# Geomagnetic Disturbances (GMD) Impacts on Protection Systems

PREPARED BY THE
Power System Relaying and Control Committee
K Substation Protection Subcommittee
Working Group K17

# Working Group ON
# GEOMAGNETIC DISTURBANCES (GMD) IMPACTS ON PROTECTION SYSTEMS

---


Chair: Qun Qiu*
Vice Chair: Luis Polanco*

Voting Members (*) and Contributors

Mark Adamiak
Abu Bapary*
Jim Campbell
Brandon Davies*
Normann Fischer
Dominick Fontana*
Rafael Garcia
Derrick Haas
Roger Hedding
Charles Henville*
Gary Kobet
Hillman Ladner-Garcia*
Van Le*
Yuan Liao*
Vahid Madani*
Amir Makki
Tapan Manna*
Sakis Meliopoulos
Adi Mulawarman*
Bruce Pickett*
Taylor Raffield
Sam Sambasivan*
Charles Sufana
Rui Sun
Michael Thompson*
Eric Udren
Reigh Walling

## KEYWORDS

Geomagnetic Disturbances (GMD), Geomagnetically Induced Current (GIC); Protection System; GIC Monitoring; Harmonics; Half-cycle Saturation;

## CONTENTS


1. Introduction ........ 1
  1.1. GMD Background ........ 2
  1.2. Historical GMD Events ........ 4
  1.3. Harmonics Produced by GIC Induced Saturation ........ 6
    1.3.1. Fundamentals ........ 6
    1.3.2. Banks of Single Phase Transformers ........ 8
    1.3.3. Three-Phase Transformers ........ 9
  1.4. GMD Impacts on Power Systems ........ 9
    1.4.1. Historical GIC Observations ........ 9
    1.4.2. Capacitor Bank Tripping ........ 11
    1.4.3. GIC Impacts on Transformers ........ 12
    1.4.4. GIC Impacts on Generators ........ 14
2. GMD Impacts on Protection Systems ........ 16
  2.1. CT Saturation due to GIC ........ 16
  2.2. GMD Impacts on Protection & Control Schemes ........ 17
    2.2.1. Capacitor Bank Protection ........ 17
    2.2.2. Transformer Protection ........ 20
    2.2.3. Generator Protection ........ 24
    2.2.4. Transmission Line Protection ........ 25
  2.3. GMD Impacts on Communications ........ 26
    2.3.1. Loss of GPS Signals ........ 26
    2.3.2. Power Line Carrier ........ 26
    2.3.3. Microwave ........ 29
3. Mitigating Impacts on Protection Systems ........ 31
  3.1. Reviewing Susceptible Protection ........ 31
  3.2. Review Settings to Prevent Misoperations ........ 32
  3.3. Methods to Modify/Harden Protection Schemes ........ 33
  3.4. GIC Blocking Device Impacts on Protection & Control ........ 33
4. GIC & Geomagnetic Field Monitoring Methods ........ 37
  4.1. GIC Monitoring ........ 37
    4.1.1. Using Hall-Effect Ct Measurements ........ 38
  4.2. Geomagnetic Field Monitoring ........ 40
5. Conclusions ........ 40

Appendix I Geomagnetic Field Measurement System ........ 42

THIS PAGE LEFT BLANK INTENTIONALLY

# 1. INTRODUCTION

This report discusses the impacts of Geomagnetic Disturbance (GMD) phenomena on protection systems. GMDs create low frequency primary currents which circulate between the transmission lines, high-side Y-grounded transformers and the ground. GMD events may cause unanticipated damage to high voltage equipment such as transformer, generator, shunt capacitor and SVC, and may have significant impacts on radio or satellite communications. GMD events may also impact the performance of protection and control systems, depending on the severity of the GMD in the area. The low frequency (quasi-DC) current created by GMD events is referred to as the Geomagnetically Induced Current (GIC). GIC may cause elevated levels of harmonics. GIC flow in Y-grounded transformers may cause high magnetic flux which could cause severe damage through overheating.

The GMD severity is measured by K-Index factor. The K-Index is a code based on maximum geomagnetic fluctuations over a 3-hour period. The "planetary" Kp index is derived by calculating a weighted average of K- indices from a network of international geomagnetic observatories and is a daily average of geomagnetic activity. K-indices are generally published by institutions working on geosciences, national observatories, space weather services, or in some instances, by military. One example is NOAA (National Oceanic Atmospheric Administration) in the United States[1].

Active stars produce disturbances in space weather, which are studied within the field of heliophysics, the science that studies such phenomena, and is itself primarily an interdisciplinary combination of solar physics and planetary science. The sun can produce intense magnetic and proton storms capable of causing large scale power outages, disruption of radio communications, railroad signaling, and other space borne communication technologies. Intense solar storms may also be hazardous to high-latitude, high-altitude aviation.

GMD impacts may be immediate, or may present themselves over time. Protection system reliability (security and/or dependability) may be affected depending on the severity of the GMD (as measured by K-Index). Many technical papers have been published regarding GMD and their impact on protection systems. This report intends to summarize the main findings of previous events and the current practical experiences on protection systems together in a single document. The report also enhances the findings of an earlier report by the Power System Relaying and Control Committee[2].

---

[1] http://www.swpc.noaa.gov/products/3-day-geomagnetic-forecast

[2] IEEE Committee report, "The Effects of GIC on Protective Relaying", *IEEE Transactions on Power Delivery*, Vol. 11, No. 2, April 1996, pp.725-739

To help the reader understand GMD phenomena, this report first provides an overview of historical GMD events. It then covers the potential impacts to primary equipment. Finally, the impact to power system protective relaying is discussed. This report is written to raise the reader's awareness on issues with equipment specification, operation and maintenance practices, and the application and setting of protection systems which may be impacted by GMD events.

## 1.1. GMD Background

A GMD event is caused by the interaction between the cloud of charged particles produced by a Coronal Mass Ejection (CME) from a solar storm, and the magnetic field of the earth. A solar storm's impact on transmission facilities depends on many factors, including:

- The intensity of solar storm activity
- Whether and where 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, and the winding connection of connected transformers
- The design of connected transformers and their connected load during the GMD

When a mass of particles from a CME strikes the Earth, Earth's geomagnetic fields are distorted. The interaction between the solar storm particles and the Earth's magnetic fields can slowly vary electric fields on the Earth's surface, which in turn drive GIC through power transformers and onto transmission lines. With sufficient intensity and duration, these quasi-DC currents could cause transformer saturation and may result in:

- transformer overheating, which can lead to transformer damage or failure,
- increased transformer reactive power consumption, which may result in lower system voltage and in extreme cases voltage collapse, and
- harmonics that may affect protection systems and may also cause problems for shunt capacitors and generators

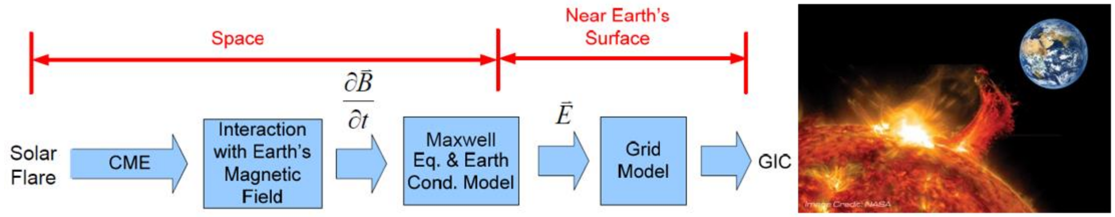



**Fig. 1-1 Solar flare interactions with "Earth" magnetic field**[3]

Most solar storms and CMEs occur during a 4-6 year period, which occurs 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 the earth (Fig. 1-1). Fluctuations of electrojet currents result in changes in the magnetic field of Earth's surface layer (geomagnetic field). Geomagnetic field changes at Earth's surface layer level induce GIC in transmission lines and associated equipment directly connected to the line (e.g., power line carrier) as well as other high voltage equipment at the substation terminated through the bus coupling (Fig. 1-2).

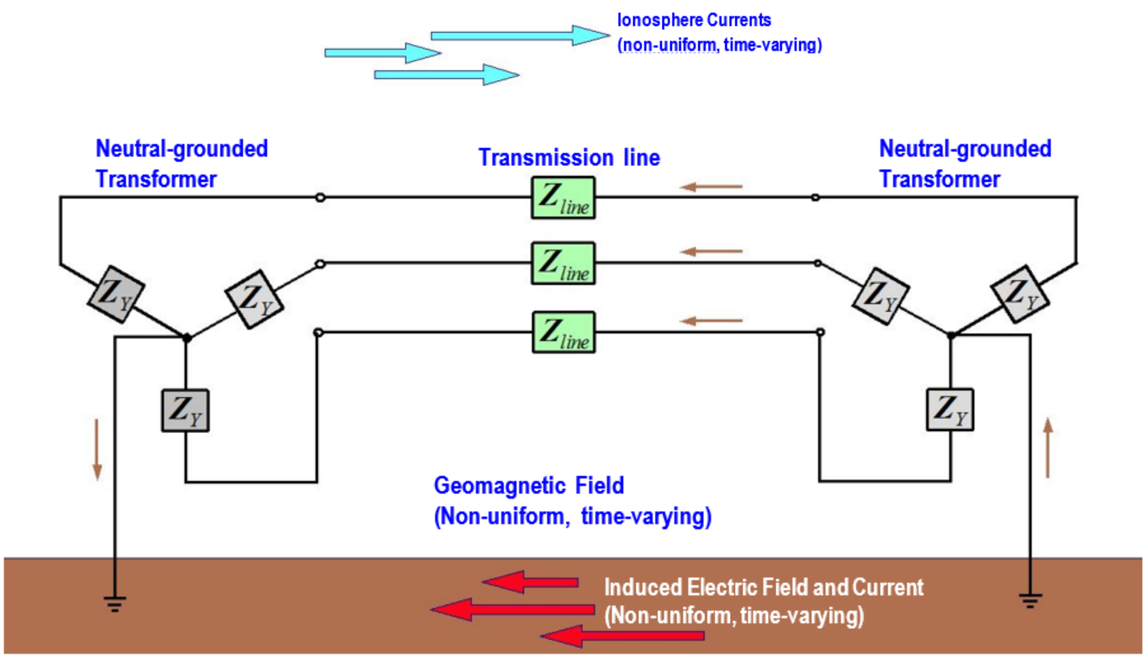



**Fig. 1-2 – Typical GIC flow as a result of a GMD event**

---

[3] NERC, "2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System," NERC GMDTF, February 2012

There are several existing indices to describe the intensity of GMD, such as *AE*, *Ap*, *Kp* and *Dst*. However, these indices are obtained at large time intervals (one hour or three hours) and cover large geographical regions. Researchers[4,5] find it difficult to accurately predict local GIC based on these indices alone. A possible solution is to install devices that directly measure GIC in the field. Local geology also contributes to the GIC formulation. In general, areas with high earth resistivity[6] are prone to higher GIC current, because the horizontal electric field increases as earth resistivity increases.

### 1.2. Historical GMD Events

Space weather disturbances (e.g. electromagnetic, geomagnetic, and/or proton storms) have been observed since before the Common Era (BCE).[7] A 2012 study (by Usoskin et al.) reported 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[8,9], is the most powerful solar storm in history as observed and recorded by ground-based magnetometers. The range of magnetic strength was from -800 nT to -1750 nT. During the Carrington Event, auroras, which are normally only seen near the poles, were seen at lower latitudes very close to the equator. Auroras over the Rocky Mountains in the United States were so bright that their glow awoke gold miners, who began preparing breakfast because they thought it was morning. People in the northeastern United States could read newspapers by the aurora's light. 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.[10]

Table 1 shows notable GMD events since 1859. Solar storms causing GMDs on the Earth's magnetosphere may have had substantial impacts on bulk power systems,

[4] L. Trichtchenko and D. H. Boteler, "Modeling Geomagnetically Induced Currents Using Geomagnetic Indices and Data," *IEEE Trans. Plasma Sci.*, vol. 32, no. 4, pp. 1459–1467, Aug. 2004

[5] J. G. Kappenman, "An overview of the impulsive geomagnetic field disturbances and power grid impacts associated with the violent Sun-Earth connection events of 29-31 October 2003 and a comparative evaluation with other contemporary storms," *Space Weather*, vol. 3, no. 8, Aug. 2005

[6] R. J. Pirjola and A. T. Viljanen, "Geomagnetic Induction in the Finnish 400 KV Power System," in *Environmental and Space Electromagnetics,* H. Kikuchi, Ed. Tokyo: Springer Japan, 1991, pp. 276–287.

[7] A. L. Melott, B. C. Thomas (2012), "Causes of an AD 774–775 14C Increase." *Nature*, 491 (7426): E1–E2

[8] R. C Carrington, "Description of a Singular Appearance seen in the Sun on September 1, 1859"

[9] *"SOUTHERN AURORA", The Moreton Bay Courier, Brisbane: National Library of Australia. September 7, 1859*

[10] "Solar storm risk to the north American electric grid." https://www.lloyds.com/~/media/lloyds/reports/emerging%20risk%20reports/solar%20storm%20risk%20to%20the%20north%20american%20electric%20grid.pdf

telecommunications systems, aircraft, submarines, and satellites. In some instances, literature references are offered within the Table 1.

| | |
|---|---|
| • Carrington Event[8,11,12] (August 28 – September 2, 1859) | • Long-range radio disruptions over the Atlantic (March 24, 1946) |
| • The Civil War Aurora (December 14, 1862) | • The Acheron Submarine Storm (February 24, 1956) |
| • The Transit of Venus Storm (November 18, 1882) | • The 1967 Solar Storms (May 18 - 23, 1967) |
| • Aurora paralyzed Telegraph systems (November 01, 1903) | • The Space Age Storm (August 02, 1972) |
| • The New York Railroad Storm (May 13, 1921) | • The Quebec Blackout Storm (March 13, 1989) |
| • The Fatima Storm (January 25, 1938) | • The Bastille Day Event (July 14-16, 2000) |
| • The Easter Sunday Storm (March 25, 1940) | • The Halloween Storm (October 29, 2003) |
| • The Playoffs Storm (September 18, 1941) | • The Solar Storm of 2012 (July 23, 2012) |

**Table 1 Major Notable GMD Events Since 1859**

[11] https://en.wikipedia.org/wiki/List_of_solar_storms
[12] http://www.solarstorms.org/SRefStorms.html

The Quebec Blackout[13] is an example of a massive power (~21.5 GW) outage caused by a GMD event. During the GMD event, power system voltage instability in the Hydro Quebec transmission grid resulted in harmonic filter banks and seven static var compensators (SVCs) tripping off in less than a minute[14]. The first SVC tripped at Chibougamau substation at 02:44:17 (EST) and the entire grid collapsed at 02:45:49 (EST)[14] The restoration process took about nine hours to reestablish 83% of grid power level (i.e., 17.5 GW), and about six million people were out of power for this time; a loss of $6.0 billion USD was estimated for the Quebec Blackout.

## 1.3. Harmonics Produced by GIC Induced Saturation

### 1.3.1. Fundamentals

Flow of GIC through transformers may cause asymmetric part-cycle saturation of the 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. The harmonic currents can directly impact power system equipment such as capacitors, harmonic filters, SVCs, and generators, and may interfere with the proper operation of protection systems.

The magnetizing current of a saturated transformer due to GIC consists primarily of unipolar pulses, which have a magnitude and pulse-width that are functions of the GIC magnitude, as shown in Fig. 1-3. Fourier analysis of the magnetizing current reveals a dc component that is equal to the GIC, a fundamental-frequency reactive current component, and harmonic components. The spectral components for a typical bank of single-phase transformers with 0.1 p.u. GIC (the p.u. base used here is the peak value of the rated winding current) is shown in Fig. 1-4. The magnetizing current includes both even and odd order harmonics and the total rms magnitude of the harmonic components exceeds the fundamental component. The second harmonic component is always the largest, and the magnitude of the components has a generally decreasing trend with increasing harmonic order. The magnetizing current from GIC is essentially the same as caused by transformer energization inrush, except that the GIC saturation can persist for an extended period.

[13] NERC, NERC Report on March 13, 1989 Geomagnetic Disturbance

[14] Guillon, S.; P. Toner; L. Gisbon; D. Boteler (2016). "A Colorful Blackout". *IEEE Power & Energy Magazine, November/December, 2016, p.59 – p.71*

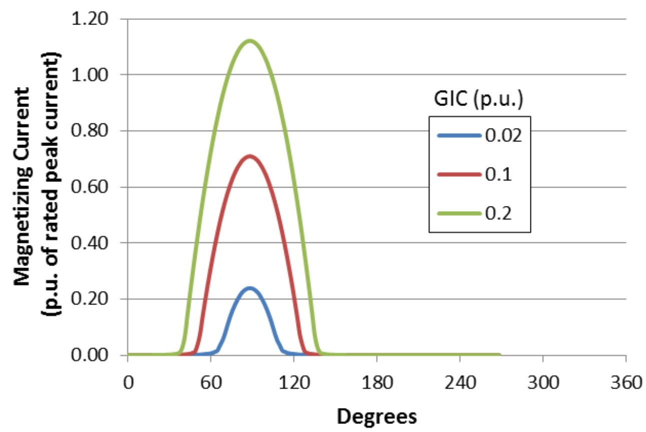



**Fig. 1-3 Magnetizing current pulses for different GIC magnitudes**

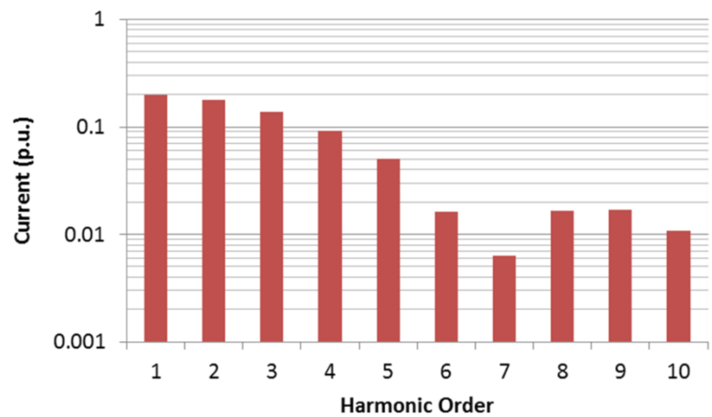



**Fig. 1-4 Spectral components of magnetizing current with 0.1 p.u. GIC in a typical transformer**

Fig. 1-5 shows the variation of the harmonic components with GIC level, where it can be seen that the higher-order harmonic component magnitudes peak and null as the magnetizing current pulses widen with increasing GIC. The apparent discontinuities of harmonic current magnitude are actually polarity reversals. The polarities of odd-order harmonics are independent of the polarity of the GIC flow, but the even-order harmonic polarities reverse with reversal of net GIC flow.

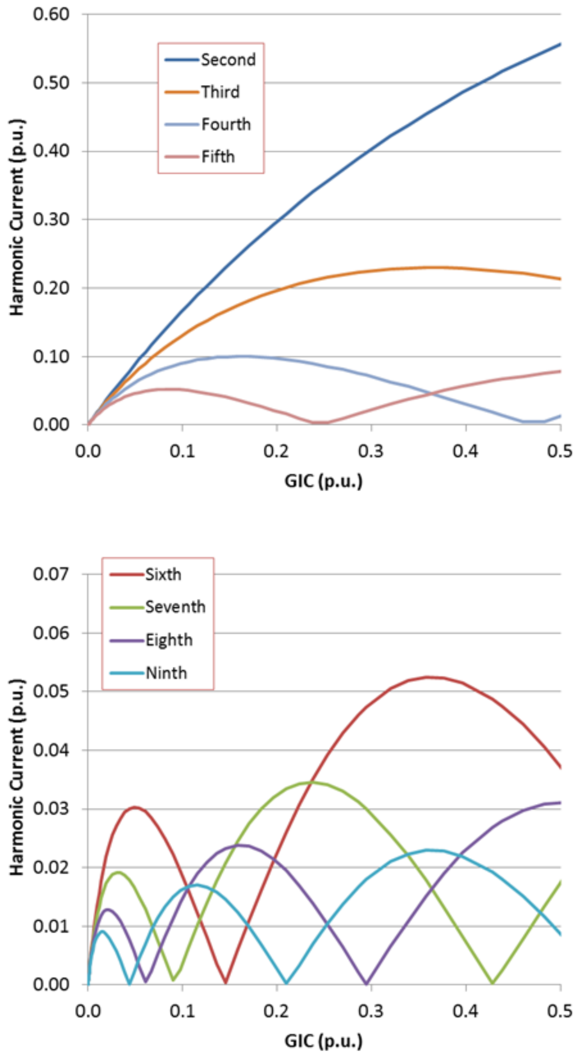



**Fig. 1-5 Harmonic component magnitudes versus per-unit GIC.**

### 1.3.2. Banks of Single Phase Transformers

The harmonic components of magnetizing current for banks of single-phase transformers can be calculated analytically using Equation (1), where $V_f$ is the per-unit fundamental voltage, $X_{ac}$ is the slope of the magnetization curve in the fully-saturated region (often called the "air core reactance"), $n$ is the harmonic order, and α is the saturation delay angle.

$$\bar{i}_n = \frac{V_f}{\pi \cdot X_{ac}} \cdot \left[ -\frac{\cos\left(n\pi/2 + (n-1)\cdot\alpha\right)}{n-1} + \frac{\cos\left(n\pi/2 + (n+1)\cdot\alpha\right)}{n+1} + 2\cdot\frac{\sin(\alpha)}{n}\cdot\sin\left(n\cdot\left(\pi/2 + \alpha\right)\right)\right] \quad (1)$$

The saturation delay angle can be determined for any level of GIC by iterative solution of Equation (2).

$$i_{GIC} = \frac{1}{2\pi} \cdot \frac{V_f}{X_{ac}} \left[ 2 \cdot \cos(\alpha) - \pi \cdot \sin(\alpha) + 2\alpha \cdot \sin(\alpha) \right] \tag{2}$$

The harmonics produced by GIC saturation of single-phase transformers fall into the classic sequence component pattern: triplen (multiples of three) harmonics are zero sequence, 3rd, 6th, etc.; 2nd, 5th, 8th, etc. are negative sequence; and 4th, 7th, 10th, etc. are positive sequence.

### 1.3.3. Three-Phase Transformers

The GIC saturation behavior of three-phase transformers is quite complex because of the interaction of the magnetic circuits of the phases. The magnetic circuits of a core are not equal. For example, the AB, BC, and CA loops in the core may be different due to unequal lengths and cross section of the yoke tying the three main core legs together. Time-domain magnetic circuit modeling is required to determine the harmonic currents. This modeling requires detailed information regarding the transformer's design and system background harmonics. Some researchers have proposed a duality-based model[15] that accurately models the core structure of a three-phase transformer, including the flux path in air and the tank wall. The magnetizing current for a transformer subject to GIC can be simulated with that model.

Because of the inherent phase imbalance of three-phase transformers when saturated by GIC, the harmonic currents do not follow the usual sequence pattern[16]. The effect is that the harmonics are not exactly equal per phase so the typical understanding of harmonics being a balanced condition is false. This affects the purity of the sequence nature of the various harmonics. For example, triplen harmonics may appear in the positive and negative sequences, as well as zero sequence, and the zero-sequence may contain harmonics other than multiple of third harmonics.

## 1.4. GMD Impacts on Power Systems

### 1.4.1. 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. These were installed to detect GIC and to assess the transformers' vulnerability to GIC during the Solar Cycles 22 & 23. For instance, from 1989 to 1994, AEP installed GIC monitors at four 765kV substations during the peak of Solar Cycle 22. For the March 13, 1989 K-9 solar storm, less than 10 amps of GIC was recorded. Other observations, such as high audible noise at one GSU,

[15] S. Jazebi *et al.*, "Duality-Derived Transformer Models for Low-Frequency Electromagnetic Transients - Part II: Complementary Modeling Guidelines," *IEEE Trans. Power Deliv.*, vol. 31, no. 5, pp. 2420–2430, Oct. 2016.

high harmonics, and voltage fluctuations were reported during the major storm. No other concerning system behavior or visible equipment damage was observed at the monitored sites. Regular dissolved gas analyses (DGA) were performed showing no evidence of transformer damage from the GMD events. For the peak of Solar Cycle 23, from 1999 to 2002, GIC monitors were installed at three substations, with the highest GIC observed being 87A at the Jefferson 765kV transformers on July 15, 2000 during a K-9 GMD event. Typical GIC readings were much lower. Fig. 1-6 shows the GIC measurements at three EHV transformer locations (Jefferson, Kammer, and Jackson's Ferry) during the July 15, 2000 K-9 GMD event[16]. Again, no failures, gassing or lasting impacts were attributed to the GMD. GMD events appeared to have more limited impacts on AEP compared to utilities closer to the Earth's poles, and the GIC monitors were removed after the solar cycle peak.

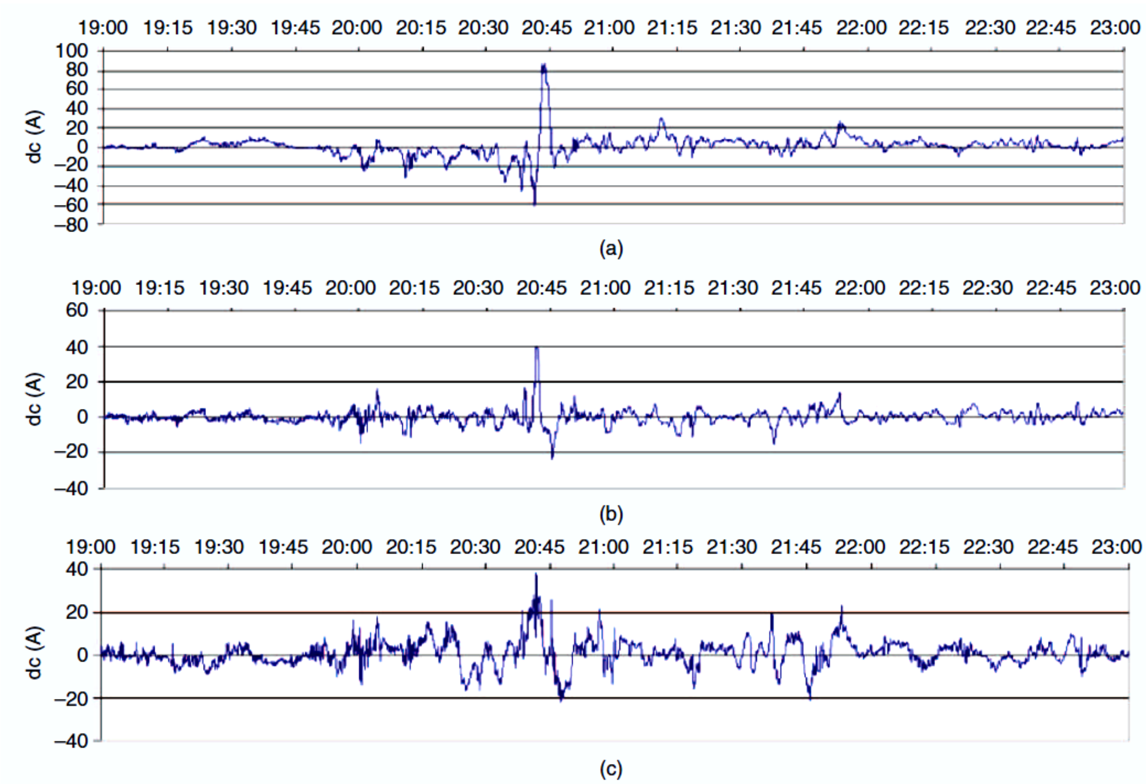



**Fig. 1-6 GIC currents observed during a Kp = 9 GMD event on 15 July 2000: (a) J-Station T1 neutral dc current, (b) K-Station T200 neutral dc current, and (c) JF-Station T1 neutral dc current.**[16]

---

[16] Q. Qiu, J. A. Fleeman and D. R. Ball, "Geomagnetic Disturbance: A comprehensive approach by American Electric Power to address the impacts", *IEEE Electrification* Magazine, December, 2015.

BC Hydro has observed GICs flowing in a 450 km long 500 kV transmission line running east-west at about latitude 54 degrees North[17]. This line is broken into three sections with two substations at intermediate points. The terminal and intermediate substations all have autotransformers that allow paths for GIC to flow to ground. Measured values of GIC during a geomagnetic storm in August 1979 recorded values of about 11 A/phase. GIC also flowed (but was not measured) in a long 138 kV transmission line running Northwest from the Western terminal station of the 500 kV line. The GIC flowing through these 500 kV and 138 kV lines caused harmonics due to half cycle saturation of the transformers. The harmonics had two significant negative effects. First, transmission line protection that was sensitive to harmonics tripped when the protection could have restrained. Second, the harmonics generated by the GMD excited a fourth harmonic resonance in the 138 kV line emanating from the western end of the 500kV line causing significant overvoltages (see Fig. 1-7)[18].

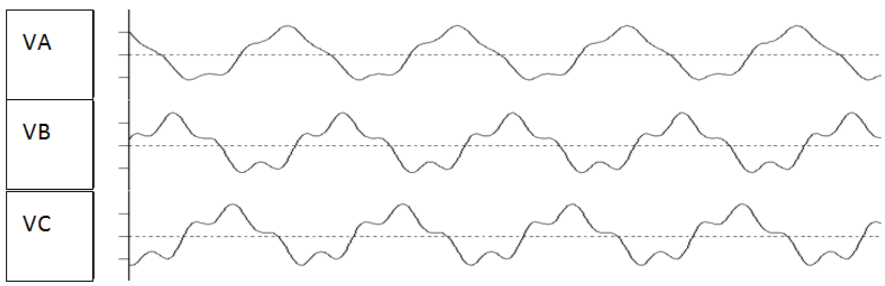



**Fig. 1-7 Harmonic resonance distorts 138 kV voltage**

The harmonic excitation in the 138 kV line was mitigated by placing a GIC blocking capacitor in the neutral of the transformer at the receiving terminal of the line[19]. This reduced the harmonic excitation, and mitigated the overvoltages.

Half cycle saturation of the transformers at the Western terminal of the 500 kV lines also caused increased reactive power absorption that reduced the voltage at that terminal. However, the voltage reduction was not severe and was mitigated by normal operating procedures.

### 1.4.2. 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

---

[17] D. H. Boteler, R. M. Shier, T. Watanabe, R.E. Horita, "Effects of Geomagnetically Induced Currents in the BC Hydro 500 kV System", *IEEE Trans. On Power Delivery*, Vol.4, No. 1, January 1989, pp. 818-823.
[18] J. H. Sawada, T. G Martinich, "138 kV Voltage Distortion Due to GIC Induced Harmonics", CEA, Spring Meeting, Vancouver, BC, March 1992

harmonic distortion.[19] This protection scheme was a neutral unbalance scheme that measured current at the neutral ground point to determine the failure of capacitor units. Though the scheme was equipped with a parallel capacitor to provide immunity to 3rd harmonics, the electromechanical relay was unable to distinguish the excessive harmonics of other orders from the fundamental frequency component flowing and, therefore, mis-operated. The disturbance did not impact grid stability since the event occurred late at night. This event has drawn close attention by DVE as it pointed out a vulnerability of the system which could increase when the system is under higher stress.

### 1.4.3. GIC Impacts on Transformers[20]

A power transformer is typically constructed with either two or three windings with one of the windings typically connected to the ground. These windings are wound around a laminated core of high silicon steel. During normal operation of a transformer there are no zero sequence components unless there is a fault from phase to ground. When a phase to ground fault occurs, there will be zero sequence components whose magnitude is dependent on the impedance of the fault. During a phase to ground fault the current waveform may become highly distorted, but it rarely contains dc components that last a significant period.

However, a GIC event will have dc from several amperes to upwards of several hundred amperes flowing in the ground connection of the power transformer that could last several minutes or more. GICs may cause the transformer core to saturate. Single phase transformers, transformers with five leg cores, and shell form design transformers are the most susceptible to applied dc current. Typically, these types of transformers are the largest in a power system and 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.

Core saturation due to GICs 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 overexcitation and GIC.

[19] Rui Sun, Mark McVey, Mike Lamb, and R. Matthew Gardner, "Mitigating Geomagnetic Disturbances: A summary of Dominion Virginia Power's efforts", *IEEE Electrification* Magazine, December, 2015
[20] IEEE PES Technical Council Task Force on Geomagnetic Disturbances, "Geomagnetic Disturbances – Their Impact on the Power Grid", *IEEE Power & Energy Magazine*, July/August 2013

Transformer localized heating due to GIC is different from transformer hot spots caused by heavy loading. Typically, most transformers do not have sensors to detect the metallic hot spots due to GIC. Some utilities have transformer specifications that require fiber optic temperature probes installed at the top/bottom yokes and tie plate in some EHV transformers, which can provide some indication of possible transformer overheating due to GIC flow, but the affected transformers are not necessarily tripped by such hot spot protection. Instead, operating procedures (reducing loading, cooling control, etc.) are put into place to address the transformer GIC overheating issue.

Direct current flowing through transformer windings will saturate the core heavily and boost the magnetizing current. As a result, the distribution of flux will be altered, leading to increased eddy current loss, var consumption, and tank wall heating. During the geomagnetic storm in 1989, a step-up transformer for Salem Unit 1 endured a large GIC, which was about 75A per phase[21]. This GIC distorted the magnetizing current and increased the var consumption by 150 ~ 200 Mvar. After an unusual increase in combustible gas, the transformer was removed from service and the replacement energy cost was about $400,000 per day. A visual inspection revealed thermally degraded insulation and melted strands of copper (Fig. 1-8). Due to the increased eddy current loss and uneven distribution of magnetizing current in the winding, the low voltage winding was severely damaged during the GMD.

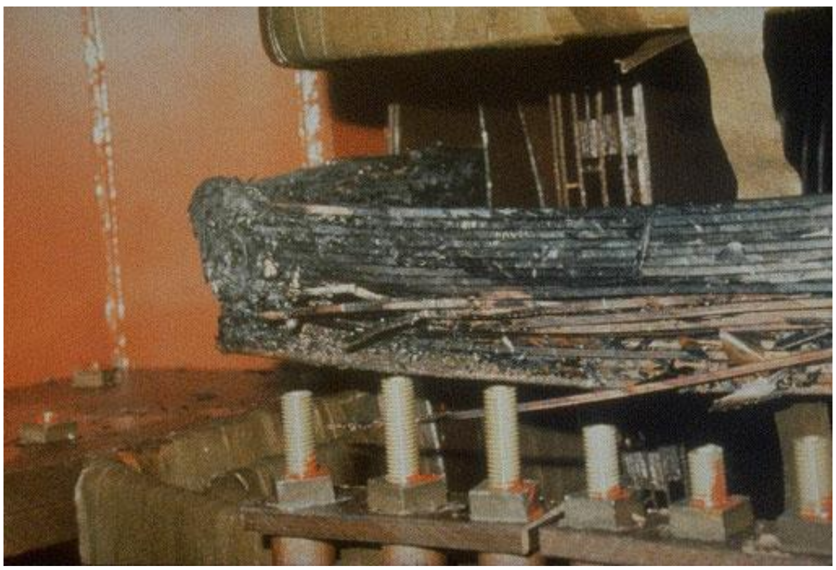


**Fig. 1-8 Transformer damaged at Salem Unit 1, year 1989**
**(Photo Courtesy of PSE&G)**

[21] NERC, NERC Report on March 13, 1989 Geomagnetic Disturbance

On September 19, 1989, the transformer at Salem Unit 2 encountered a similar problem during another geomagnetic storm. The transformer was removed from service and an inspection found damage similar to the Salem Unit 1 transformer, but to a lesser extent.[21]

### 1.4.4. GIC Impacts on Generators

#### a. Generator Harmonics

Generators are usually interconnected to the 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 these pose a considerable risk to the machine if excessive. The harmonic currents flowing into a generator are not necessarily just those caused by saturation of the GSU transformer. Saturation of other transformers in the grid may provide a substantial contribution to generator harmonic current flow. 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 GSU connection. Both positive and negative sequence harmonics create impacts similar to negative-sequence fundamental currents. Since harmonics are not balanced per phase (Section 1.3.3), it results in crossover between the sequences. What would typically be a positive sequence harmonic such as the $4^{th}$ harmonic, due to the unbalance in phases will have some negative sequence and zero sequence components as well. This is no different with pure fundamental waves that are unbalanced. But, a positive sequence harmonic such as the $4^{th}$ will induce currents in the rotor that appear to be $3^{rd}$ harmonic frequency due to the fact that the rotor is rotating at fundamental frequency. If there is an unbalance in the $4^{th}$ harmonic, there will be a negative sequence component to it. This component will appear to be $5^{th}$ harmonic frequency to the rotor.

#### b. Rotor Heating

Positive sequence harmonic currents flowing into the stator of a generator cause an air-gap magnetic field that rotates in the 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 the reverse direction at $n$ times the synchronous speed. In the rotor reference frame, the apparent speed is $n$+1 times synchronous speed.

Both the 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. The eddy currents cause heating that can potentially be damaging or destructive to the generator. At low levels, this heating over an extended period of time will accelerate degradation of field winding insulation. High levels of negative-sequence heating, however, can potentially result in rapid subsequent machine failure. One failure mode of concern is yielding or loosening of the aluminum rotor slot wedges that retain the field windings in the slots. High temperatures cause aluminum to substantially lose mechanical strength, and these slots are exposed by high centrifugal loadings. If the rotor wedges fail to retain the field winding bars, catastrophic destruction of the generator can result. Other failure modes include arcing across the field winding insulation and failure of the rotor retaining rings.

IEEE Standards C50.12[22] and C50.13[23] specify negative sequence current withstand capabilities for salient-pole and cylindrical-rotor synchronous generators, respectively. The continuous negative sequence current capability for these machines is specified by these standards as a function of machine type, rating, and cooling design. The latest versions of these standards now include a formula to convert stator current with harmonic distortion into an equivalent negative sequence ($I_2$) fundamental current. This equivalent $I_2$ has the same rotor heating potential as the same amount of negative-sequence fundamental current, Equation (3).

$$I_{2eq} = \sqrt{I_2{}^2 + \sum_n \left( \sqrt{\frac{n+i}{2}} \cdot I_n{}^2 \right)} \tag{3}$$

### c. 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.

A turbine-generator shaft is a complex mechanical system with many modes of natural-frequency torsional vibration. Stimulation of a resonant mode can result in substantial amplification of the response. When sufficiently amplified by mechanical resonance, the deflections can cause material fatigue and possible failure.

Negative sequence fundamental current results in torsional stimulus at twice the fundamental frequency (i.e., 120 Hz in 60 Hz machines). Generators are routinely exposed to negative sequence fundamental, both on a continuous basis due to transmission line impedance imbalance and load imbalance, and more severely for shorter durations due to unbalanced grid faults. Considerable attention during turbo-generator design is focused on ensuring that torsional resonances are sufficiently separated in frequency from 120 Hz. Providing frequency separation of higher-frequency torsional oscillation modes from integer multiples of the fundamental, however, is more difficult. Torsional resonant frequencies change to some degree with operating conditions, and these changes become more pronounced for higher-frequency modes.

[22] IEEE C50.12-2005 - IEEE Standard for Salient-Pole 50 Hz and 60 Hz Synchronous Generators and Generator/Motors for Hydraulic Turbine Applications Rated 5 MVA and Above

[23] IEEE C50.13-2014 - IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz Synchronous Generators Rated 10 MVA and Above

There is also substantial uncertainty in the calculation of higher-frequency turbo-generator torsional modal frequencies.

Bulk transmission systems, under normal circumstances, have limited amounts of ambient harmonic distortion. The most significant background distortion under normal conditions in most transmission systems tends to be at the 5th and 7th harmonics. Attention is given during turbo-generator design to avoid torsional resonance near the 6th harmonic (in the rotor reference frame), as this is stimulated by 5th harmonic negative sequence currents and 7th harmonic positive sequence currents. Harmonic distortion during a GMD, however, will tend to involve harmonic orders that are not typically experienced at significant magnitude during normal conditions, such as even-order harmonics. Levels of distortion are likely to be far more severe during a GMD than the normal levels of distortion which the industry has experienced. It is likely that a torsional frequency stimulated by harmonics during a GMD may coincide with the resonant frequencies of one or more torsional modes.

Higher frequency torsional mode shapes tend to involve participation by the turbine blades. If a blade vibration mode coincides with a stimulated frequency, the potential for loss of blades from fatigue due to torsional vibration may be significant. Thus, it appears that there is a plausible risk to turbo-generators from severe harmonic distortion during a GMD. However, there have been no documented cases of such failures as the result of GMD.

Turbo-generator manufacturers could be contacted to obtain their recommendations regarding the ability of specific machines to withstand abnormal harmonic distortion. Vibration test analysis of machines can also be used to indicate the correlation of torsional resonance modes with harmonic frequencies.

# 2. GMD IMPACTS ON PROTECTION SYSTEMS

## 2.1. CT Saturation due to GIC

GIC levels have some effect on conventional instrument current transformer (ct) performance. However, the expected GIC levels are small compared with Ct ratings in typical protection applications. One study using computer simulations and laboratory tests analyzed Ct performance with very low frequency currents, and then used computer simulation and laboratory tests to verify Ct performance[24]. Part of this report was an analysis of how cts are applied to protective devices in practice to minimize the impact of day-to-day phenomena such as anti-aliasing. The analysis found that the GIC impact may

[24] B. Kasztenny, N. Fischer, D. Taylor, T. Prakash, "Do CTs Like DC? Performance of Current Transformers With Geomagnetically Induced Currents" 42nd Annual Western Protective Relay Conference, October 2015

be minimal by nature of application. However, applications vary for different users. The user may want to consider their specific applications and environment to determine the impact of low frequency quasi-DC on the magnetic core of the ct.

As shown in the report[24], GIC had very little impact on the cts used for transmission line and transformer protection. The quasi dc drives the flux linkage close to the knee-point of the Ct excitation curve. However, the ac ratio current is still reproduced reasonably well. The error is increased, compared with no dc present, but the difference is not as dramatic as one might expect.

The following conclusions can be drawn with respect to protection elements that can be impacted by steady-state Ct saturation due to GICs:

- Line distance and overcurrent elements may slightly underreach due to Ct errors caused by GICs. This is not a concern for instantaneous tripping as these elements do underreach under normal system contingencies, such as fault resistance, and are therefore backed up by other protection elements. Time-coordinated distance or overcurrent elements apply overreaching margins, and with typical margins, they retain dependability, despite the GIC-caused Ct errors.
- Line differential elements typically incorporate a means to address Ct saturation.
- Transformer differential elements include percentage restraint to cope with Ct errors, and they too remain secure for external faults even under GICs.

Transient Ct saturation due to GICs can be very substantial. The saturation is, however, short-lived. The following comments address this:

- 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 GICs.
- 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 the errors during transient Ct saturation from the GICs are short-lived.
- Similar points can be made about transformer differential relays as line differential relays.

It can be concluded that the impact of GIC-induced Ct saturation on protective relays is minor. Slightly degraded dependability (underreaching, slower operation) is no different than for a number of other well-known factors concerning Ct saturation. Existing means to deal with Ct saturation due to the well-recognized factors ensure security for Ct errors due to GICs.

## 2.2. GMD Impacts on Protection & Control Schemes

### 2.2.1. Capacitor Bank Protection

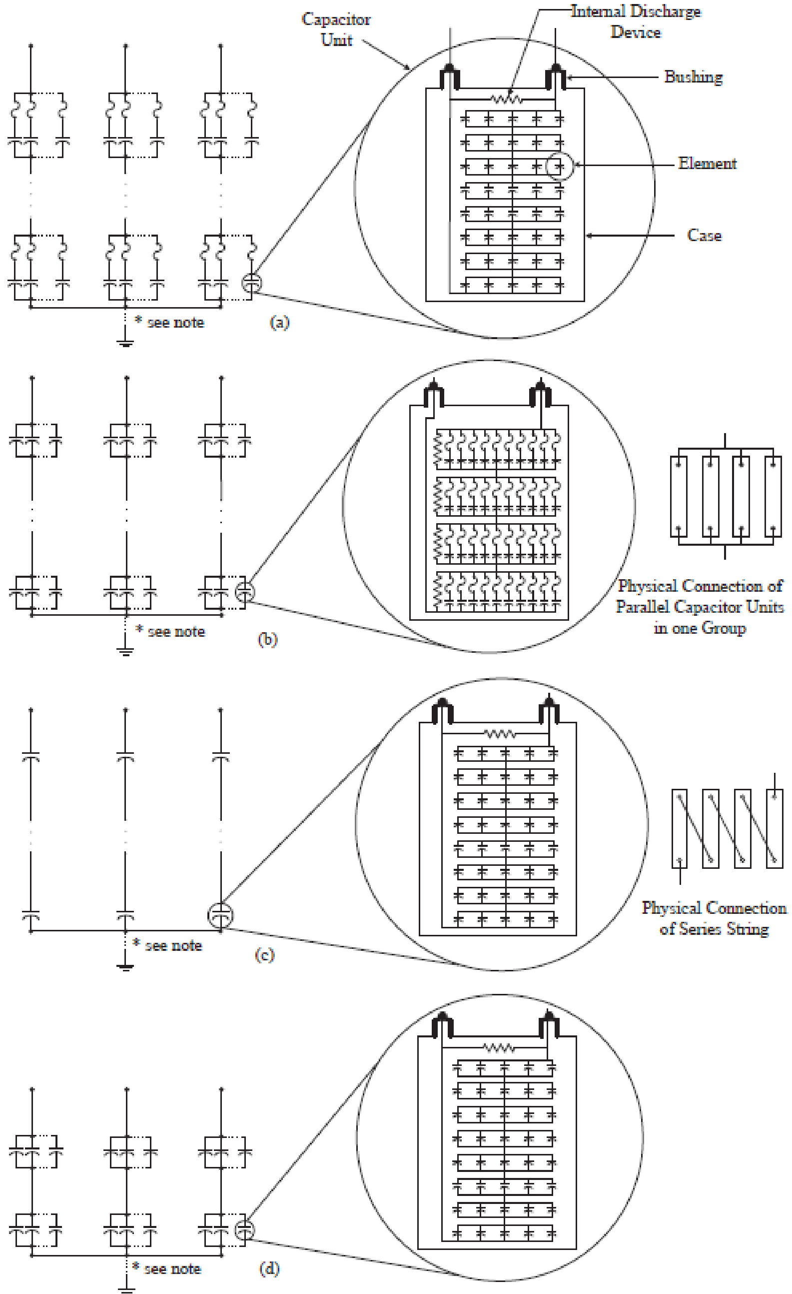
Transmission capacitor banks are composed of tens to hundreds of individual capacitor units that are connected in series and parallel. Capacitor banks are often wye, double wye or delta connected and grounded or ungrounded. Each bank is composed of three phases of capacitor groups formed by individual capacitor units.

Four types of capacitor units and their respective connections are widely used:

a) Externally fused, with individual fuses for each capacitor unit
b) Internally fused, with each element fused inside the capacitor unit
c) Fuseless, with capacitor units connected in series strings between line and neutral (or between line terminals)
d) Unfused, with capacitor units connected in a variety of series and parallel arrangements

Besides the internal or external fuses, unbalance protection is the widely accepted scheme for capacitor bank protection for the following fault conditions:

a) Faulted capacitor element
b) Fault from capacitor elements to case, bushing failure, faulty connection in capacitor unit
c) Fault in capacitor bank other than in unit (arcing fault in bank)
d) Continuous overvoltage on capacitor elements or units due to faulted elements or fuse operations within the bank.




(a) Externally-fused
(b) Internally-fused
(c) Fuseless (may use multiple strings per phase)
(d) Unfused

*Note - Capacitor banks may be grounded

**Figure 2-1 Wye Connected Capacitor Bank – Grounded or Ungrounded**[25]

A variety of sensitive protection schemes are available to measure unbalanced currents or voltages between various parts of the bank and identify possible failures of individual units that could cause unacceptable overvoltages across healthy units in other parts of the bank. Capacitor bank protection schemes are described in IEEE Std C37.99-2012[25]. 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).

Most digital relays are designed to measure fundamental frequency currents and filter all other frequencies out of the measured parameters. Such relays could be useful for capacitor bank protection applications that require high sensitivity and accuracy in the presence of a significant proportion of harmonics.

On the other hand, electromechanical relays as well as some static relays may be susceptible to undefined performance in the presence of harmonics. In some early events (e.g., as noted in Section 1.4.2 in this report), though the capacitor banks were equipped with parallel capacitors to filter out certain harmonic orders, the electromechanical relays were unable to distinguish the excessive harmonics of other orders from the fundamental frequency components and, therefore, mis-operated. Replacing electromechanical relays with digital relays enables protective functions to filter all harmonics and dc offsets to provide more predictable performance to fundamental frequency measurements in capacitor bank sensitive protection applications. These sensitive applications will usually be measuring unbalances and differential current or voltage between various parts of the bank.

It should also be noted however, that the filtering provided by digital relays will prevent them from protecting 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 required to measure total phase currents into a bank exposed to harm due to excessive harmonic absorption.

### 2.2.2. Transformer Protection [26]

Basic transformer electrical protection consists of differential and/or restricted earth fault and overcurrent protection. In this section, the impact of GIC on these elements under three system conditions will be examined:

- Normal system operating conditions,
- an external fault condition, and

[25] IEEE C37.99-2012 Standard, IEEE Guide for the Protection of Shunt Capacitor Banks, March 8, 2013
[26] IEEE C37.91-2008 Standard, IEEE Guide for Protecting Power Transformers, May 2008

- an internal fault condition.

To understand the impact of GIC on a digital/numerical transformer protection relay the data acquisition of a digital protection relay may be examined. Figure 2-2 is a basic sketch of data acquisition schematic for a digital protection system.

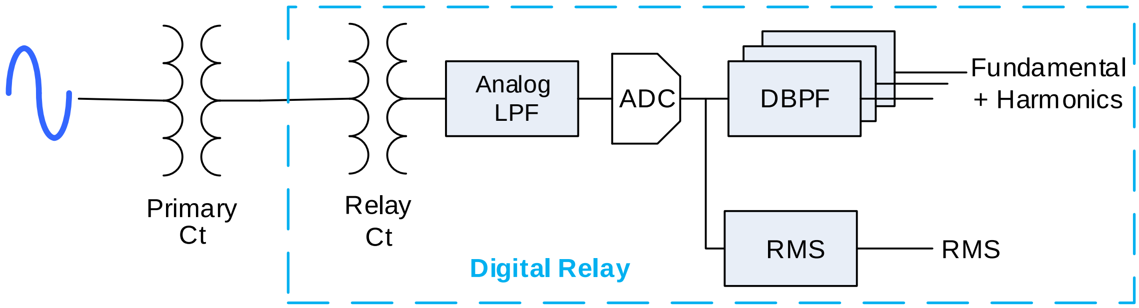



**Figure 2-2 Sketch of a simplistic data acquisition of a digital relay**

Figure 2-2 shows that the data acquisition system, within a relay, begins with a stepdown ct. This discussion will focus on the stepdown Ct since this is the only component the GIC can affect. As discussed in section 2.1, a GIC has negligible impact on a primary ct; in fact, the primary Ct acts as a high pass filter, basically filtering out the low frequency component of the primary signal (the GIC component - quasi dc - of the primary signal) and allowing the nominal frequency component to be correctly scaled down without much loss of signal integrity. Therefore, the Ct in the protective relay input is not affected by the GIC since the primary Ct does not reproduce the GIC component contained in the primary current.

### a. Normal Operating Conditions

Should GIC occur under normal power system conditions, the excitation current of the transformer will increase depending upon the magnitude of the GIC. The magnitude of the GIC current also determines the harmonic content of the transformer magnetizing current. To see what effect this has on the transformer protection each of the protection elements should be examined separately.

#### 1. Differential Element

The result of GIC in a transformer is an increase in the magnetizing current of the transformer. All transformer terminals connected to a source (see Figure 2-3 below) supply this magnetizing current.

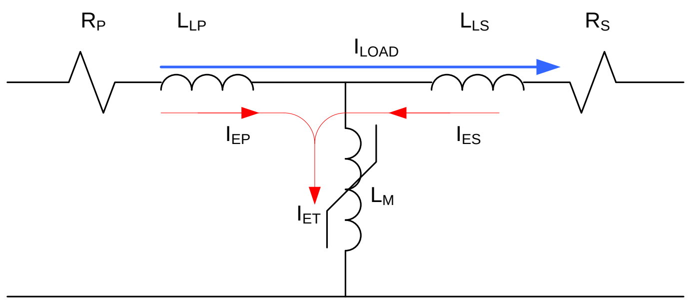



**Figure 2-3 Electrical equivalent diagram for a two-winding transformer showing how the magnetizing current manifests itself as a differential or operating current**

As it can be seen in Figure 2-3, the magnetizing current (IET) appears to be a differential, or operating current (IOP). As mentioned previously, the magnitude of IET is dependent on the magnitude of the GIC as is the magnitude of the harmonics generated by the magnetizing branch of the transformer. In general, the GIC current is not large enough to generate sufficient operating current in the differential element to jeopardize the security of the element, i.e., this IOP current is below the pickup current to operate the differential element.

### 2. Restricted Earth Fault Element (REF)

As mentioned in Section 2.1, the GIC current does not result in the saturation of the phase or neutral cts but may result in the transformer drawing a larger magnetizing current. This magnetizing current will be symmetrical (i.e., it will not contain zero sequence current) and therefore will not jeopardize the security of the REF element. Should only one of the legs of the transformer saturate due to the GIC current (which is highly unlikely), that phase will draw a larger magnetizing current. This current will flow out of the neutral of the transformer as though it is an external ground fault, and, as a result, the REF element will remain stable even though the magnetizing current contains zero sequence current.

### 3. Overcurrent Element

The transformer overcurrent element may be set to prevent mechanical damage to the transformer. As mentioned previously, the Ct secondary current does not contain GIC content, and as such, the GIC current will not influence the overcurrent element; even if the GIC current is large, and even if the overcurrent element uses rms current as the operating quantity. However, the GIC current will result in the transformer drawing a larger magnetizing current than under normal operating conditions. The vector sum of the transformer nominal load current and magnetizing current, even under GIC conditions, is unlikely to drive the current to be above the operating threshold of the overcurrent element. This is true for operating quantities for the overcurrent element that are rms or fundamental frequency current. However, if the transformer was overloaded during a GIC event, the security margin of the O/C element that exists under normal system conditions with the same overload condition may be decreased due to the higher magnetizing current.

## b. External Fault Conditions

Under external fault conditions, there may be a concern that a GIC condition could jeopardize the security of transformer protection elements. Investigation of the behavior of these elements under an external fault condition in the presence of GIC may help resolve this concern.

#### 1. Differential Element

GIC current causes the transformer to draw an above average magnetizing current which results in the differential current (IOP) being elevated. This IOP, as stated in section 2.2.2 a.1, should be below the trip set point. When a fault occurs on the power system, the voltage across the power system will decrease. This will result in the voltage across the magnetizing branch decreasing as well, reducing the magnetizing current of the transformer and increasing its through current. This will result in the differential element becoming more secure since the percentage of operating current versus restraint current will have decreased. However, due to the GIC current the primary Cts are more susceptible to saturation (the GIC current behaves similarly to a residual current). If the primary Cts are selected with GIC current in mind (similar to taking account of remanence/residual flux), this is a non-issue and the differential element remains stable for an external fault during a GIC condition. In addition, many modern differential relays employ logic to secure the differential element during external fault conditions.

#### 2. Restricted Earth Fault Element

The greatest concern for the REF element during an external ground fault is the performance of the primary Cts. The element operates using filtered quantities and, as stated previously, the primary Cts secondary current should not contain any GIC current. If the Cts performance can be guaranteed during an external fault with remanence taken into account, there is no concern for the security of this element during an external ground fault.

#### 3. Overcurrent element

The behavior of the overcurrent element during an external fault condition is dependent on the performance of the primary Cts during this period.  If the rms current is used as the operating current instead of the fundamental frequency current component, the operating element security may be compromised by the harmonic content from the increased magnetizing current of the transformer. As mentioned previously, a fault condition decreases the magnetizing current due to the depression in the voltage. When the overcurrent device is using fundamental current as the operating quantity, the security margin is not compromised.

### c. Internal Fault Conditions

For an internal fault condition, the concern is that the element will lose dependability and fail to operate during an internal fault condition. This section examines each element individually to determine how these elements perform for an internal fault condition during a GIC occurrence.

#### 1. Differential Element

As mentioned previously, GICs will cause the transformer magnetizing current to increase, and this magnetizing current will be rich in harmonics. However, a time coincident fault inside the transformer could depress the voltage across the magnetizing branch, thereby reducing the magnetizing current accordingly. Also, the ratio of the magnetizing current to fault current is a very small number (fault current is dependent on the source strength), so the harmonic current content of the total fault current will be well below the typical relay harmonic blocking level (harmonic current content/fundamental current content < 15%). An internal fault during a GIC event is therefore not likely going to result in the differential element losing dependability nor will it effectively reduce the operating time of the element.

#### 2. Restricted Earth Fault Element

The restricted earth fault element uses fundamental current as the operating quantity. This element is generally not blocked or inhibited by the harmonic current content of the operating quantity, and as such, a GIC condition will not negatively impact the dependability or operating time of this element.

#### 3. Overcurrent Element

In power transformers, the overcurrent element may be used to protect the transformer from mechanical damage[27]. In cases where the transformer is only protected by a REF element and an overcurrent element, the overcurrent element is used to provide protection for phase-to-phase faults and is set accordingly. Should a phase-to-phase fault occur during a GIC event, the magnitude of the fault current would typically be much larger than the GIC current even if the Ct does not faithfully reproduce the true fault current (see section 2.1 above).

### 2.2.3. 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 has not been standardized. This means that it is not yet possible to define an acceptable level of harmonics that will not damage a given 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 ignore harmonic currents completely. Legacy electromechanical and static generator protection negative sequence overcurrent relays use phase shifting circuits intended to calculate the negative sequence component of fundamental current. These phase shifting circuits do not provide the proper phase shift to identify negative sequence currents at

[27] IEEE C37.91-2008 Standard, IEEE Guide for Protecting Power Transformers, May 2008

harmonic frequencies. Therefore, these legacy relays may over or under protect a generator. The IEEE PSRC Committee report[28] identified 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. It is probable that increased penetration of microprocessor-based generator negative sequence overcurrent protection systems that filter out harmonics will result in a reduced number of alarms due to GMD-induced harmonics. Note that negative sequence overcurrent protection is not intended to protect a generator from harmonic currents, because the impacts from harmonic currents are not limited to negative sequence harmonics. Because of the unique nature of GMD events, and unspecified generator capability, there may be a significant gap in generator protection throughout the bulk grid. As noted in IEEE PSRC Committee report, some sort of thermal protection may need to be provided if generator damage due to GMDs is expected. However, experience so far has not identified any documented damage to generators due to harmonics caused by GMD events.

### 2.2.4. Transmission Line Protection

It is unlikely that transmission lines will suffer physical damage from harmonics or low frequency current due to GMD. However, the protection systems, particularly legacy protection systems, may misoperate due to their unknown response to the harmonic currents flowing in the lines. Numerical, phasor based, transmission line protection is not particularly susceptible to harmonics, as these protective devices respond primarily to fundamental frequency components. Although the IEEE PSRC Committee report did not mention the impact of GMD on transmission line protection, other papers[29, 30] have and BC Hydro has experienced trips by legacy protection using sensitive unbalance (negative and zero sequence) overcurrent protection due to a GMD. One of the mis-operations on BC Hydro's system was mitigated by modifying the filtering on a solid-state negative sequence overcurrent device to increase the rejection of harmonics[31]. In another mis-operation on BC Hydro's system, the legacy solid state analog ground time overcurrent relay undesirably responded to harmonic distortion, it was replaced with a numerical ground overcurrent relay that had high harmonic rejection.

---

[28] IEEE PSRC Committee report, "The Effects of GIC on Protective Relaying", *IEEE Transactions on Power Delivery*, Vol. 11, No. 2, April 1996, pp.725-739

[29] T. I. A. H. Mustafa, S. H. L. Cabral, L. B. Puchale, M. G. Fuch, L. E. C. Lima, F. T. Flores "A Study of Correlation between Protection Trips and Geomagnetically Induced Currents in a Power Transmission Line in Brazil", Proc. Of 2013 International Symposium on Electromagnetic Capability (EMC Brugge, Belgium), September 2-6, 2013

[30] F. Sui, A. Rezaei-Zare, M. Kostic, P. Sharma , "A Method to Assess GIC Impact on Zero Sequence Overcurrent Protection of Transmission Lines" Proc. 2013 IEEE Power & Energy Society General Meeting

[31] D. H. Boteler, R. M. Shier, T. Watanabe, R.E. Horita, "Effects of Geomagnetically Induced Currents in the BC Hydro 500 kV System", *IEEE Trans. On Power Delivery*, Vol.4, No. 1, January 1989, pp. 818-823

## 2.3. GMD Impacts on Communications

### 2.3.1. Loss of GPS Signals

The availability of an accurate time reference, such as a GPS signal, over a large geographic area allows Intelligent Electronic Devices (IEDs), such as protective digital relays, to synchronize the system data for precise event report alignment. This facilitates off-line analysis functions, such as operational analysis after an operation, and troubleshooting of a possible mis-operation. Precise event time stamping is critical to determine sequence of events throughout the power grid.

The IEDs have internal clocks used for time-tagging relay element and power system equipment operation. These internal clocks can be synchronized to a known time base with an IRIG-B signal or via the Precision Time Protocol (PTP) or Simple Network Time Protocol (SNTP) over the Ethernet port.

Substations have GPS clocks that allow utilities to date and time stamp fault records to the microsecond. The loss of these clocks during a large operational event would hamper the transmission operators and Protection & Control groups in troubleshooting suspected mis-operations. 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.[32]

There have been no GPS disruptions (total loss of GPS signal due to solar eruption) reported to date. However, there have been internal reports of alarms from a GPS receiver on loss of the GPS signal temporarily but not from the other GPS receiver at the same location, and this is probably due to software glitches in the receiver reporting the alarms.

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 the loss of a GPS clock. Utilities should plan for the loss of a GPS clock when implementing any feasible wide area control schemes.

### 2.3.2. Power Line Carrier

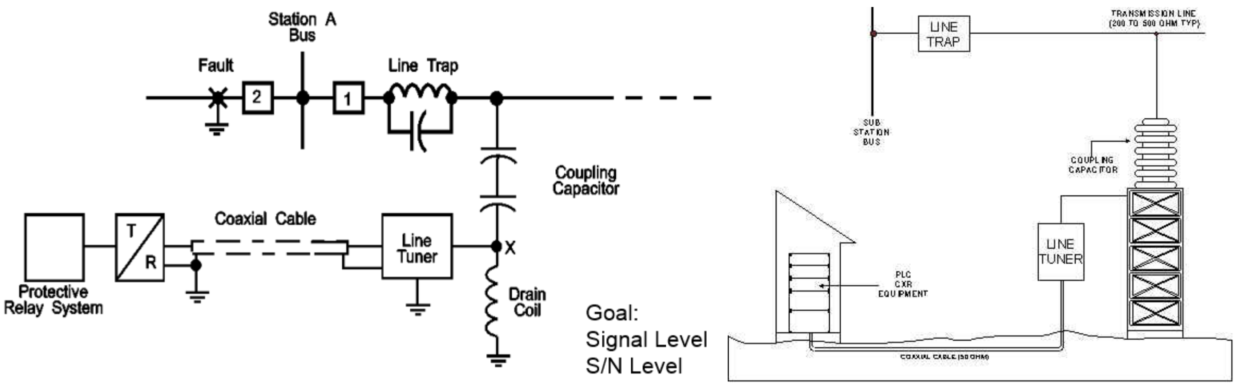
Power line carrier is a protective relaying communications system that couples high frequency radio signals (typically in the 50 kHz to 300 kHz range) onto the power line itself for terminal relay to relay communications. Two systems are generally employed, “On-Off” carrier and frequency shift keying (FSK). The “On-Off” system is used to provide high speed clearing for faults anywhere on the line, while FSK systems are

[32] NERC, “2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System,” NERC GMDTF, February 2012

typically used in transfer trip applications for transformers and failed breakers. In the "On-Off" systems the signal is either present or not, while the FSK systems transmit a guard frequency full time and a frequency-shifted signal when tripping needs to occur.

## a. Carrier System Components

The components making up a power line carrier system are shown in Figure 2-4.




*CXR - Carrier Transmitter & Receiver

**Figure 2-4 Carrier System Components**

Line Trap – These devices are basically tuned circuits designed to pass 60Hz signals while "trapping" the relatively low power carrier frequency (on the order of 10 watts) to the power line so its power is not dissipated into the line terminal equipment. Physically it is a large coil with a "tuning pack" to vary the resonant frequency or a band of frequencies. They can be single or double frequency resonant or wide band type.

Coupling Capacitor – In most cases these devices take the form of a coupling capacitor voltage transformer which is dual purpose and provides low voltage intelligence to the relaying and metering for the line. The capacitance of these devices presents a very low impedance to the relatively high carrier frequencies to be coupled to the line. The higher the capacitance value, the greater the coupling efficiency of the carrier signal to the power line.

Drain Coil – This device is an inductor which provides a high impedance path to ground for the carrier frequency but a low impedance path for the power frequency current.

Line Tuner – Together with the coupling capacitor, the line tuner provides a low loss path for the carrier frequency or frequencies and provides the fine tuning of these frequencies trapped by the line trap. The line tuners can be resonant or wide band.

Coaxial Cable – The coaxial cable between the line tuner and transmitter/receiver provides a low impedance path but also provides copper braid RF shielding that can be grounded.

Transmitter/Receiver or Transceiver - This is the end device "On-Off" or FSK carrier unit used to transmit and receive the carrier signals.

Protective Relay – This relay is used to digitally key the carrier transmitter or receive carrier indication from the receiver. On the transmitting end, this relay can be a line protective, breaker failure or transformer protective relay. On the receiving end, this relay can be a line protective relay or a tripping relay for transfer trip applications.

### b. Susceptibility to GMD Events

There is some history of GMD impacts on wire-based communications systems. A great auroral storm occurred in late August to early September 1859, and there were many reports of telegraph circuit disruption (there were about 100,000-125,000 miles of telegraph lines worldwide at the time). French telegraph operators reported lines that were completely useless. They also reported sparks flying upon opening of the telegraph conductor. On the other hand, some operators reported they were able to "work the wires" on the aurora current alone with the galvanic battery disconnected. It is assumed that the GMD's were inducing currents (GICs) into the telegraph wires thereby providing sufficient dc voltage needed to operate the telegraph system.

In 1958, the Bell System transatlantic cable experienced induced voltages of 2700 volts, resulting in disrupted phone conversations.

Again, in 1958, Swedish telecommunication plants reported numerous fires caused by arcing carbon block protectors experiencing overvoltages between the lines and earth. Overvoltages of approximately 2200 volts were experienced.

It was discussed earlier in this technical report that GICs are most likely to be introduced into today's power systems where grounded power transformers exist at the terminals of transmission lines (see Fig. 1-2), and that they are very low frequency or "quasi-DC" in nature. It is difficult to conclude that an induced quasi-DC current would couple into a carrier communications system owing 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 the carrier signal (Fig. 2-5). This is probably the greatest exposure of a power line carrier system to GICs 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. The impact of a lower SNR could be a failure to trip or an overtrip, depending on the type of protective relay scheme used.

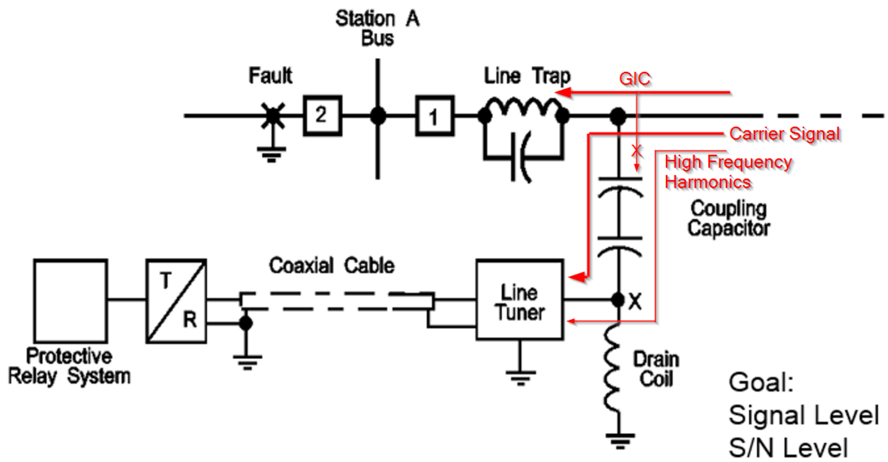



**Fig. 2-5 GIC Flow Path with the Carrier Communication System**

### c. Potential Mitigating Methods or Strategies

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

1. The use of single or double frequency resonant traps may have better harmonic blocking characteristics than the wide band type. This would serve to limit introduction of harmonics onto the conductor used for the carrier signal. The blocking impedances of the resonant type traps are typically higher also.
2. The carrier sets employed today can be purchased with higher power output ratings. Typically supplied with carrier signal power ratings of 10 watts, 100 watt units are also available.
3. Consider using a fiber-based communication/protection system as they are effectively immune to the effects of GIC.

## 2.3.3. Microwave

Microwave is the general term used to describe radio frequency waves that start from ultra-high frequency to extremely high frequency (the frequencies from 300 MHz to 300 GHz). Microwave signals have been used for both satellite and ground-based communications. The impacts of GMD on satellite-based communications have been reported in several references.

According to Omatola, et al.[33], a sudden increase of x-ray radiation from a solar flare causes substantial ionization in the lower region of the ionosphere producing ionospheric disturbances of radio signals, sudden phase anomalies, sudden enhancement of signals and short wave fade. Solar flares also produce a wide spectrum of radio noises. The impacts of GMDs on satellite communications include:

- Increased scattering of satellite-to-ground ultra-high frequency transmissions or scintillation can seriously interfere with direct satellite communications links
- Radio frequency interference
- Loss of phase lock
- Severe distortion of data transmissions from geosynchronous satellites
- Erroneous positioning information from single frequency Global Positioning System
- Drastic loss in spacecraft electrical power due to inability to reposition craft
- Faraday rotation of the plane of polarization effect on satellites that employ linear polarization up to 1 GHz.

A 1992 IEEE transaction paper[34] discusses potential effects of solar phenomena on communication systems used by the electric utility industry, and reports on the known impacts of the solar storm that occurred in March 1989. The impacts of GMD on satellite operations include

- A previously stable low-altitude satellite began episodes of uncontrolled tumbling which 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.
- A series of seven commercial geosynchronous communications satellites had considerable problems maintaining operational attitude orientation within specified ranges. They required 177 manual operator interventions to make thruster adjustments in orbit to maintain the required attitude, which was more than is normally required of controllers during a year of routine operations.
- A NASA satellite was said to have made good recordings of conditions during the disturbances, but "it dropped in altitude as it hit a brick wall". It fell half a kilometer at the start of the solar storm, and dropped a total of three miles during the entire period.

[33] K. M. Omatola, I. C. Okeme, Impacts of Solar Storms on Energy and Communications Technologies, Applied Science Research, 2012, 4 (4):1825-1832.
[34] Solar Effects on Communications, a paper prepared by the IEEE Communications Committee Working Group on Solar Effects, *IEEE Transactions on Power Delivery*, Vol. 7, No. 2, April 1992.

According to the paper “Solar Storms Effects on Nuclear and Electrical Installations”[35], since satellite communications use the higher microwave frequencies, they 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 impact their operation. For example, flares create clouds of solar particles that strike the satellites, causing large voltage differentials across the length of the satellite. The voltage differentials can create discharges which will cause solid state devices within the satellite to mis-operate or to actually fail. Several satellites were powered down during the March 13, 1989 storm to avoid possible damage.

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 which are considering the use of satellite communications for monitoring and controlling their transmission and distribution systems should be aware of these potential effects.

Other known impacts on communications systems reported due to GMD effects include[35]:

- A minor solar storm in October-November 2003 disabled the USA Federal Aviation Administration’s new global positioning system, a GPS-based navigation system, for 30 hours and damaged electrical systems from Scandinavia to South Africa. These storms interfered with satellite communications, produced a brief power outage in Sweden, and lit up the skies with ghostly auroras as far south as Florida and Texas.
- Solar storm on February 16, 2011 caused temporary radio blackouts and increased risks of damage to satellites.

# 3. MITIGATING IMPACTS ON PROTECTION SYSTEMS

## 3.1. Reviewing Susceptible Protection

Although the current magnitude induced by GMD is relatively small compared to a typical fault on the system, or an overvoltage condition due to GMD is also relatively small compared to nominal voltages, protection based on harmonics, sequence current and voltage components will have some degree of susceptibility to GMDs/GICs. The degree of susceptibility is driven by the level and magnitude of harmonics, overcurrent and overvoltage components.

[35] Magdi Ragheb, Solar Storms Effects on Nuclear and Electrical Installations, February, 17, 2018

Capacitor bank protection that uses current at the neutral ground point to determine the failure of capacitor units may be susceptible. However, a voltage differential scheme that uses voltage comparison between readings from two taps of the bank will be immune to harmonic interference.

Generator protection that uses electromechanical relays and thermal based sensors will be susceptible. Transformers may go into saturation and cause harmonic currents that may damage the transformers as well as generators connected to them, but transformer protection should overall not be affected.

On transmission lines, harmonics can cause overvoltages if a pre-existing resonance becomes excited. Any protection equipment that does not filter out harmonics will be susceptible to some level.

Any protection equipment that is designed to exclusively use the fundamental frequency component to operate will be less susceptible, hence, microprocessor based protection will be less susceptible to GMD/GIC induced problems compared to non-microprocessor (electromechanical/solid state) based protection because of frequent use of filtering to extract the fundamental frequency phasor.

## 3.2. Review Settings to Prevent Misoperations

Most of the items below apply to non-microprocessor relays

- Review transformer differential slope setting to ensure it can handle Ct measurement/accuracy error necessary to accommodate a GIC/GMD event.
- Review distance and overcurrent elements for line protection. If those elements are intended for overreaching protection, make sure they have enough margin, since these elements can underreach during a GMD/GIC event.
- Review any relay that does not filter out harmonics in its operating current or voltage.
- Review any highly sensitive negative and zero sequence trip settings.

In addition, further actions can be taken to prevent relay misoperations during a GMD event:

- Develop a method to quantify the harmonic, overcurrent and overvoltage levels during a GMD/GIC event in order to provide better guidelines on how much a relay engineer may need to desensitize settings and still have good protection reliability.
- If the protection setting cannot or will not be changed either temporarily or permanently, consider using a supervision function that will allow manual disabling of the particular element from tripping if adequate backup protection will still be retained. An alarm may be required to indicate the abnormal protection condition.

## 3.3. Methods to Modify/Harden Protection Schemes

Protective relays for switching shunt capacitor banks, and static var compensators, can mis-operate due to the GIC dc offset and the resulting harmonic currents produced by saturated transformers. During severe solar storms, the total harmonic distortion (THD) can reach over 10-30% in the transmission network.[36, 37, 38] Protective relays, if not capable of distinguishing THD and dc offset from the fundamental frequency current, may fail in certain protection schemes by mistaking harmonics for a fault or overloading. These protection schemes include but are not limited to current unbalance, transformer neutral overcurrent, line residual overcurrent and voltage unbalance schemes. The capacitor banks and SVCs that tripped in the 1989 Hydro Quebec blackout were equipped with electromechanical relays and current unbalance protection schemes measuring excessive currents at the capacitor bank neutral circuit. However, both the relays and the schemes were not harmonically desensitized and the SVCs and capacitor banks tripped out during the GMD event[39].

Mitigation methods in this area are primarily based on protection upgrades to the following:

- Replace existing electromechanical relays with harmonically desensitized models. Almost all modern digital relay models are equipped with harmonics and dc filters that will allow processing of protective computations without the effects of GMD. Some modern relays are functionalized to detect GIC and system harmonics with built-in logic.
- Replace problematic protection schemes with hardened schemes that are unaffected by GICs/harmonics.

## 3.4. GIC Blocking Device Impacts on Protection & Control

The strategies to mitigate the effects of GMD were investigated in the past and included the use of passive devices to block the flow of GIC as well as 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 device would be one that blocks GIC

[36] IEEE Task Force, V. E. Wagner, Effect of Harmonics on Equipment IEEE Transactions on Power Delivery, Vol. 8, No. 2. August 1993

[37] G. Benmouyal, H. Bilodeau, S. R. Chano, G. Sybille, "New Algorithm for Protection of Capacitor Banks Exposed to Harmonic Overvoltage", *IEEE Transactions on Power Delivery*, Vol. PWRD-8, pp 898-904, July 1993

[38] R. Sun, M. McVey, M. Lamb, R. Gardner, "A Summary of Dominion Virginia Power's Efforts to Mitigate Geomagnetic Disturbances", *IEEE Electrification* Magazine, Publication Year: 2015, Page(s): 1 – 12

[39] P. R. Barnes, D. T. Rizy, B. W. McConnell, "Electric Utility Industry Experience with Geomagnetic Disturbances", Oak Ridge National Laboratory & F. M. Tesche, 1991

flow from passing into the power system through the neutral of grounded wye connected transformers without compromising the normal ac 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[40]. While the application of capacitors is the best 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. Concerns, most likely, are:

- Operation of a large power transformer with a neutral capacitor may lead to ferroresonant or transient overvoltage conditions. It may also weaken the existing equipment insulation coordination and surge protective device application.
- Neutral capacitors may alter the characteristics of fault currents and associated neutral currents, and as a result may obstruct the ability of relay systems to detect and differentiate the fault events.

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 faults occur and the neutral voltage increases above the MOV rating[41].

The addition of resistance or capacitance to the neutral of a transformer is not desirable under normal system operation without GICs or during ground faults since they affect effective system grounding and the zero sequence current contribution of the transformer. To mitigate this concern, the blocking capacitance can be sized with a sufficiently small impedance to retain effective system grounding. 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 based on known solar flare activity. The blocking elements will be bypassed during normal system operation[42]. Other control schemes may leave the blocking elements in service and bypass them when fault currents are detected. Additionally, MOVs, spark gaps or other equipment may be used to protect the elements within the blocking device against damage during faults[43, 44].

---

[40] J. G. Kappenman, S. R. Norr, G. A. Sweezy, D. L. Carlson, V. D. Albertson, J. E. Harder, B. L. Damsky, "GIC Mitigation: A Neutral Blocking/Bypass Device to Prevent the Flow of GIC in Power Systems." *IEEE Transactions on Power Delivery*, 1991, Vol.6, Issue 3, p.1271 – p.1281

[41] EMP/GIC Mitigation, A Novel Application of Surge Arresters

[42] Power Grid Geomagnetic Disturbance (GMD) Modeling with Transformer Neutral Blocking and Live Grid Testing Results

[43] Power Grid Geomagnetic Disturbance (GMD) Modeling with Transformer Neutral Blocking and Live Grid Testing Results

[44] IEEE, Power Grid Stability Protection against GIC Using a Capacitive Grounding Circuit

In the early 1990s, TransÉnergie and IREQ, two divisions of Hydro-Québec, worked on a project in collaboration with GE to develop a dc current-blocking series capacitor to mitigate problems in HVDC systems operation with ground-return mode. HVDC operation with ground-return mode produces dc voltages around the electrodes, causing the dc flow through the HVDC transformer's neutrals, and similarly, the GIC flow through the power transformer neutrals during geomagnetic storms.

In early 2000, a neutral dc current-blocking device (NCBD) was developed by Hydro-Québec[45]. This device consists of three parallel capacitors of total 2.7-mF with an electronic control for bypass and service restoration. It was designed to withstand a steady-state peak voltage of 1500V and carry a 395A current with a bypass fault current capability of 6500 A asymmetrical.

The NCBD successfully went through all laboratory tests at Hydro-Quebec's High Power Laboratory and was later installed in the neutral of a 120/25-kV voltage transformer at Waterloo Substation with no disruption or undesirable operation.

In 2015, another neutral blocking device was developed[46, 47] to protect power transformers against GIC flow. This device provides a normal metallic grounding path for transformers through two high-current breakers. When GIC flow is detected by the system electronics, the grounding breaker assembly is opened and a parallel connected capacitor bank then provides the ac ground path for the transformer neutral, while simultaneously blocking the quasi-DC current (GIC). The presence of a GMD event is detected by the GIC flow through the transformer, thus activating the protective mode of operation.

---

[45] L. Bolduc, M. Granger, G. Paré, J. Saintonge, L. Brophy, "Development of a DC Current-Blocking Device for Transformer Neutrals." *IEEE Transactions on Power Delivery*, January 2005, Vol. 20, No. 1, p.163 – p.168

[46] F. R. Faxvog, W. Jensen, G. Fuchs, G. Nordling, D. B. Jackson, B. Groh, N. Ruehl, A. P. Vitols, T. L. Volkmann, M. R. Rooney, R. Neal, "Power Grid Protection against Geomagnetic Disturbances (GMD)." 2013 IEEE Electrical Power & Energy Conference, 2013, p.1 – p.13

[47] T. J. Overbye, F. R. Faxvog, W. Jensen, G. Fuchs, G. Nordling, D. B. Jackson, B. Groh, N. Ruehl, A. P. Vitols, T. L. Volkmann, D. Fromme, G. Edmiston, A. Walker, M. R. Rooney, "Power Grid Geomagnetic Disturbance (GMD) Modeling with Transformer Neutral Blocking and Live Grid Testing Results.", 2014 Minnesota Power Systems Conference (MPSC)

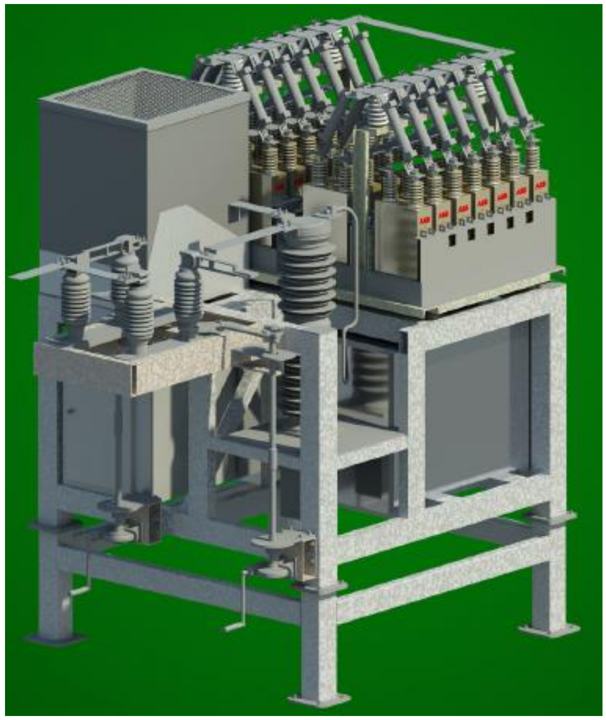


**Fig. 3-1 GIC Blocking Device (Photo courtesy of ABB)**

In recent years, the American Transmission Company (ATC) installed a GIC protection device (as shown in Fig. 3-1) in the neutral of a key transformer in the ATC network[48]. To determine a long-term strategy against GIC flow through transformer neutral and mitigate its impacts, a GIC study should be performed[47,48]. Prior to installing a GIC blocking device, it is important to study the impact of the NCBD on neighboring networks, as well as develop a vetted plan for optimal placement of the devices on identified power transformers[49, 50].

GIC blocking device designs vary greatly from application to application and manufacturer to manufacturer making it important for protection engineers to work with the planning engineers and equipment manufacturers during specification and procurement to identify and understand the impact of blocking devices on the transformer fault contribution and protection systems. These impacts should be analyzed in each

---

[48] K. Shetye, T. J. Overbye, "Modelling and Analysis of GMD Effects on Power Systems." *IEEE Electrification* Magazine, December 2015, p.13 – p.21

[49] A. H. Etemadi, A. Rezaei-Zare, "Optimal Placement of GIC Blocking Devices for Geomagnetic Disturbance Mitigation." *IEEE Transactions on Power Systems*, November 2014, Vol. 29, No. 6, p.2753 – p.2762

[50] H. Zhu, T. J. Overbye, "Blocking Device Placement for Mitigating the Effects of Geomagnetically Induced Currents." *IEEE Transactions on Power Systems*, July 2015, Vol. 30, No. 4, p.2081 – p.2089

possible operating mode (GIC blocking element in service vs. bypassed) and for cases with and without GICs present.

# 4. GIC & GEOMAGNETIC FIELD MONITORING METHODS

## 4.1. GIC Monitoring

Quasi-DC current in the neutral can be detected either by measuring the voltage across a shunt resistor in series with the neutral termination of the transformer or through the use of a non-invasive dc sensor, such as a Hall Effect sensor, to measure the dc flow in the conductor. Neutral dc monitoring alone may not reliably predict whether the specific transformer core has become saturated. If dc neutral current is used alone, the system operator may make an incorrect decision to reduce transformer load prematurely. Reducing the loading on transformers without regard to core saturation may put undue strain on the system if transformer cores are not in saturation. However, not unloading the transformer soon enough on transformers whose cores are saturating may result in equipment damage from overheating which could compromise the dielectric integrity of the transformer insulation system. There are other effects to capacitor banks and SVCs that are collateral to the effects on a transformer that is undergoing core saturation due to GIC.

In addition, measurement of harmonics on the individual phases on the high voltage, low voltage and tertiary windings without considering quasi-DC current flow on the transformer neutral is not a perfect method to determine core saturation from GIC. There may be other operating conditions that mimic the specific harmonics associated with GIC. Also, some power transformer designs will vary in their harmonic spectrum, making it extremely complex to determine if the harmonics are a result of GIC or from the load or source connected to the transformer.

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.

As previously mentioned, GIC can cause quasi-DC current flow in the neutral connection of the transformer and the GIC magnitude may not always predict that the transformer core will saturate. However, when the core does saturate, the ac waveform on the phase conductors, specifically the outer windings, becomes highly distorted and the even harmonics will be greater than the odd harmonics. To raise confidence in the correct identification of core saturation due to GIC, the even harmonic will always be greater than the adjacent odd harmonics. That is, the 2nd harmonic will be greater than the 3rd harmonic, the 4th harmonic greater than the 5th harmonic and 6th greater than the 7th.

A comprehensive GIC monitoring instrument simultaneously measures quasi-DC current in the neutral by using a Hall Effect transducer and the harmonics from the phase connected Cts. Figure 4-1 below illustrates the application of a GIC monitoring device.

In addition to temperature, the device will monitor the harmonics generated by transformer saturation stemming from GICs. The device will collect data from neutral current transducers and trigger GIC alarms based on GIC current, harmonics, transformer temperature, and loading conditions. 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

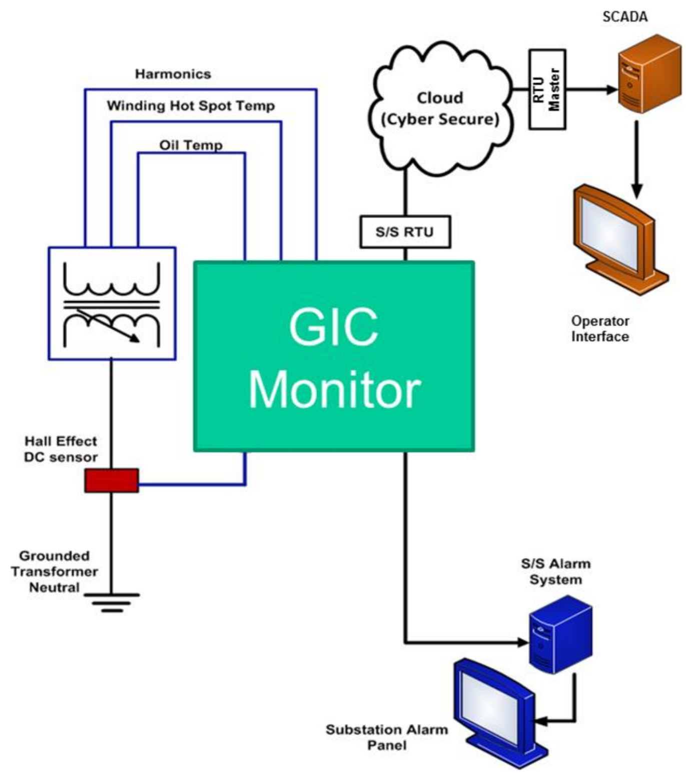



**Figure 4-1 GIC Monitoring System**

### 4.1.1. 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. 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).

The output is linear within the sensitivity range of the sensor. A scale factor and dc offset numbers are generally required for calibration. Depending on the model and manufacturer, the sensitivity range may vary from 0.1-15 A to 1-150 A. The distance from the sensor to the cable affects its sensitivity. The further the sensor is from the cable the less sensitive it is because the strength of the induced field weakens as the sensor moves away from the cable (reciprocal of the distance). In some implementations, the sensor is intentionally placed 0.25 inch away from the cable because lower sensitivity increases monitoring range[51].

An example sensor is shown in Figure 4-2. The sensor uses a clothespin-like enclosure. The actual Hall-Effect chip is visible in the center of the sensor and is covered by a curved mu-metal strip used for shielding against external magnetic fields and amplifying internal ones. The output is provided over a shielded RJ45 cable. This type of enclosure provides for installation on live wires without the necessity for removing equipment from service[52].

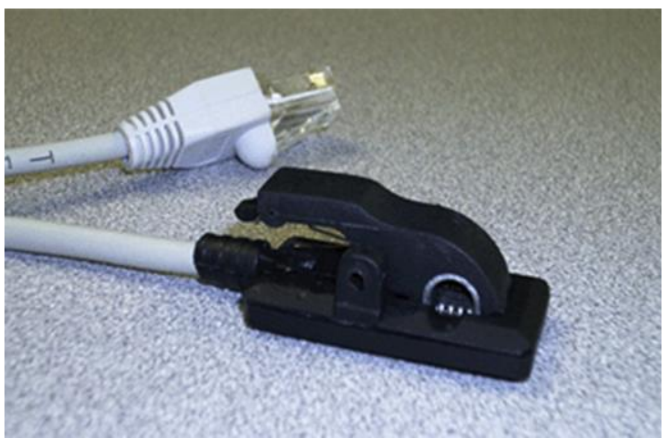


**Figure 4-2 Hall-effect ECT with Shielded Clothespin Enclosure**

[51] IEEE PES PSRC Working Group I24 Report, "Use of Hall Effect Sensors for Protection and Monitoring Applications", September 2016

[52] A. Makki, S. Bose, T. Giuliante, J. Walsh, "Using Hall-Effect Sensors to Add Digital Recording Capabilities to Electromechanical Relays", Proceedings of the 63rd Annual Conference for Protective Relay Engineers, Texas A&M University, College Station, March 2010

The frequency response for the depicted sensor is 0 to 100 kHz (meaning it can measure high order harmonics from 50 and 60 Hz sources). The sensor does not saturate like a Ct does. It clips above the sensitivity range and distorts below it (due to noise). The magnitude accuracy is within 1% and the phase is within 1 degree. The magnitude is affected by temperature extremes but not the phase. The magnitude accuracy is constant in the range 32 to 100 °F but drifts linearly up to 0.5% as the temperature decreases from 32 to 0 °F or increases from 100 to 140 °F.

Hall-Effect sensors are useful for a wide range of equipment monitoring applications in the substation. The applications include but are not limited to breaker trip currents, inrush currents, secondary three-phase and neutral currents, and GIC signatures. As for the type of recording equipment used, it is necessary to minimize errors caused by digitization and signal conditioning methods. Good accuracy can be achieved when recording unfiltered with a resolution of 16-bits at a sampling rate at or above 2 kHz.

### 4.2. 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, a secondary purpose of monitoring geomagnetic fields is to build a ground model for a system using GIC and magnetic field measurements. Such a model would enable, for example, generation of tailored (for specific sites of interest) extreme GIC scenarios and future tailored GIC forecasts.

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 provides additional information on installing a geomagnetic field monitoring system.

## 5. CONCLUSIONS

Protective relays come in many styles and vintages with different operating principles. Some will operate only on the fundamental frequency component, by utilizing digital signal processing techniques to remove the dc and harmonic components of the signals. Others are designed to measure the peak current/voltage and/or include the harmonics in the measurement for protective functions. Examples of this type are 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. Mis-operation of these type relays protecting capacitor banks and SVC's have been reported as one contributing factor to the major disturbance during the March 13, 1989 GMD Event.

Relays that are designed to filter harmonics and dc components from the signals may not be completely immune to the effects of GMD. If the harmonic content is excessively high or if sub-frequency components are present in the signals, the relay's phasor measurement may have errors which could lead to mis-operations in some sensitive applications. For example, some grounded capacitor banks use sensitive neutral overcurrent relays to detect capacitor failures; if the settings are very sensitive, mis-operation caused by the excessive harmonic content could occur. Similarly, the differential voltage protection for ungrounded capacitor banks may also be susceptible because one of the voltages is taken from the neutral potential device.

The risk of false tripping of capacitor banks or harmonic filter banks due to GICs can be reduced by careful relay studies and settings which 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.

## APPENDIX I GEOMAGNETIC FIELD MEASUREMENT SYSTEM

As an example, a typical geomagnetic field measurement system and its installation are discussed in this section. Suggested specifications for the three major components of the geomagnetic field measurement are also briefly discussed. The three major components are: a fluxgate magnetometer sensor assembly, a Power Supply Unit (PSU), and a data acquisition system including an analog low pass filter.

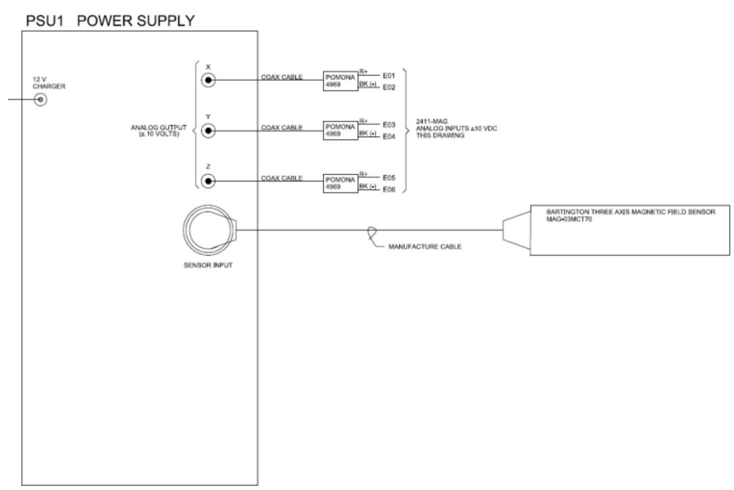
### a. Magnetometer

A magnetometer consists of tri-axial magnetic sensors housed in a variety of enclosures. Each tri-axial magnetometer channel produces three independent analog output voltages in response to the magnitude and direction of the orthogonal components of a magnetic field. The analog three-component fluxgate magnetometer is capable of monitoring the magnetic field intensity to the full range of the earth's magnetic field in the frequency range from dc to 500 Hz. They are available with measuring ranges from ±70 to ±1000μT.

In addition to the tri-axial magnetic sensors, the enclosure also contains the associated electronics needed to precisely convert the magnetic field strength at the sensors into analog signal voltages.

### b. Power Supply Unit

The fluxgate of a magnetometer operates by creating an alternate saturation of the sensing element's core. For instance, this can be done by an excitation signal at a frequency of 16 kHz generated by a Power Supply Unit (PSU). As shown in the example in Figure A-1 b), the PSU is powered from any ±12V supply with its outputs in the form of three analog voltages from 0 to ±10V, corresponding to the X, Y and Z measurements of a magnetic field.




a) Magnetometer Sensor Assembly    b) Diagram of Magnetometer Connecting to a PSU

**Figure A-1 Magnetometer and its Power Supply Unit**

### c. Data Acquisition

On the X, Y and Z signal, though most of this excitation signal is filtered out, there are some remaining components which create high-frequency noise. In order to further filter out the high-frequency noise, it is recommended that an analog filter be placed between the sensor output and the data acquisition unit before sending the measurements to a centralized data collection system.

The sampling rate for the analog input of a typical low-pass filtering relay is every 5 ms, and it has a built-in filter with a ~2Hz cut-off frequency.

### d. Magnetometer Installation

To avoid interference from installed hardware, it is recommended that non-conductive mounting brackets and screws be used. It is also recommended that the use of magnetic materials in cable connectors be avoided. The magnetometer sensor should be mounted in the vertical direction with the connector pointed up. Conventional to geophysical measurements, the orientation of the magnetometer sensor is also important, and it should be installed to orient the sensor with the X axis pointing in the true north direction, the Y axis pointing East and the Z axis pointing down. At the installation, it is required to check the levelling with one axis vertical, and the others horizontal. A marker at the top of a magnetometer indicates the positive X (or North) direction. (Figure A-2)

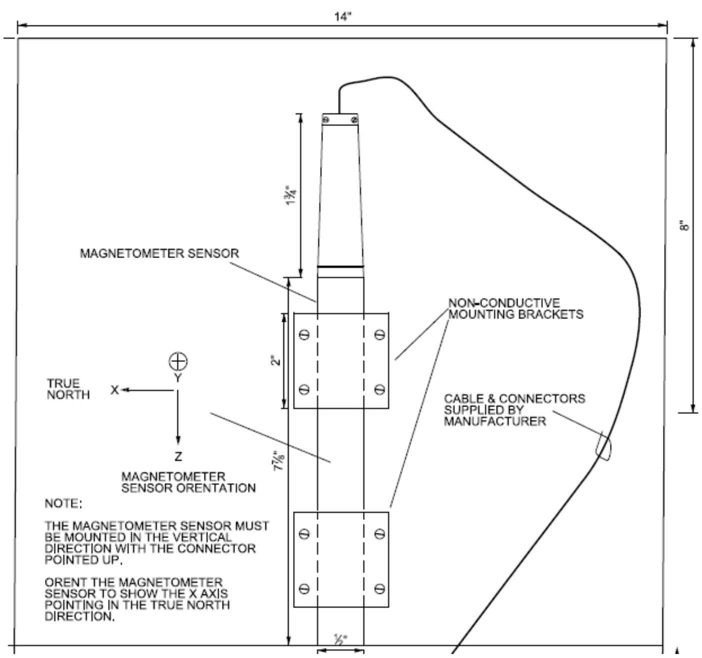



**Figure A-2 Magnetometer Sensor Enclosure and Installation Assembly**

As far as aligning to geographical north is concerned, this is a complicated procedure, requiring some observatory training to be capable of completing. This procedure would require to setup what is referred to as an absolute magnetometer (Declination/Inclination Magnetometer – DIM) and a total field magnetometer. These instruments are used to establish the absolute orientation of the geomagnetic field at a moment in time. The DIM instrument utilizes a non-magnetic theodolite, which can be used to swing an arc on a local landmark. The orientation of the true north vector and that of the vector between the theodolite and the landmark would need to be established. This allows measuring the orientation of the magnetic field relative to true north. The information from the fluxgate is used to establish the orientation of the magnetic field incident on the fluxgate. The orientation of the fluxgate is then adjusted until the sensor is aligned with geographic north. The United States Geological Survey (USGS) does not orient their sensors to geographic north because they use the procedure above to monitor the difference between the sensor orientation and true north on a weekly basis. The guide[53] published by International Association of Geomagnetism and Aeronomy provides a complete description on the procedure.

If the cable between the low pass filter and the data acquisition unit exceeds a certain length (e.g., > 100 feet), proper cable shielding is recommended to reject potential interference from the environment.

The electromagnetic field interference from the high voltage equipment at a substation will affect the magnetic field measured by a magnetometer. Whether a magnetometer can be installed near a substation environment depends on the effectiveness of filtering out ac interference components; this needs to be verified. ac signals at 60Hz can easily be removed, however, nearby transformers may generate a more static magnetic field. Depending on the location of the mast, if the background field is too high, it may be either suitable to increase the range of measurement of the sensor to limit saturation or move the sensor away from a transformer.

It also needs to be ascertained that there is no transformer with a strong dc component near the sensor. If multiple magnetometers are installed in a system, it is recommended setting their sensors all in the same direction in all stations to ensure comparison of data.

It is suggested to place the magnetometer (or at least a reference magnetometer) 500 feet away from a substation or a transmission line corridor to provide a reference that is not subjected to interference from the transmission system. This will ensure the ambient geomagnetic field measurements are recorded and used as a reference for the E-field and GIC calculation.

[53] J. Jankowski and C. Sucksdorff, *IAGA Guide for Magnetic Measurements and Observatory Practice*, 1996, ISBN: 0-9650686-2-5