure 2 shows GIC flow path within the PLC system. The interference signal into PLC is likely the greatest exposure of a PLC system to GIC, as the capacitance of the coupling capacitors provides a low impedance path for the high frequency harmonics, which will enter into the transceivers along with the carrier signal. This can result in a lower signal to noise (SNR) ratio. Impact of a lower SNR could be a failure to trip or an overtrip, depending on the protective scheme used.

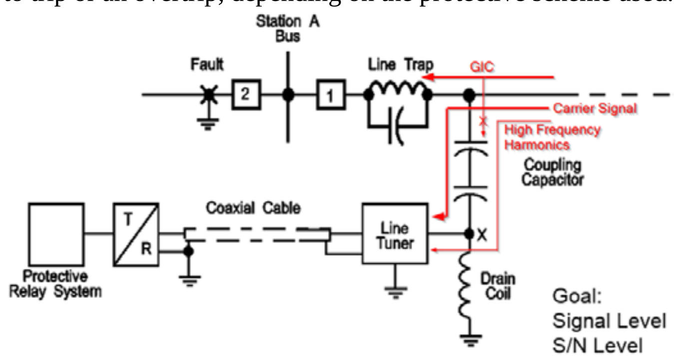

Fig. 2 GIC Flow Path with the Carrier Communication System

The following methods may be employed on longer lines most susceptible to GIC. This would include the lines with grounded transformers at the terminals.

1. Use of single or double frequency resonant traps may have better harmonic blocking characteristics than the wide band

type, to limit introduction of harmonics onto the conductor used for the carrier signal. Blocking impedances of resonant type traps are typically higher also.
2. Carrier sets employed today can be specified with higher power output ratings. Typically supplied with carrier signal power rating of 10 watts, 100-watt units are also available.
3. Fiber-based communication/protection system are effectively immune to the effects of GIC.

Microwave and Satellite

Microwave is the general term used to describe radio frequency waves that start from ultra-high frequency to extremely high frequency, e.g. 300 MHz to 300 GHz. Microwave signals have been used for both satellite and ground-based communications. Impacts of GMD on satellite-based communications have been reported in several references. Sudden increase of x-ray radiation from solar flare resulting in substantial ionization in the lower region of the ionosphere, sudden enhancement of signals and short wave fade, and presence of a wide spectrum of radio noises are presented in a 2012 report by Applied Science Research [9].

Potential effects of solar phenomena (including the March 1989 solar storm) on communication systems used by the electric utility industry are detailed in a report by the IEEE Power System Communications Committee [10]. Notable impacts on satellite operations include:

- A previously stable low-altitude satellite began episodes of uncontrolled tumbling that interfered with its operational functions;
- The GOES 7 satellite had a communications circuit anomaly, lost imagery, and had a communications outage;
- A Japanese geostationary communications satellite had a severe problem that involved failure and permanent loss of half of the dual redundant command circuitry onboard, and
- Geosynchronous communications satellites had problems maintaining operational attitude orientation.

A 2018 paper [8] explains how satellite communications' use of the higher microwave frequencies are less affected by solar storms than terrestrial radio communications. However, because satellites are unprotected from the sun, they are exposed to additional phenomena that affect their operation. Several satellites were powered down during the March 13, 1989 storm to avoid possible damage. Solar storm on February 16, 2011 caused temporary radio blackouts and risk to satellites.

Gusts of solar wind can also affect a satellite's ability to navigate, possibly causing a satellite to go out of control, especially for a satellite that uses momentum wheels for orientation. If solar wind gusts are successfully predicted, satellite operators can switch to back-up momentum control systems, thereby minimizing risk to the satellite.

Utilities that are considering use of satellite communications for monitoring and controlling power system should be aware of these potential effects.

IV. Mitigating GMD Impacts on Protection Systems

Modern microprocessor relays are less susceptible to GMD/GIC than electromechanical or solid-state relays as most microprocessor relays are designed to filter out frequencies above the fundamental frequency within threshold. To help prevent relay misoperations, setpoints on electromechanical and solid-state relays may be checked to ensure that they do not misoperate during a GMD/GIC event. Likewise, any protective element that operates based on harmonics, neutral point measurements, or sequence components may be checked as well. In order to adequately perform the coordination checks listed above, a method to quantify the effects of a GMD/GIC event in a power system may be created. To harden an entire protective system, existing relays that are unable to filter out harmonics from relay inputs need to be upgraded. In addition, protection schemes that are known to be an issue for GICs/harmonics may be upgraded or replaced.

Neutral Blocking Device

The strategies to mitigate the effects of GMD have been investigated in the past. One solution is use of passive devices to block flow of GIC. Another is use of active devices that are capable of injecting counterposing currents into a designated transformer to cancel out the effect of the GIC in that transformer. The ideal solution would be a device that blocks GIC flow from passing into the power system through the neutral of grounded wye connected transformers without compromising the operation of the power systems. Practically, the addition of a capacitance or resistance between the neutral of the wye connected winding and ground, essentially increases the impedance at the very low, near DC, frequency associated with GICs, hence, provides the GIC blocking function [13]. While the application of capacitors is a good option for blocking GIC flow, capacitors in the neutral connection of a transformer without the application of protective devices would risk safe operation of the AC system during faults [11]. Other GIC blocking device designs use specially rated MOVs to act as open circuits during normal transformer operation and GMD events and as a short circuit when system ground fault occurs and the neutral voltage increases above the MOV rating.

To mitigate the impact of addition of resistance or capacitance to the neutral of a transformer to mitigate for GIC, blocking capacitance can be sized with a sufficiently small impedance to retain effective system grounding for ground faults not caused by GIC, to allow the zero-sequence current contribution of the transformer. Characteristics of GIC generated ground current are different from ground faults. In addition, many GIC blocking designs utilize circuit breakers or power electronics to automatically switch these elements into service when GICs are detected through monitoring equipment within the blocking device, or when GICs are expected from solar flare activity.

GIC blocking device designs may vary greatly from application to application and manufacturer to manufacturer making it important for protection engineers to work with the system planning and procurement engineers and equipment manufacturers during specification, to identify and understand the impact of blocking devices on the transformer fault contribution and protection systems. These impacts should be analyzed for each possible operating mode (GIC blocking element in service vs. bypassed) and for GIC present scenarios.

Figure 3 shows a neutral DC current-blocking device, which is installed in Wisconsin American Transmission Company (ATC) power grid. Refer [4] for design and development approaches and application of neutral DC current-blocking devices (NBD) in North America. Several DC current-blocking devices have been installed by Hydro Québec, ATC and others.

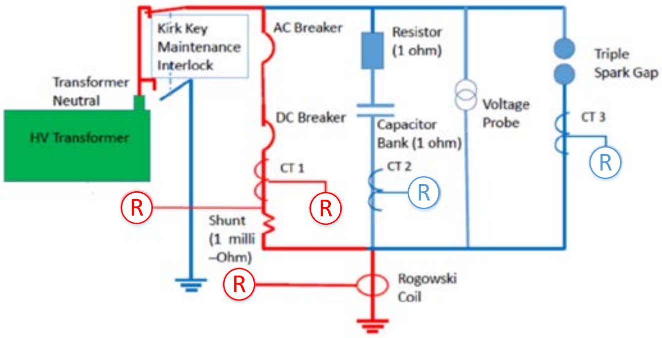

Fig. 3 Neutral Blocking Device Example at ATC [14]

V. GEOMAGNETIC CURRENT AND FIELD MONITORING METHODS

A. GIC Monitoring

Quasi-DC in the neutral can be detected with a non-invasive DC sensor, such as a Hall Effect sensor, to measure the DC flow in the conductor.

There are monitoring devices available to reliably detect core saturation of a power transformer due to GIC. This type of monitoring allows the operators and owners to make better decisions on how to operate their systems and enact contingency plans to handle the load and at the same time save a valuable and expensive power transformer.

A comprehensive GIC monitoring instrument simultaneously measures quasi-DC in the neutral by using a Hall Effect transducer and the harmonics from the phase connected CTs. Figure 4 illustrates the application of a GIC monitoring device.

All information can be telemetered to the System Control Center for developing an effective operator tool. The following steps can be used to supplement existing System Operation GIC Response Procedures. For each of the monitored transformers:

- Minor GIC Alarm – Measured Neutral GIC current exceeds a threshold after a preset time delay.
  - ➢ Operator action – Notify Substation operator and monitor GIC current and temperatures at all monitored transformer locations
- Major GIC Alarm – Minor GIC Alarm plus sufficient magnitude of harmonics - this indicates core saturation.
  - ➢ Operator action – Reduce load on the transformer and monitor temperatures.
- Critical GIC Alarm – Major GIC Alarm plus transformer temperature exceeding guideline.
  - ➢ Operator action – Remove the transformer from service

B. Using Hall-Effect CT Measurements

A Hall-Effect sensor is an electronic current transducer (ECT) that measures the electromagnetic field around a cable. With proper shielding, the sensor can be used to accurately represent the current flowing through the cable.

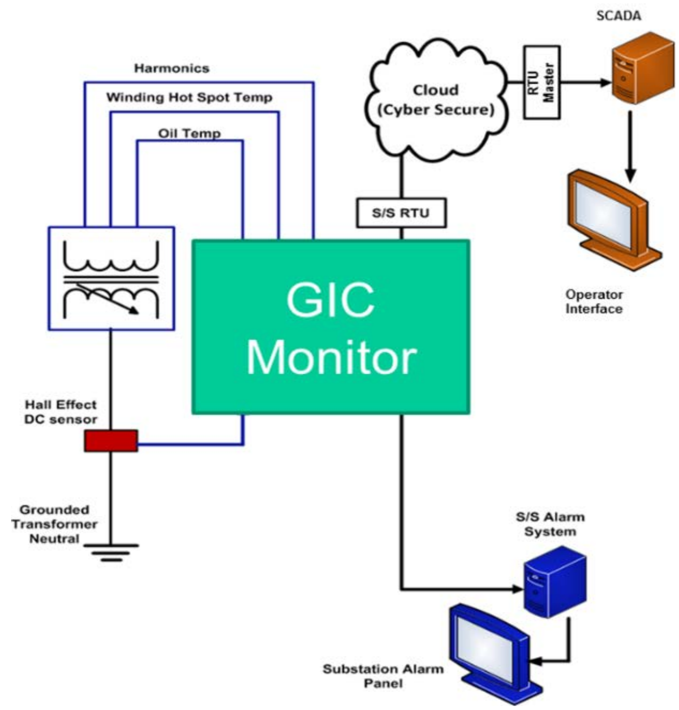

Fig. 4 GIC Monitoring System

The sensor is sensitive to DC and AC flows including both magnitude and phase. Depending on the intended use, the sensor can produce either a voltage or current output. If the recording equipment is close by, then a voltage output is sufficient. Otherwise, a current output is preferable (because of voltage drop over long runs).

C. Geomagnetic Field Monitoring

GIC flow through a transformer could create harmonics, which are injected into a power system, hence affecting the performance of protection systems. It is beneficial to measure the GIC flow with GIC monitors or to calculate the GIC flow from geoelectric fields, which, in turn, can be simulated from measured geomagnetic fields using a so-called Earth's electrical ground conductivity model (or GIC system ground model).

In addition to validating a GIC system ground model, monitoring geomagnetic fields allows building a ground model for a system using GIC and magnetic field measurements.

A typical geomagnetic field measurement system includes three major components: a fluxgate magnetometer sensor assembly, a Power Supply Unit (PSU), and a data acquisition system including an analog low pass filter. Appendix I of the TR-72 report shows an example of GMD monitoring system.

During GMD events, two major physical quantities are measured to illustrate the severity of GMD/GIC. The first one is the DC through the neutral of power transformers and reactor banks. This current directly represents the magnitude of GIC. Hall-effect CTs are required to measure this DC component. The second quantity is the phase currents and extraction of the phase current harmonics. Due to the saturation of power transformers during severe GMD events, the distorted magnetizing currents produce harmonics. An illustration is shown in Figure 5. In addition, the error introduced by the instrumentation channel needs to be considered during the harmonic analysis [15]. Due to harmonics and saturation during a GMD, measurements at the burden resistor of the instrumentation channel may not be linearly proportional to the actual primary current/voltage. This error needs to be reduced to support accurate harmonic analysis. State estimation instrumentation channel error correction, for example, can assist with recovery of the actual primary quantities.

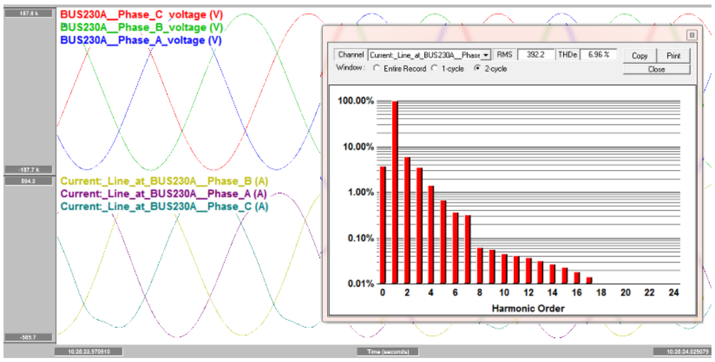

Fig. 5 Illustration of Harmonics Extraction from Phase Measurements during GMD [15]

The harmonic signature shown in Figure 5 is characteristic of GIC. Note that harmonic signature includes all harmonics and their respective magnitude decay almost linearly. This characteristic together with the DC measurement at the neutral provide a reliable measure of GIC that can be used for alerting operators of actual onset of GIC. If a utility has measures against geomagnetic disturbances, these indicators can be used to trigger the measures.

VI. Concusions

Protective relays come in many styles and vintages with different operating principles. Some are designed to measure the peak current and voltage or include the harmonics detection for protective functions. Examples of this type are electromechanical relays or overcurrent or overvoltage relays based on solid-state technology, generally operating on peak value detection for shunt capacitor banks or harmonic filter banks of Flexible AC Transmission System (FACTS) devices.

The risk of false tripping of capacitor banks or harmonic filter banks due to GICs can be reduced by careful relay coordination studies and implementation of relay settings that should have sufficient margins to handle GIC effects. Modern IED relays are less susceptible to GMD-caused harmonics, and GMD susceptibility may help justify replacing legacy electro-mechanical or solid-state relays in the bulk transmission system, especially for protecting those capacitor banks and SVC's that are critical to maintaining voltage stability during GMD events where the reactive power demand is high. If those legacy relays cannot be replaced, it may be necessary to desensitize the element by providing additional security margin to ride through the increased harmonics.

Conventional transformer protection using digital relays will normally operate reliably in the presence of GMD. However, these relays are not designed to protect transformers from damage due to excessive heating caused by GMD events. Specialized monitoring systems may provide operators with additional information to reduce the risk of transformer damage due to severe GMD if such damage is deemed possible.

There is still some uncertainty on the impact of severe GMD on generators. Presently there is no generally accepted practice to protect generators against damage due to excessive harmonics caused by severe GMD events.

Finally, the non-operation of protection and control (P&C) devices during a GMD event does not necessarily mean that the GMD impact was insignificant. It is desirable that most electrical equipment including P&C devices are inspected to detect potential failures or misoperation during GMD events.

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