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# The Effects of Geomagnetic Disturbances on Electrical Power Systems

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THE EFFECTS OF GEOMAGNETIC DISTURBANCES ON ELECTRIC POWER  
SYSTEMS

by

Benjamin J Hynes

A Thesis Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Masters of Science

in Engineering

at

The University of Wisconsin – Milwaukee

May 2016

# ABSTRACT

## THE EFFECTS OF GEOMAGNETIC DISTURBANCES ON ELECTRIC POWER SYSTEMS

by

Benjamin J Hynes

The University of Wisconsin – Milwaukee 2015  
Under the Supervision of Professor Ronald Perez

Abstract: Solar storms that generate coronal mass ejections are a cause for concern due to the damage that they cause in high voltage power grids. Geomagnetically induced currents can be introduced onto the grid and cause many adverse effects. The vulnerability of the bulk electric power systems to such events has increased during the past few decades because the power system transmission lines have become more interconnected and have increased in length. Real and reactive power flows, voltage fluctuations, frequency shifts, undesired relay operations, higher order harmonic currents, undesired damage to assets and failure of assets are all possible outcomes from a large geomagnetic disturbance. A 100 year solar storm could cause mass blackouts and colossal damage to any high voltage power grid, if proper monitoring and mitigation techniques are not used.

This thesis presents an in-depth background on geomagnetic disturbances and how they affect the electrical power grid. The thesis will model geomagnetic disturbances on a theoretical grid using the simulation software OpenDSS. The thesis will also discuss monitoring and mitigation techniques that can be applied to the power grid to lessen the

chance of failure or damage to assets, and analyze real world data collected from a Midwestern solar storm that had an effect on two power transformers equipped with online monitoring.



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## LIST OF ABBREVIATIONS

CME – Coronal Mass Ejection

CIP – Critical Infrastructure Protection

CT – Current Transformer

EPRI – Electrical Power Research Institute.

ESP – Earth Surface Potential (quasi-dc)

GIC – Geomagnetic Induced Current

GMD – Geomagnetic Disturbance

GSU – Generation Step Up

Hz - Hertz

IEEE –Institute of Electrical and Electronic Engineers

IMF - Interplanetary Magnetic Field

NASA – National Aeronautics and Space Administration

NERC – North American Electric Reliability Corporation

nT – Nano Tesla

PD – Partial Discharge

SP –Surface Potential

SVC – Static VAR Compensator

VAR – Volt Ampere Reactive

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I would like to thank my wife, Allison Hynes, for having the patience to allow me to continue my never ending love for learning, the encouragement to get me through the hard times and the support that I have received to help me complete some truly amazing things.

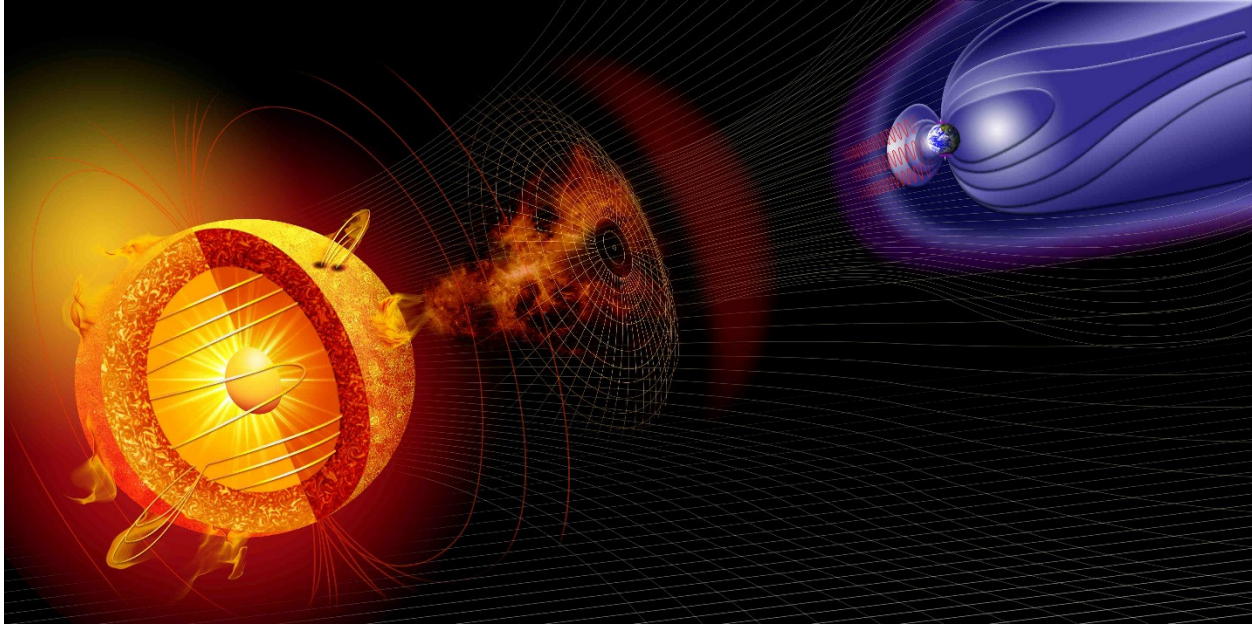
I would like to thank Tony Pink and Mark Tostrud from Dynamic Ratings for introducing me to the Power Industry. I truly appreciate the time and efforts they have spent to help me develop myself as a Project Manager and Electrical Engineer in this industry. Being surrounded by the brightest people who are actively working to make the industry a safer, more reliable place is truly inspirational.

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## Chapter 1 Introduction

Reliable electrical power systems are something that most people in the United States take for granted. Every time you turn on a light switch, you expect the light to come on. The electrical power system has become so reliable that most utilities, especially Wisconsin Electric, brag about their percentage of uptime. Electrical power systems are vulnerable to widespread disturbances, which can be outside of the control of man. A popular example of this vulnerability is the March 13<sup>th</sup>, 1989 blackout where 6 million people were affected by one intense Geomagnetic Induced Current (GIC) event. Large scale outages, such as the example just listed, can have severe economic impacts. Understanding the vulnerability of the electric power system, monitoring GIC in systems and deploying a mitigation program can reduce negative impacts on the electric power system and reduce the likelihood of a large scale outage in the future.

Geomagnetic storms are a major threat to the electrical power system. Geomagnetic storms are a temporary disturbance of the Earth's Magnetosphere caused by a solar wind derived from a cloud of magnetic particles that have been discharged from the Sun which interact with the magnetic field around the Earth. The Magnetosphere of the Earth is compressed from the solar wind pressure. The transfer of energy, to the magnetosphere from the solar winds magnetic field, is caused by interactions of the plasma's movement through the magnetosphere.

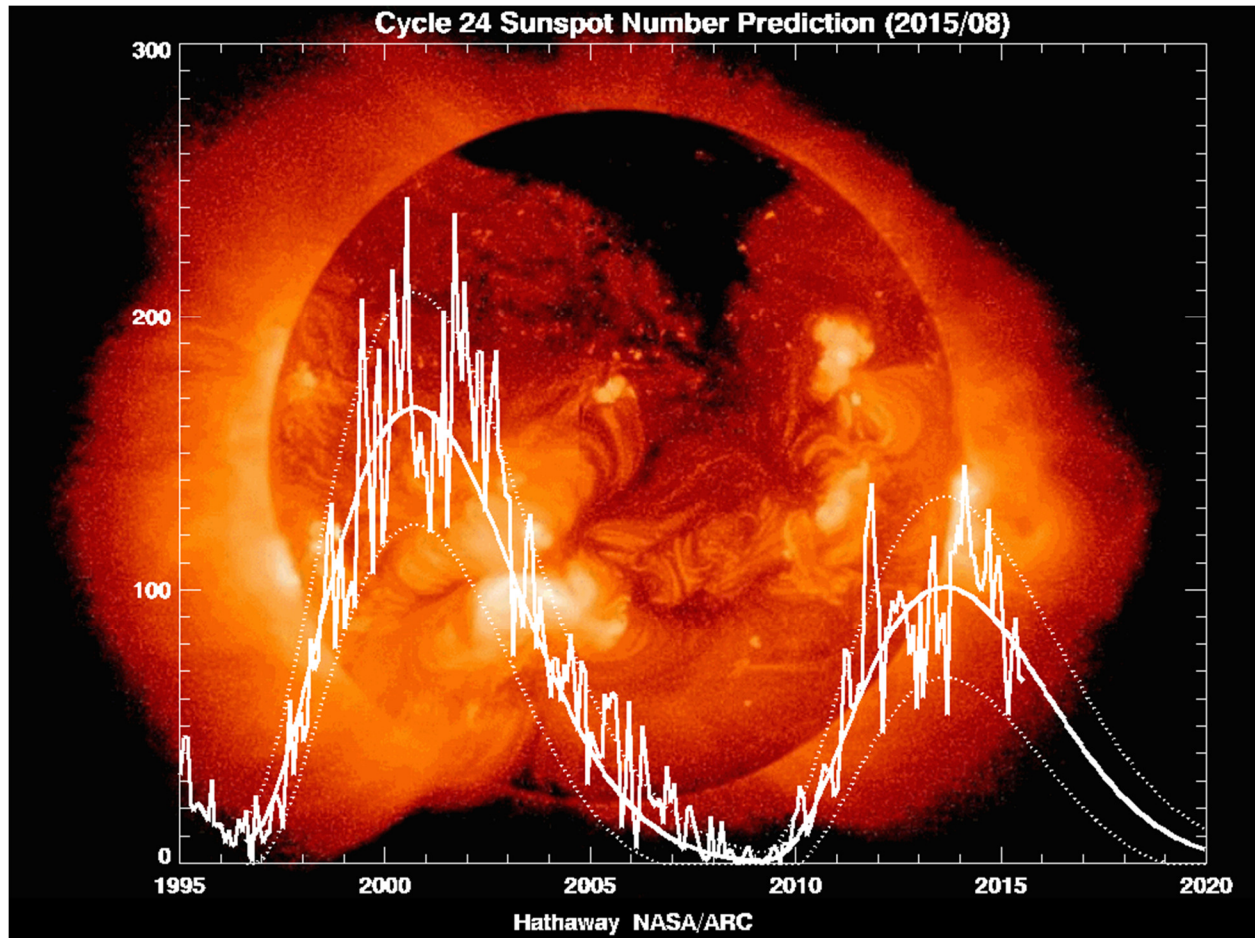


**Figure 1 Earth's magnetic field interacting with solar activity [1]**

Coronal mass ejections are the major source of geomagnetic storms. Coronal mass ejections occur when the outer solar atmosphere violently releases gas and magnetic fields. A large coronal mass ejection can contain a billion tons of matter that can be accelerated to several million miles per hour. On average, a coronal mass ejection can travel from the sun to the Earth in approximately 98 hours, and can range in speed from 200 kilometer per hour to 1000 kilometer per hour [2]. Intense geomagnetic storms with aurora electrojets of solar particles (1 million amperes or more) are the source of the aurora borealis and aurora australis. These intense geomagnetic storms also cause distortions in the Earth's magnetic field that may interfere with communications and electrical power systems [3]. During periods of high solar activity, it is estimated that 50-100 small to medium solar events occur each day; larger events that significantly affect communications occur weekly [4]. Solar activity has fairly predictable cycles, it peaks about every 11 years. The Earth is on the downward peak of solar cycle 24 [5], which



peaked during April of 2014 and is depicted in Figure 2. Even though we are past the peak of the cycles, the largest geomagnetic storms occur two to three years after cycle peaks [6].



**Figure 2: Solar Cycle 24 [7]**

The intensity of geomagnetic storms is monitored by the Space Weather Prediction Center of the National Oceanic and Atmospheric Administration. The intensity of each geomagnetic store is rated on a logarithmic scale called the K-index. This scale quantifies disturbances in the horizontal component of the Earth's magnetic field with a value of 0-9, with nine being the most violent. The label K comes from the German work Kennziffer meaning "characteristic digit". The K-index value is derived from the maximum

fluctuations of horizontal components observed on a magnetometer during a three hour interval. The  $K_p$  index may also be seen in solar storm references. The  $K_p$  index can be derived by calculating a weighted average of K indices from a network of geomagnetic observatories. Table 1 contains an overview of  $K_p$  values, frequency between occurrences, common issues associated with the storm, and severity.



## NOAA Space Weather Scales



Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
<b>Geomagnetic Storms</b>			$K_p$ values* determined every 3 hours	Number of storm events when $K_p$ level was met; (number of storm days)
<b>G 5</b>	Extreme	<u>Power systems:</u> widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. <u>Spacecraft operations:</u> may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. <u>Other systems:</u> pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).**	$K_p=9$	4 per cycle (4 days per cycle)
<b>G 4</b>	Severe	<u>Power systems:</u> possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. <u>Spacecraft operations:</u> may experience surface charging and tracking problems, corrections may be needed for orientation problems. <u>Other systems:</u> induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).**	$K_p=8$	100 per cycle (60 days per cycle)
<b>G 3</b>	Strong	<u>Power systems:</u> voltage corrections may be required, false alarms triggered on some protection devices. <u>Spacecraft operations:</u> surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. <u>Other systems:</u> intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).**	$K_p=7$	200 per cycle (130 days per cycle)
<b>G 2</b>	Moderate	<u>Power systems:</u> high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. <u>Spacecraft operations:</u> corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. <u>Other systems:</u> HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).**	$K_p=6$	600 per cycle (360 days per cycle)
<b>G 1</b>	Minor	<u>Power systems:</u> weak power grid fluctuations can occur. <u>Spacecraft operations:</u> minor impact on satellite operations possible. <u>Other systems:</u> migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).**	$K_p=5$	1700 per cycle (900 days per cycle)

\* Based on this measure, but other physical measures are also considered.

\*\* For specific locations around the globe, use geomagnetic latitude to determine likely sightings (see [www.swpc.noaa.gov/Aurora](http://www.swpc.noaa.gov/Aurora))

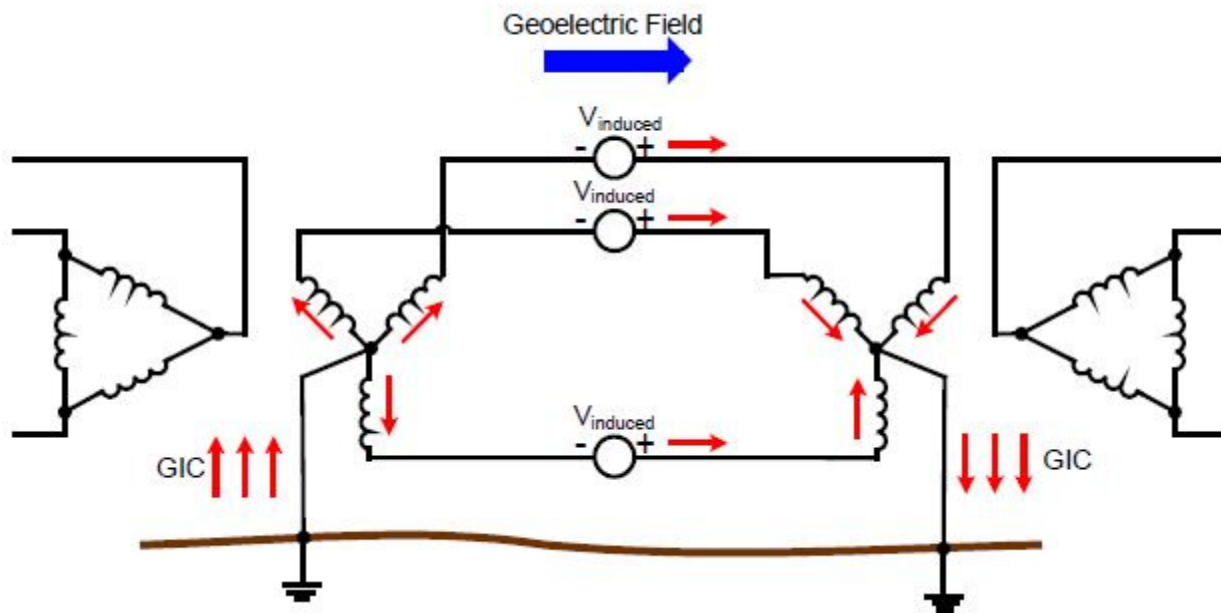
**Table 1 NOAA Space Weather Scales [8]**

The eight daily K-index values can also be averaged to find the daily A-index.

Geomagnetic field fluctuations are measured in units of nano-Tesla (nT).  $1 \text{ nT} = 1 \text{ gamma} = 10^{-5} \text{ gauss}$ . To put this into relative terms, the Earth's magnetic field at the poles is approximately equal to  $70,000 \text{ nT} = 0.7 \text{ gauss}$ .

The K-index is not a useful indicator of how intense a geomagnetic storm will impact electric utility systems. It does not account for the rate of change associated with the variation. For example, a K-9 geomagnetic storm with relatively fast variations will be more disruptive than a K-9 storm that slowly changes the Earth's magnetic field. The Earth's magnetic field fluctuations are a result from an electrical potential gradient of low frequency quasi-dc along the Earth surface, typically in an east to west direction. Quasi-dc potentials exist in geoelectric fields, characterized by relatively slow time variation values of the same polarity. Quasi-dc potentials are also commonly referred to as Earth surface potentials. This potential gradient is a function of the Earth conductivity and the rate of change in the magnetic field. The greater the rate of change of this magnetic field, the greater the potential difference between two points on the Earth's surface which will cause the greatest conditions to Geomagnetically induce currents in to the utility power system.

Geomagnetic storms influence electric power systems by causing GIC's to flow in power lines through the neutral of grounded wye transformers. In a grounded wye transformer, the common grounded neutral lead create the closed loop circuit in association with the Geo-Electric Field. A sample circuit that grounded wye transformers create is seen in Figure 3. Longer transmission lines typically see larger GIC, due to the size of the transmission line acting as a larger antenna for the GIC and having a larger area for the magnetic induction to act on. Electric utilities in the far northern latitudes typically see more GIC activity, due to their location in relation to the auroral electrojet currents.

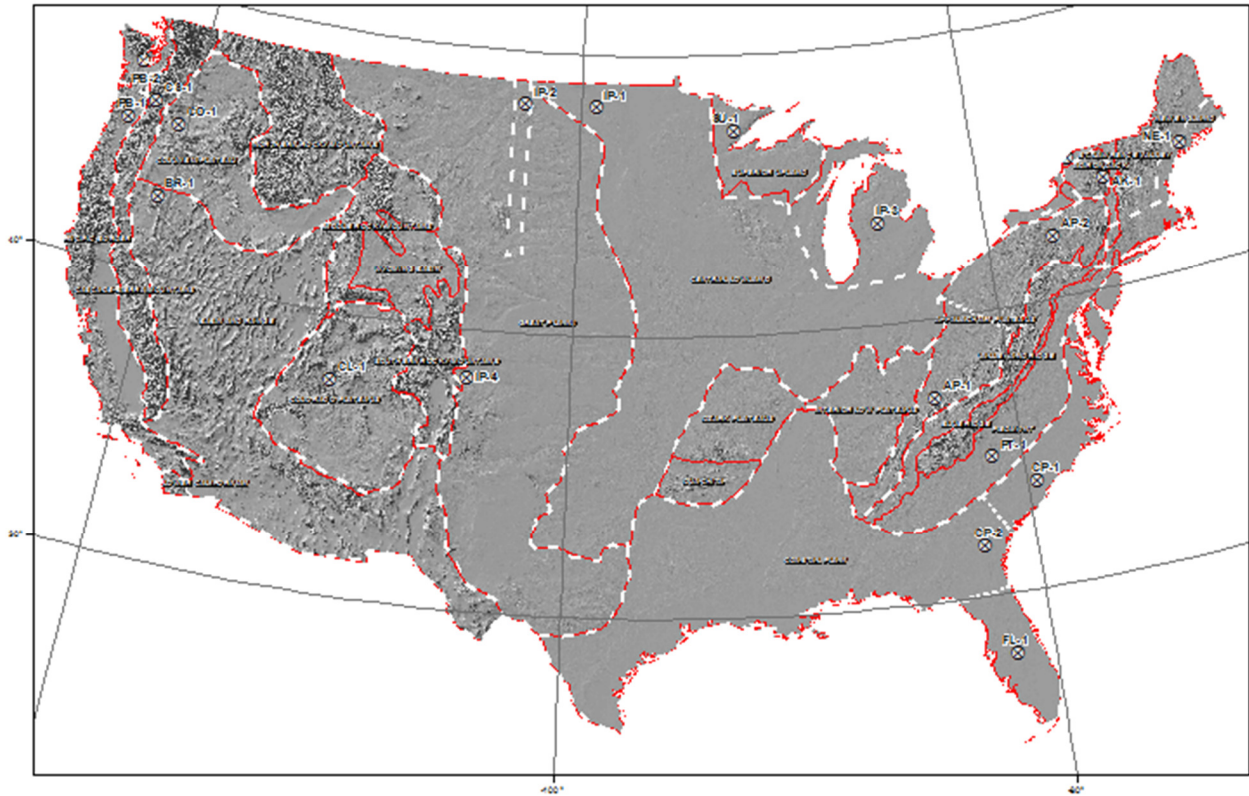


**Figure 3 Grounded Wye Transformer Circuit [9]**

The geology of the Earth also plays a key role in GIC activity. Since the current is being conducted through the neutral of the grounded wye through the Geo-Electric Field that of Earth, the conductivity of the region of the event can cause greater vulnerability to events. Figure 4 shows the different regions across the United States of America. For the purpose of this thesis, I will be focusing on the state of Wisconsin which consists of three different regions: The Interior Plains (Michigan) IP-3 Region, The Interior Plains (North Dakota) IP-1 Region and The Superior Upland SU-1 Region. The Resistivity per depth charts are located in



## Appendix A.



**Figure 4 Map of USA resistivity [10]**

The Geomagnetically induced quasi-dc currents that flow through the grounded neutral of a transformer during a geomagnetic disturbance can cause the core or the transformer to magnetically saturate on alternate half cycles. Saturated transformer cores cause harmonic distortions and creates additional reactive power or Volt Amp Reactance (VAR) demands on the electric power systems. This increase of VAR demands can lead to a reduction in system voltage and overloading of long transmission lines. Additionally, the compounding factor of harmonics to the system can cause protective relays to operate improperly and cause shunt capacitor banks to overload. Both the increase of VAR's on

the power distribution system and the addition of unwanted harmonics can have a cascading effect of damage which can cause major power failures.

During the last two to three decades there has been a trend of smaller generation plants closing, and the ones that remain open adding extra generation capacity and operating closer to their limits. This creates a power transmission system that is operated closer to their upper limits, increasing the vulnerability to widespread geomagnetic disturbances. As more and more power is transmitted over longer distances to meet the grown demand [11], stability margins are further reduced. Projected continued growth in higher population load centers without corresponding growth in generation and distribution capacity and the public's resistance to add new high capacity lines in large urban areas will further compound this issue in the future. If proper monitoring and mitigation techniques are not deployed over the power system, large scale outages could become more common in the near future.

## Chapter 2 Effects of GIC on the Electrical Power System

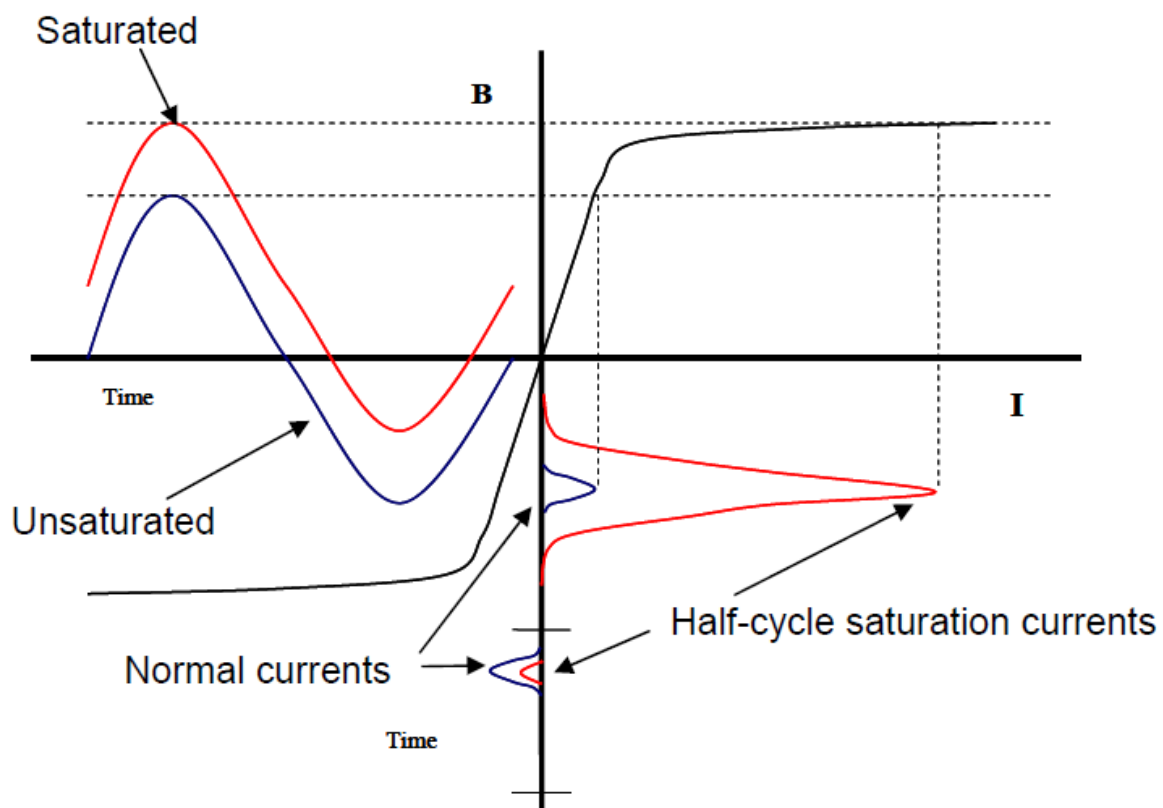
The first recorded event of GIC having negative impacts on the electrical power system dates back to a solar storm on March 24th, 1940. VAR variations of up to 20% were recorded. Multiple transformers tripped offline as a result of this storm in the Maine and Ontario region of North America. New York City encountered VAR variations of up to 10%. [12]. This event in 1940 triggered the start of recording and investigating the coloration of solar activity and its effects on the utility power system.

The average activity on the sun has little effect on utility power systems. When activity rises above the G-1 level from Table 1, the cause for concern greatly rises, and utility power systems should heighten their awareness to the possibility of GIC activity. The greater the G scale event is, the higher the probability of unwanted damage from GIC.

Geomagnetic storms can cause large variation in the Earth's magnetic field which influences the Earth's surface electric potential. The most severe geomagnetic storms can produce surface potentials that reach  $5,000 \text{ V/m}$  and can last for several minutes. For comparison, the current in the global electrical circuit is approximately  $100 - 150 \text{ V/m}$ . [13] The induced voltages produce slowly oscillating GIC on the utility power systems that can be on the order of tens to hundreds of amperes, and have a frequency in the millihertz range. This unwanted GIC can have a huge impact on the bulk power system by saturating transformer cores and changing VAR flow causing large power fluctuations on the grid. If assets are not properly monitored and taken offline when high values of GIC are encountered, equipment failure or improper operation of equipment can

cause large losses of assets to the utility power companies. The increased injection of harmonic currents into the system from saturated transformers can increase burden on static capacitors as well as interfere with operation of control and protection systems [14].

GIC in a grounded wye transformer can cause major damage. The presence of the quasi-dc GIC in the transformer windings causes a half cycle saturation or shift of the transformers operations range on the magnetization curve as seen in Figure 5 [15].



**Figure 5 Saturated Half Cycle Graph [16]**

GIC in the transformer offset the magnetic flux. The offset magnetic flux causes a magnetizing current waveform with a greatly increased amplitude that is typically present on either the positive or negative peaks of the AC wave form. When power transformers



are operated near capacity, even a small amount of saturation can push the unit outside of the design specifications causing premature failure or even catastrophic failure. When GIC in the transformer offsets the unwanted magnetic flux, one can typically see currents between 1-100 amperes from the grounded wye connection to the Earth's ground. For comparison, power transformers in normal operations will have less than one ampere from the grounded wye connection to Earth's ground.

VAR consumption by the transformer and an increase of harmonics generated by the half cycle saturations are unwanted side effects of GIC activity. Half cycle saturation of the transformer for an extended amount of time will cause stray flux to be introduced into the transformers structural tank members and current windings. When stray flux is found in the current windings, the windings will increase in temperature. The increase in temperature can cause many damaging side effects. It can cause damage to the insulation of the windings and leave permanent damage as seen in Figure 6 [17]. Unwanted overheating of the core can also cause an increase of gas content in the transformer. A Dissolved Gas Analyzer will be able to detect these key gasses in the transformer oil, but not in time to prevent any damage from occurring and hence is not a good way to mitigate damage to power transformers from GIC activity.



**Figure 6 Core Damage to Power Transformer Windings [18]**

During GIC events, load tap changing transformers can see increases of usage. Autotransformers on the bulk power system are fitted with mechanical load tap changers to compensate for the voltage fluctuations on the power grid, interconnecting different winding configurations to buck or boost the voltage. When GIC events cause system voltage variations, caused by increased VAR demands, the load tap changing transformers will keep up with the requests to steady the voltage across the system. This causes unwanted wear of the tap changing device from the more than average operation of the device during a geomagnetic storm.

GIC can cause relay and protection systems of the utility power systems to fail in three distinct ways. The first and most common failure mode of relaying and protection systems is due to GIC is when Static VAR compensators, capacitor banks and line relay operations can mistake harmonic currents produced by the saturation of transformers for a fault current overload. This may cause items to be pulled out of service when there truly

is not a problem and also may cause local outages in the bulk power system. The second and most severe failure mode for relays and protections systems due to GIC is when the relay fails to operate. Current transformers, used to monitor load on transformers, can become distorted due to GIC activity and cause the protection scheme not to operate when there is a detected fault condition. This type of event causes the most damage to the bulk power system. The last type of failure mode for relay and protect systems of the utility power system is when GIC activity causes a delayed or slowed response of the protection device due to remnant flux in the current transformer. The remnant flux reduces the current transformers time to saturate, and may not present any signs of warning for days [19]. Differential relay schemes on transformers are particularly susceptible to GIC events and should not be used.

Differential relay schemes that protect transformers are susceptible and are known to malfunction during GIC activity. Current transformer saturations and harmonics generated by the saturation for the power transformer cause the relay to fail to operate if there are simultaneous faults in the power transformer. Modern relays have increased their sensitivity to harmonics generated during transformer energization current inrush lessening the possibility of this failure mode, but many of the legacy equipment on our bulk power system are still susceptible to this type of failure if the relay equipment has not been upgraded in the past decade or two.

GIC events can cause an increase of wear on utility power system circuit breakers. During GIC events, an increase in secondary arc currents inside the circuit breaker may occur, which is caused by the current that flows through a fault arc during and after a single line to ground fault caused by electromagnetic and electrostatic coupling from the

two energized phases. This increase in secondary arc current due to GIC may be as high as ten times normal operation. This increase of current causes difficulty extinguishing the arc contained in the circuit breaker. The time of which the circuit breaker trips and senses zero current is therefore increased causing the recovery time of circuit breakers to be longer than normal. In the United States, a re-closure typically tries three times before remaining fully open. The added time to sense zero current can cause altered readings. As a result, the re-closures will be prevented from actuating, remaining open and causing unwanted localized outages.

Static VAR compensators installed in the bulk power system along with capacitor banks are becoming more common. When used in conjunction with each other they can rapidly control real and reactive power flow. Both are susceptible to GIC events and can be negatively impacted. A grounded wye connected capacitor bank can quickly trip out, for protection reasons, when excess current is detected on the path to Earth's ground. Tripping the capacitor bank out of service will prevent the system experiencing excess voltage which can cause a cascading failure of the capacitor cans in the bank. When capacitor banks combined with SVC's trip out, the bulk power system can see massive power fluctuations. The power fluctuations can cause damage to any item that is still actively connected to the bulk power system. This cascading effect has occurred in the past, as was the case in the large scale outage in 1989, and if proper monitoring and mitigation techniques are not applied to the system we all depend on, will occur again.

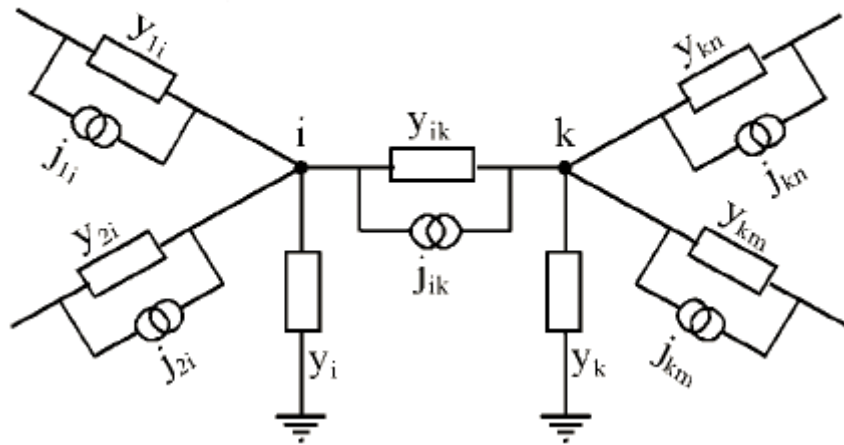
The distribution system of the United States power system ultimately will see the outages generated by GIC events. The cascading effects of transformer, protection, SVC, capacitor banks being tripped offline, and distribution fuses blowing will cause unwanted

short term outages. If proper monitoring and mitigation techniques are not deployed across the bulk power system, unwanted catastrophic failure of assets will happen causing the outages to last until the assets can be replaced which may take weeks to months.

## Chapter 3 Mathematical Modeling of GIC

GIC events can be modeled in simple dc circuits, due to their low frequency quasi-dc nature, making bulk power system GIC mathematical modeling quite easy. Using the nodal admittance matrix method, one may convert the driving voltages to equivalent current sources. The following power network is comprised of nodes connected together and to ground. For a voltage source  $e$  and impedance  $z$ , the equivalent circuit has components  $y = 1/z$  and  $j = e/z$ , where  $y$  is the admittance and  $j$  is the current. A matrix solution is calculated for the voltage of each node, and the node voltages are then used to obtain the GIC in the network.

To develop general equations for the nodal admittance matrix method, consider nodes  $i$  and  $k$  in the middle of the network in Figure 7. Here,  $y_{ik}$  represents the admittance of the transmission line between nodes  $i$  and  $k$ , and  $y_i$  and  $y_k$  represent the admittances to ground from nodes  $i$  and  $k$  respectively.



**Figure 7: Modeling GIC using the nodal admittance matrix method [20]**

Applying Kirchhoff's current law, the equivalent equation for any node  $i$  will be in the form:

$$\sum_{k=1}^N i_{ki} = i_i$$

$$k \neq i$$

The current in a transmission line is determined by the current source, the voltage differences between nodes of the transmission line and the admittance of the line.

$$j_{ki} + (v_k - v_i)y_{ki} = i_{ki}$$

Inserting Kirchhoff's current law into the prior formula, the following is derived.

$$\sum_{k=1}^N j_{ki} + \sum_{k=1}^N (v_k - v_i)y_{ki} = i_i$$

The total of the equivalent source currents directed into each node is as follows, and substituted into the prior.

$$\sum_{k=1}^N j_{ki} = J_i$$

$$J_i + \sum_{k=1}^N (v_k - v_i)y_{ki} = i_i$$

The equation above involves the nodal voltages  $v_i$  and the current to ground from each node  $i_i$  is unknown. The nodal voltage  $v_i$  is related to the current to ground  $i_i$  by Ohm's law so one can substitute for either  $v_i$  or  $i_i$  to obtain equations involving only one set of unknowns. In this derivation we will make the following substitution.

$$i_i = v_i y_i$$

Substituting  $i_i$  gives the following equation only involving the node voltage  $v_i$  as the unknown:

$$J_i + \sum_{k=1}^N (v_k - v_i) y_{ki} = v_i y_i$$

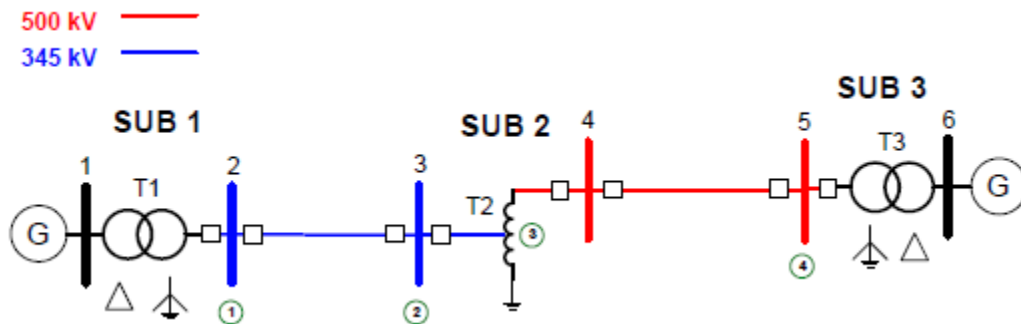
Or:

$$J_i = v_i y_i + \sum_{k=1}^N v_i y_{ki} - \sum_{k=1}^N v_k y_{ki}$$

The prior formula may be converted in matrix form:

$$[J] = [Y][V]$$

Using the prior matrix form, the following theoretical six bus system can be analyzed using GPS coordinates throughout the state of Wisconsin.



**Figure 8 Six Bus Example Power System [20]**

Tables 2 through 4 contain required data to calculate estimated GIC.



Name	Latitude	Longitude	Grounding Resistance (Ohms)
Sub 1	46.554666	-90.990730	0.2
Sub 2	43.113731	-89.232048	0.2
Sub 3	43.019590	-88.040024	0.2

**Table 2 Example Substation locations and ground grid resistance**

Line	From Bus	To Bus	Length (km)	Resistance (Ohms/Phase)
1	2	3	407	4.334
2	4	5	97	4.028

**Table 3 Example Transmission line information**

Name	Resistance W1 (Ohm/Phase)	Resistance W2 (Ohm/Phase)
T1	0.5	N/A
T2	0.2 (Series)	0.2 (Common)
T3	0.5	N/A

**Table 4 Example Transformer and Autotransformer Winding Resistance Values**

One must properly calculate the distance between two points to accurately derive the estimated GIC. It is necessary to take into account the latitude for the substation when converting its longitudinal separation into the distance due to the ellipsoidal shape of the Earth. Using the WGS84 model, the ellipsoidal model of the Earth is used and distances will be more accurately calculated.

Parameter	Symbol	Value
Equatorial Radius	A	6378.137 km
Polar Radius	B	6356.752 km
Eccentricity squared	E <sup>2</sup>	0.00669437999014

**Table 5 Parameter of the WGS84 Earth Model**

The North-South distance is given by:

$$L_N = \frac{\pi}{180} M * \Delta Lat$$

M is equal to the radius of the curvature in the meridian plane and is calculated by the following formula:

$$M = \frac{A (1 - e^2)}{(1 - E^2 \sin^2 \varphi)^{1.5}}$$

$$\varphi = \frac{LatA + LatB}{2}$$

Substituting values from Table 5, the North South distance in kilometers can be calculated.

$$L_N = (111.133 - 0.56 \cos(2\varphi)) * \Delta Lat$$

$\Delta Lat$  is the difference in latitude in degrees between the two substations A and B.

Similarly the East-West distance is given by:

$$L_E = \frac{\pi}{180} N \cos \varphi * \Delta Long$$

$$N = \frac{A}{\sqrt{1 - E^2 \sin^2 \varphi}}$$

Substituting the values from Table 5, the following formula is derived for East-West distances in kilometers.

$$L_E = (111.5065 - 0.1872 \cos(2\varphi)) * \cos \varphi * \Delta Long$$

Line	From Bus	To Bus	Northward Distance (km)	Eastward Distance (km)
1	2	3	-382.387	138.078
2	4	5	-10.459	97.103

**Table 6 Example Eastward and Northward distance calculation results**

Assuming an electrical field magnitude of 10 V/km with an Eastward direction, Table 7 was calculated using:

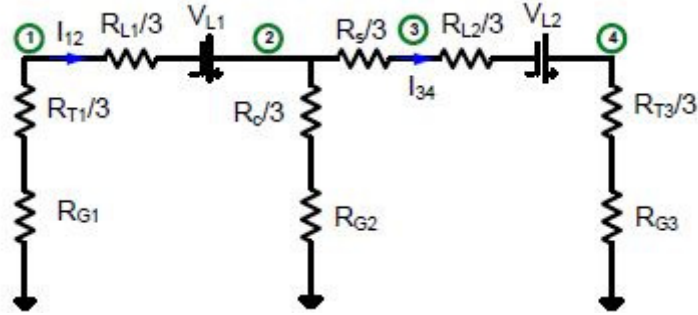
$$\vec{E} \cdot \vec{L} = E_x L_x + E_y L_y$$

Where  $\vec{E}$  is the geoelectric field at the location of the transmission line and  $\vec{L}$  is the incremental length vector.

Line	From Bus	To Bus	Induced Voltage (Volts)
1	2	3	1380.78
2	4	5	971.03

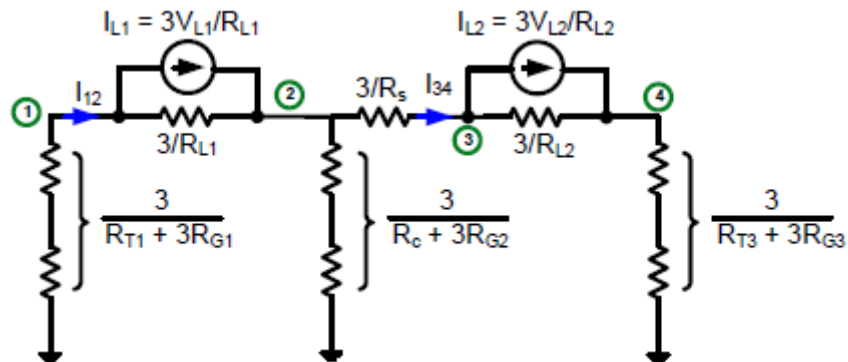
**Table 7 Example Induced Voltage Calculations**

The next step is to construct an equivalent circuit of the system as shown in Figure 9.



**Figure 9 Example Equivalent Circuit of System [20]**

The circuit in Figure 9 can be solved as is, but it is more convenient to perform the calculations using nodal analysis where the voltage sources are converted to current sources and all impedance elements are converted to their equivalent admittances as seen in Figure 10.



**Figure 10 Example Circuit of system in Nodal Form [20]**

The admittance matrix of the circuit shown in Figure 10 can be constructed as is shown in the following formula.

$$Y = \begin{bmatrix} \frac{3}{R_{T1} + 3R_{G1}} + \frac{3}{R_{L1}} & -\frac{3}{R_{L1}} & 0 & 0 \\ -\frac{3}{R_{L1}} & \frac{3}{R_S} + \frac{3}{R_{L1}} + \frac{3}{R_C + 3R_{G2}} & -\frac{3}{R_S} & 0 \\ 0 & -\frac{3}{R_S} & \frac{3}{R_S} + \frac{3}{R_{L2}} & -\frac{3}{R_{L2}} \\ 0 & 0 & -\frac{3}{R_{L2}} & \frac{3}{R_{T3} + 3R_{L2}} + \frac{3}{R_{L2}} \end{bmatrix}$$

Substituting the values into the prior matrix, the following matrix is calculated.

$$Y = \begin{bmatrix} 3.578 & -0.692 & 0 & 0 \\ -0.692 & 19.442 & -15 & 0 \\ 0 & -15 & 15.745 & -0.745 \\ 0 & 0 & -0.745 & 3.472 \end{bmatrix} mhos$$

The current vector can be calculated using the nodal currents as shown in the following matrix.

$$I = \begin{bmatrix} -I_{L1} \\ I_{L1} \\ -I_{L2} \\ I_{L2} \end{bmatrix}$$

Nodal current injections can be found using the following equations:

$$I_{L1} = \frac{3 V_{L1}}{R_{L1}} = 955.78 \text{ amps}$$

$$I_{L2} = \frac{3 V_{L2}}{R_{L2}} = 723.21 \text{ amps}$$

Using Ohms Law, the node voltages are calculated.

$$V = [Y]^{-1}I = \begin{bmatrix} 0.287 & 0.039 & 0.038 & 0.008 \\ 0.039 & 0.205 & 0.198 & 0.042 \\ 0.038 & 0.197 & 0.254 & 0.055 \\ 0.008 & 0.042 & 0.054 & 0.299 \end{bmatrix} \begin{bmatrix} -955.78 \\ 955.78 \\ -723.21 \\ 723.21 \end{bmatrix} = \begin{bmatrix} -258.729 \\ 45.838 \\ 8.050 \\ 209.682 \end{bmatrix}$$

The three phase GIC flow is calculated using the various relationships derived from the circuit. The following calculations can further be divided by three to obtain the per phase GIC flow.

$$I_{T1} = V_1 \left( \frac{3}{R_{T1} + 3R_{G1}} \right) = -705.625 \text{ amps}$$

$$I_{12} = I_{L1} + (V_1 - V_2) \left( \frac{3}{R_{L1}} \right) = -367.404 \text{ amps}$$

$$I_S = (V_3 - V_{21}) \left( \frac{3}{R_S} \right) = 566.62 \text{ amps}$$

$$I_C = V_2 \left( \frac{3}{R_C + 3R_{G2}} \right) = 171.893 \text{ amps}$$

$$I_{34} = I_{L2} + (V_3 - V_4) \left( \frac{3}{R_{L2}} \right) = 573.037 \text{ amps}$$

$$I_{T3} = V_4 \left( \frac{3}{R_{T3} + 3R_{G3}} \right) = 571.86 \text{ amps}$$

## Chapter 4 Computer Simulation of GIC

The mathematical modeling of GIC is a fairly simple process as seen in Chapter 3 Mathematical Modeling of GIC. When the system becomes large (more than a few nodes) the system matrix becomes very large quite quickly. Computer simulations can make the calculations required for analyzing a large complex system with many nodes an easy process. One option for a computer simulation of GIC is a free simulation tool developed by the Electrical Power Research Institute called OpenDSS.

The OpenDSS is a comprehensive electrical power system simulation tool primarily for electric utility power distribution systems. It supports nearly all frequency domain (sinusoidal steady-state) analyses commonly performed on electric utility power distribution systems. In addition, it supports many new types of analyses that are designed to meet future needs related to smart grid, grid modernization, and renewable energy research. The OpenDSS tool has been used since 1997 in support of various research and consulting projects requiring distribution system analysis. Many of the features found in the program were originally intended to support the analysis of distributed generation interconnected to utility distribution systems and that continues to be a common use. Other features support analysis of such things as energy efficiency in power delivery and harmonic current flow. The OpenDSS is designed to be indefinitely expandable so that it can be easily modified to meet future needs.

The example circuit from Chapter 3 will be used for the following simulation using OpenDSS.

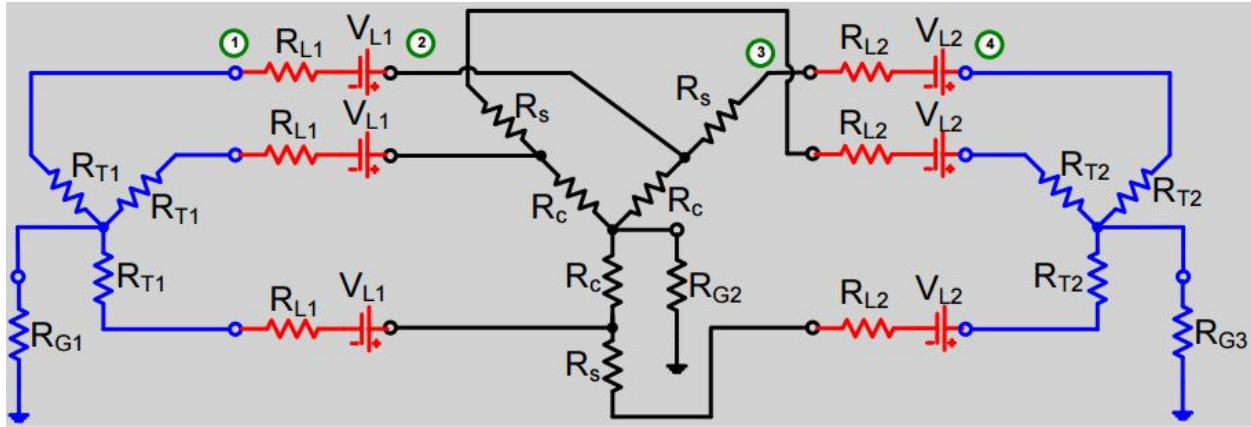


Figure 11 Example Three-Phase Equivalent Circuit [20]

Name	Latitude	Longitude	Grounding Resistance (Ohms)
Sub 1	46.554666	-90.990730	0.2
Sub 2	43.113731	-89.232048	0.2
Sub 3	43.019590	-88.040024	0.2

Table 8 Example Substation locations and ground grid resistance

Line	From Bus	To Bus	Length (km)	Resistance (Ohms/Phase)
1	2	3	407	4.334
2	4	5	97	4.028

Table 9 Example Transmission line information

Name	Resistance W1 (Ohm/Phase)	Resistance W2 (Ohm/Phase)
T1	0.5	N/A
T2	0.2 (Series)	0.2 (Common)
T3	0.5	N/A

Table 10 Example Transformer and Autotransformer Winding Resistance Values

Note: OpenDSS does not take into account the ellipsoidal shape of the Earth in its computation as described in the Chapter 3 Mathematical Modeling of GIC.



The OpenDSS simulation has three main components. First, the transmission line models are generated use a quasi-dc voltage, computed internally using Faraday's Law.

The line of code for transmission line 1 follows:

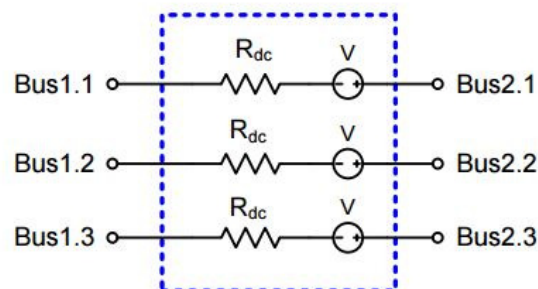
Object Class      Object Name      Bus Names      LAT/LON of Bus 1

**New GICLine.1 bus1=1 bus2=2 R=4.334 Lat1=46.554666 Lon1=-90.990730**

**Lat2=43.113731 Lon2=-89.232048 EE=10.00 EN=0.00**

LAT/LON of Bus 2      E Field (V/km)

**Figure 12 Example OpenDSS Transmission Line Input**



**Figure 13 OpenDSS Transmission Line Model [20]**

The second component required for GIC simulations with OpenDSS is the Transformer Model. There are three options available for the Model; Delta-Grounded Wye (GSU), Grounded-Wye Grounded Wye (with or without delta tertiary) and Grounded Why Autotransformers (with or without delta tertiary). Only connections to ground are included in the model, delta and ungrounded wye windings are excluded. For the simulations we will use an Autotransformer and two GSU's.

Object Class      Object Name      Bus Names      Parameters

New GICTransformer.T2 busH=3 busX=2 busNX=3.4.4.4 R1=0.2 R2=0.2 type=Auto

Figure 14 Example OpenDSS Autotransformer Input

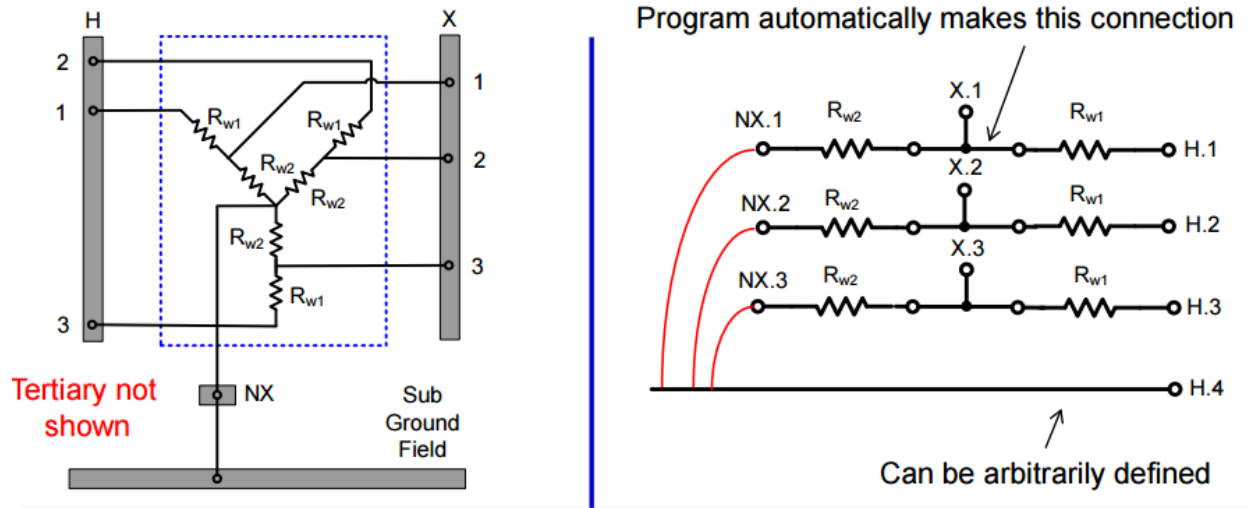
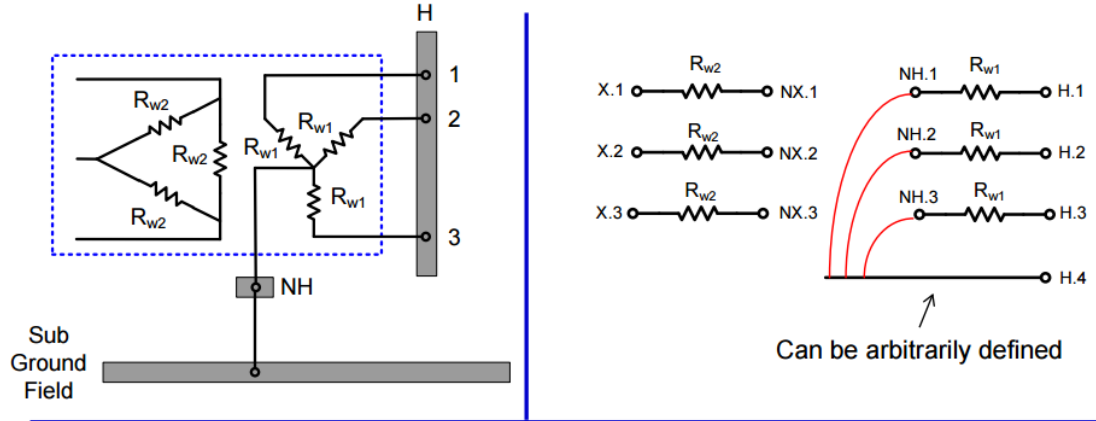


Figure 15 OpenDss Autotransformer Circuit [20]

Object Class      Object Name      Bus Names      Parameters

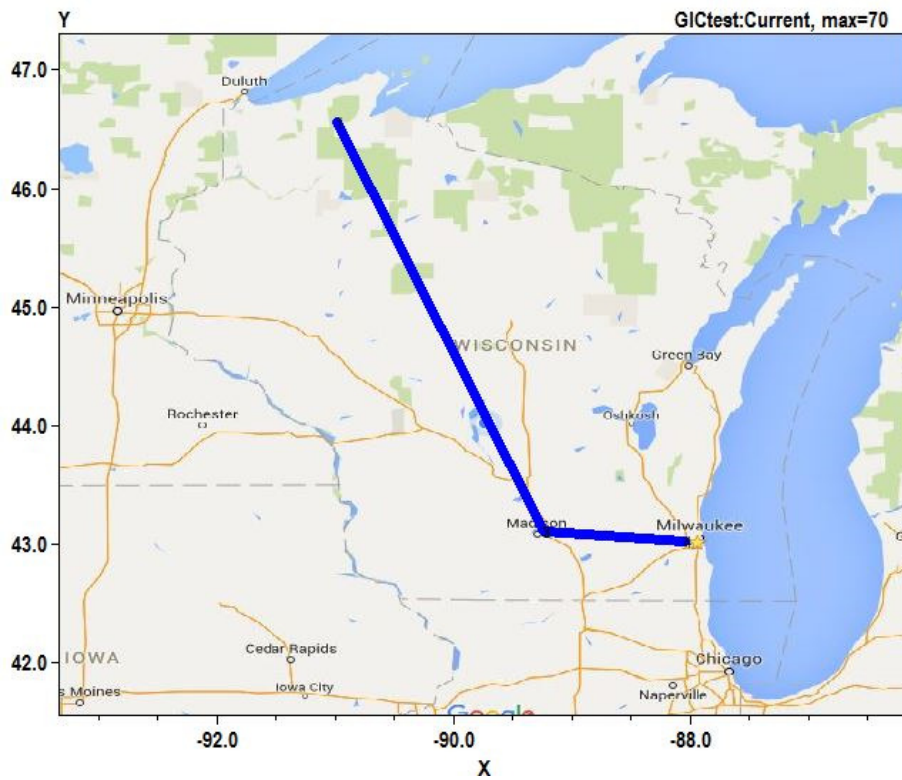
New GICTransformer.T1 busH=1 busNH=1.4.4.4 R1=0.5 type=GSU

Figure 16 Example OpenDSS GSU Input



**Figure 17 OpenDSS GSU Model [20]**

After entering all the parameters and running the code (Appendix B OpenDss Code with Results), the results were generated. Figure 18 depicts the simulated transmission lines in relation to the arbitrarily chosen GPS coordinates in the state of Wisconsin. The arbitrary GPS coordinates represent the bulk power system in Wisconsin, per available maps published by The America Transmission Company. The simulation used a calculated average ground resistivity derived from the resistive values from Figure 25, Figure 26 and Figure 27 in Appendix A. If this simulation was run for the same equipment, but in a different geographical location, the resistivity of the new location would have to be taken into consideration.



**Figure 18 OpenDSS GIC Simulation with Map**

## Chapter 5 Evaluation of Susceptibility of Power Transformers

The Total GIC Susceptibility of utility power assets is a complicated topic. Design, location, age, life expectancy and many others factors need to be taken into consideration to approximate the susceptibility that power transformers and other bulk power system assets will be damaged during GIC events. The treatment or replacement of expensive assets and application of mitigation techniques are costly and sometimes unneeded. Having each individual asset thermally tested for susceptibility can be avoided if general asset screenings are performed to a power utility's fleet. Higher voltage transformers maybe exposed to higher levels of GIC, and are costly to repair. The cost to monitor is just a fraction of the replacement cost of the asset. It is in the best interest of the power utility to monitor expensive assets to prevent unnecessary damage during GIC activity. Transformers greater than 200 kV on the primary should be monitored for GIC susceptibility regardless of condition or location due to the cost to replace if damaged [21].

The evaluation of the susceptibility of a transformer to the effects of GIC can be completed in multiple steps. The first step is to determine the susceptibility of the transformer based solely on its design. The second step of the evaluation process is to consider the location and the expected levels of exposure to GIC. Combining design information and the GIC level susceptibility information is critical to determine the Total Susceptibility of a transformer to effects of GIC [22]. A susceptible design type may be located in an area where the expected levels of GIC are low, therefore the Total GIC

Susceptibility of the transformer would be much lower than that indicated by only its design.

A fleet of transformers can be divided into the following categories to define its design based susceptibility classification to the effects of GIC:

**Classification-A:** Transformers not susceptible to effects of the GIC

**Classification-B:** Transformers least susceptible to core saturation but susceptible to high magnetizing current.

**Classification-C:** Transformers susceptible to core saturation and possible structural parts overheating.

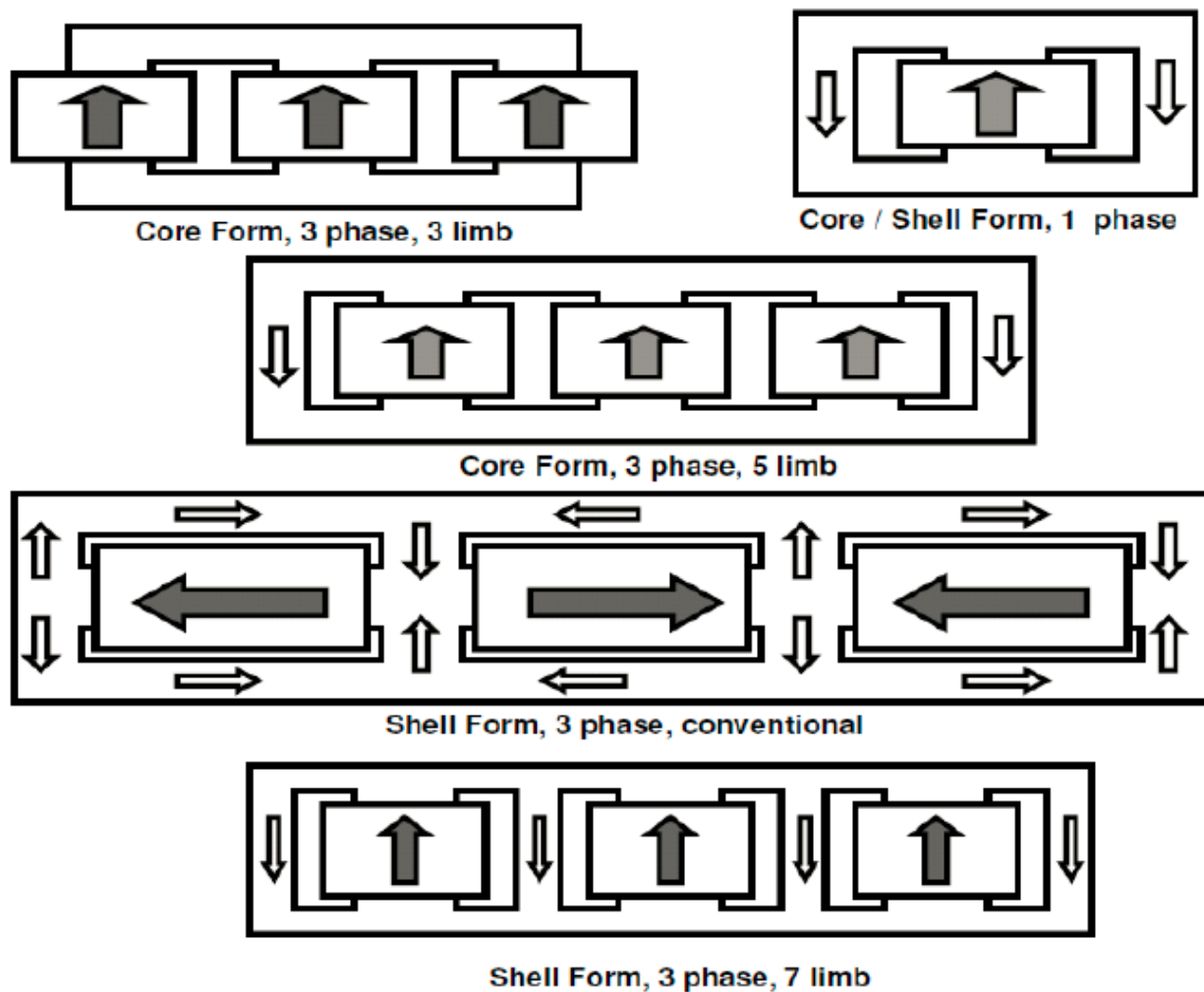
**Classification-D:** Transformers susceptible to core saturation as well as possible damaging windings and structural parts overheating.

The evaluation of the Design – Based susceptibility may consider the following key electrical parameters and core and winding design of a transformer.

**Transformer winding design:**

- If the HV winding of the transformer is connected in delta, the transformer is not susceptible to GIC and may be considered to be in Classification A.
- In transformers with core types other than the three-phase, three-limb core, if the LV winding of the transformer is delta-connected, or if the transformer has a delta connected tertiary winding the transformer may be susceptible to possible significant winding overheating and should be considered to be in Classification D.

**Transformer type:**



**Figure 19 Core DC flux path in various core types [7]**

- Three-phase core form transformer with a three-limb core has lower susceptibility to core saturation but it is susceptible to high levels of magnetizing current and tank heating may be considered to be in Classification B.
- Transformers with core types other than the three-phase three-limb core, using a T-beam (shell 1 form), or near-core flitch-plates or tie-rods (core form) are susceptible to core saturation and structural parts overheating and may be considered to be in Classification C.

- Transformers with core types other than the three phase three limb cores with magnetic steel bolts through the core limbs or yokes are susceptible to overheating of core bolts during core saturation and may be considered in Classification D.
- Some of the pre–1970 shell form designs could be susceptible to appreciable winding overheating due to high circulating currents in the low voltage windings when the core saturates and may be considered to be in Classification D.

For power transformers designs not mentioned in the criteria above, a full assessment should be performed to determine the susceptibility of the design to GIC activity.

The GIC level-based assessment represents the other part in the process of evaluating the Total Susceptibility of a transformer. As stated in the above, the Total Susceptibility of a transformer cannot be accurately analyzed without considering the level of GIC the transformer may be exposed to. This level of GIC is determined by a number of factors, such as the region where the transformer is located, the resistance of the soil in that location, and other factors. These items have been discussed in Chapter 2. The process of evaluating the GIC Level–Based susceptibility divides transformers into three exposure categories;

- High (greater than 75 amperes per phase)
- Medium (greater than 15 amperes per phase but less than 75 amperes per phase)
- Low (less than 15 amperes per phase).



These categories may be determined using calculated relative levels of GIC that transformers in a certain location, and would be subjected to for the benchmark GMD storm.

The process of assessing the Total Susceptibility of a transformer to GIC events combine the results of the Design – Based Susceptibility Assessment analysis and the GIC Level–Based Susceptibility Assessment.

- Transformers assessed to have a high level of Total Susceptibility to GIC effects (Category IV) are those which belong to design classification D and are, at the same time, located in high or medium GIC level areas. For this group of transformers, both magnetic and thermal GIC capability (winding hotspot and structural parts hotspot) evaluation may be considered.
- Transformers assessed to have a medium level of Total Susceptibility to effects of GIC (Category III) are those which are determined to be either in Design Classification B or C and are located in high GIC level areas. For this group of transformers, both magnetic modeling and thermal assessment of structural parts may be performed.
- Transformers assessed to have a low Total Susceptibility to effects of GIC (Category II) are those which are determined to belong to Design Classification B or C and are located in medium GIC level areas. For this group of transformers, only magnetic modeling may be performed.
- Transformers assessed to have practically no susceptibility to effects of GIC (Classification A) are those which are determined to be either:
  - I) Design Classification B or C and are located in low GIC level areas, or

## II) Design Classification A

- For Category 1, no further action may be considered.

Due to the nature of this thesis, it is important to note here that identifying a group of transformers to be highly susceptible to winding or structural parts overheating does not imply that these transformers will experience this overheating. It only identifies those transformers that need detailed thermal assessment. Table 11 is a summary of Category versus GIC Exposure Level Classification.

Classification of Transformer Design Based Susceptibility	Low Exposure ( $\leq 15$ A)	Medium Exposure ( $>15$ to 75 A)	High Exposure ( $>75$ A)
Not Susceptible (A)	1	1	1
Least Susceptible (B)	1	2	3
Susceptible (C)	2	3	3
Highly Susceptible (D)	2	4	4

**Table 11 Transformer Total Susceptibility to the Effects of GIC in Amperes per Phase**

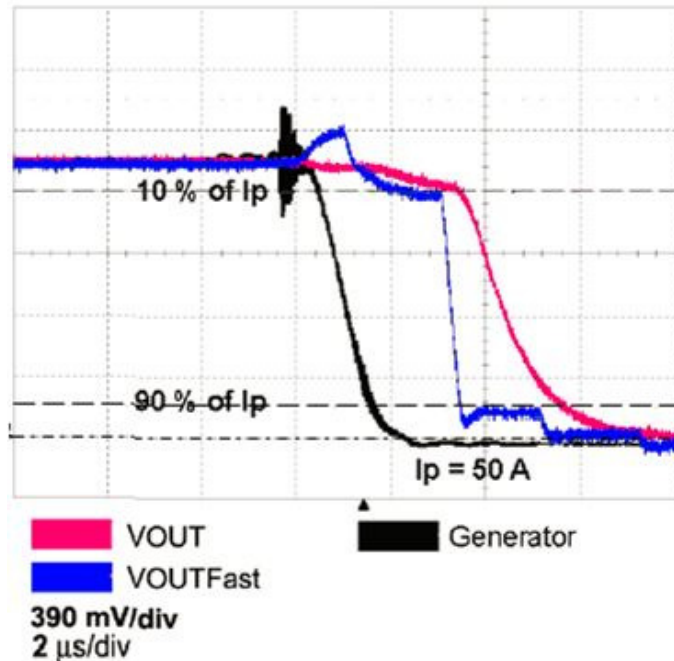
After the susceptibility of the assets are calculated, the utility industry may choose appropriate actions to take to prevent damage from GIC. If the Transformer Total Susceptibility is greater than two, online monitoring can be installed. Online monitoring can take measurements of GIC on assets around the clock, making the tripping of assets offline in the quickest time causing the least amount of damage.

## Chapter 6 Monitoring Techniques for GIC

Future GIC events are going to have an effect on the bulk power system. Massive blackouts and costly damage to utility assets are some of the major risks that we face. One way to prevent this is to establish specific parameters and performance characteristics for power transformers to help minimize the risk and impact that GIC may cause when events occur effecting the bulk power system.

Monitoring GIC activity of transformers is relatively easy. Hall Effect sensors are a non-intrusive CT that can be installed on the neutral conductor to measure both ac and dc currents. Hall Effect sensors are available in split core designs to make retrofitting a GIC monitoring solution on a transformer simple. A short outage on the assets may be required if safety clearances to the high voltage energized lines must be breached. The split core Hall Effect sensor design does not required disconnecting any cabling to install.

Monitoring the cause for the damage from GIC flow through the neutral conductor to ground is the approach that will prevent the most amount of damage to utility assets. Other options that monitor the effects caused by GIC, such as increased transformer saturation current, increased VAR consumption, harmonic content of the saturation current, transformer overheating, tank wall overheating and DGA results are unable to trip the transformer offline prior to the damage occurring. Harmonic measurements, while able to monitor GIC, are only able to make measurements once the transformer's core has undergone half-cycle saturation. By this time irreversible damage may have occurred. Monitoring the GIC flow through the neutral conductor can trip a transformer offline prior to the damage that harmonics may cause.



**Figure 20 Response time of Dynamic Ratings Hall Effect Sensor**

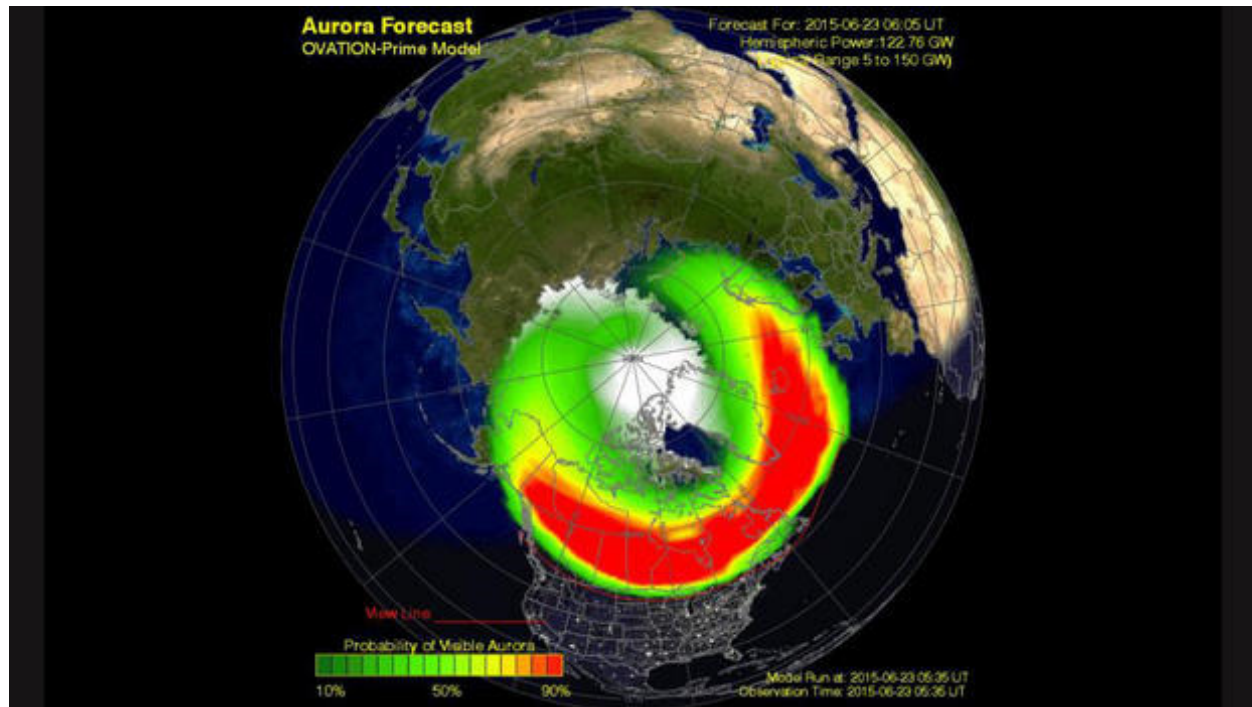
The Dynamic Ratings Inc. GIC sensor has a very good response time at  $6 \mu\text{s}$ , as depicted in Figure 20. The sensors are installed on the neutral conductor to ground prior to any grounded restraints of the cable or bus bar. An example installation is shown in Figure 21. The red circle is the Hall Effect sensor. It is installed as close to the neutral bushing as possible and the conductor is centered in the sensor.



**Figure 21 Dynamic Ratings GIC Sensor Installed on Transformer**

Starting on April 21<sup>st</sup> 2015, large concentrations of solar winds were ejected from a coronal mass ejection. Three distinct CME's were the source of concentrated solar winds and caused an injection of electrically charged particles into the Earth's magnetosphere. The individual events caused geomagnetic disturbances around the world. Three recorded instances occurred on June 21 at 16:45 UT, June 22 at 5:45 UT and June 22 at 18:30 UT. By standard measures, this magnetic solar storm was the second largest of the present solar cycle. As is typical for magnetic storms, activity was particularly intense at high latitudes. At the USGS Barrow observatory in northern Alaska, for example, the direction of the Earth's magnetic field fluctuated by almost 10 degrees in less than an hour. You could actually measure the effect of this storm on a simple compass [23]. The aurora borealis were seen across Alaska, Canada and in many states in the lower continental United States as far south as North Carolina, Georgia and Texas.

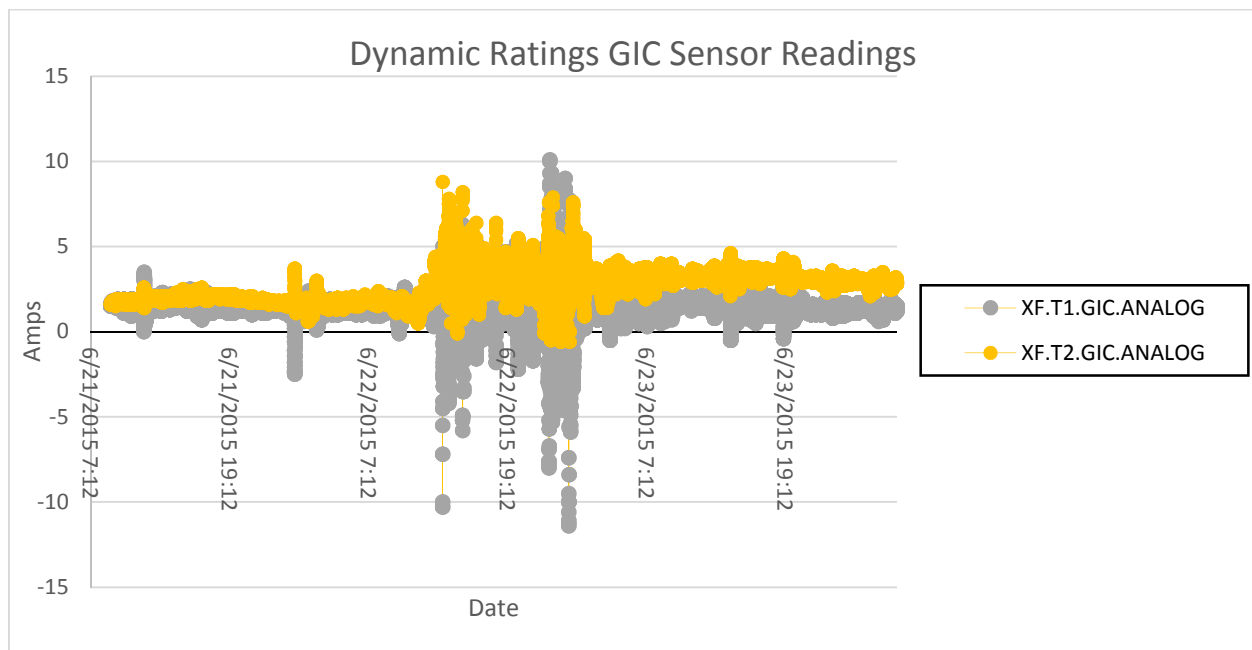
The results of this event reached sever G4 levels on the National Oceanic and Atmospheric Administration's space weather scale.



**Figure 22 NOAA June 23, 2015 Aurora Forecast [24]**

After the arrival at Earth of the third CME, data from NASA's Advanced Composition Explorer satellite indicates that the solar wind's interplanetary magnetic field was southward directed. The southward orientation is optimal for connection of the interplanetary magnetic field onto geomagnetic field lines. Once this connection occurred, the magnetosphere was effectively opened up to the solar wind allowing electrically charged energetic particles to be deposited into the magnetotail, or the main source of the polar aurora, and into the westward-flowing equatorial ring current of the inner magnetosphere. This storm saw a maximum  $-195$  nT on June 23 at about 04:30 UT.

The conditions were all in favor for large GIC events occurring in the bulk power system in northern parts of North America. Two transformers, with Dynamic Ratings GIC sensors, were online collecting data throughout the time period of the storms. In Figure 23, the recorded GIC amperage results are graphed. One can clearly see the peaks of the three distinct events.



**Figure 23 Dynamic Ratings GIC Sensor Readings June 21-24**

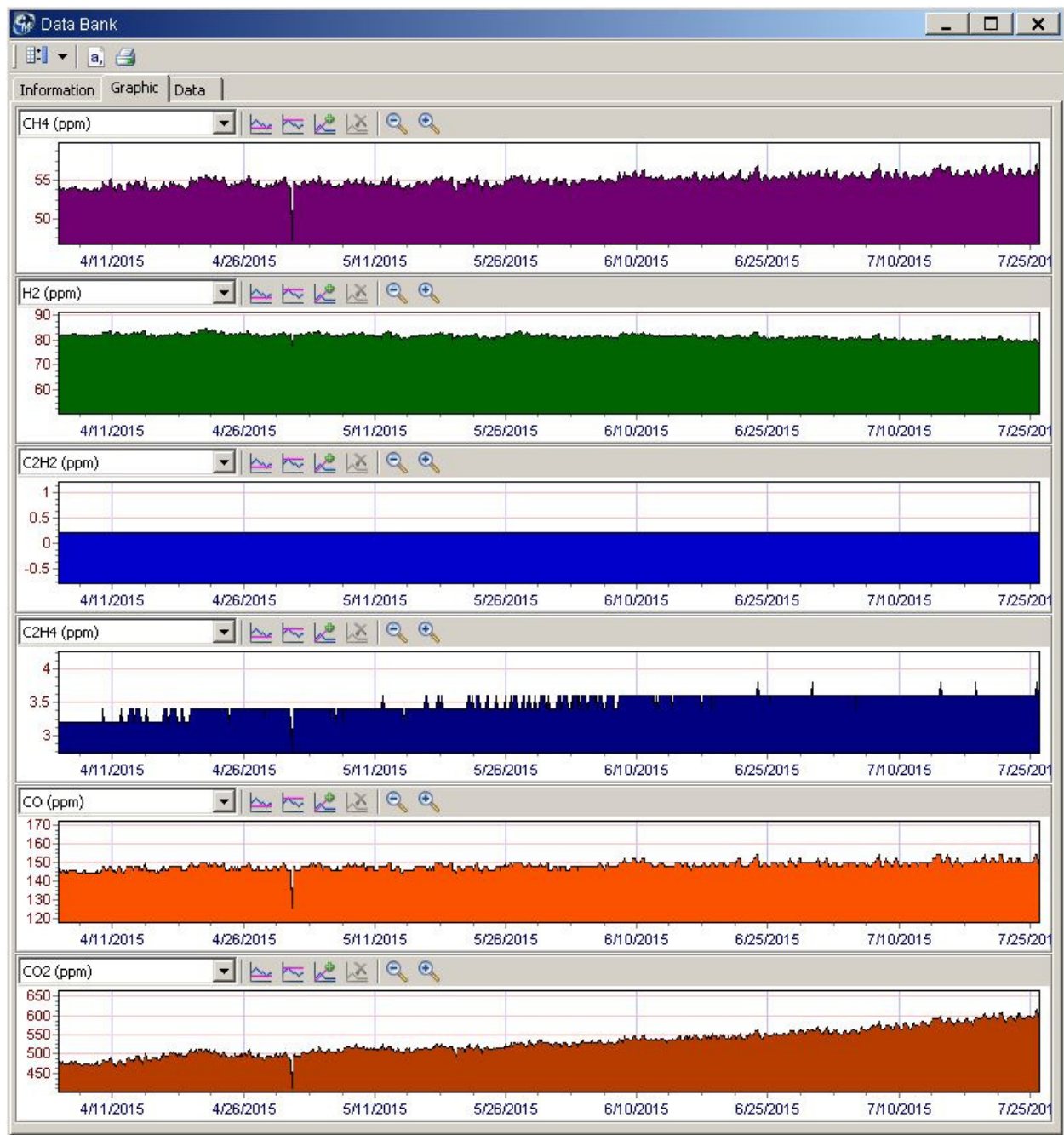
The two assets, with Dynamic Ratings GIC monitoring, were in the Midwest of the United States and were clearly showing signs of GIC activity. The Transformer T1 asset was located further north and experience a higher value GIC because it was located inside the predicted area of high activity from Figure 22. Transformer T1 experienced short bursts of  $\pm 10$  amperes on multiple occasions during the second of the two events. As discussed in

Chapter 5 Evaluation of Susceptibility of Power Transformers, both transformers have a susceptibility of greater than three. Both assets should be monitored closely due to their location and probability of being effected by solar storms in the future. Luckily, this was a short lived event and the asset presented no signs of damage caused by GIC.

To further investigate this storm, this thesis will also investigate the dissolved gas analyzer recordings to see if this event caused any internal gassing. Transformer T1 has a Morgan Schaffer Calisto 9 installed for online monitoring purposes. As mentioned in prior chapters, a dissolved gas analyzer will only trigger alarms after the damage to the asset has occurred. The off gassing is a result of the damage to the transformer. Using Morgan Schafer's program Calisto Manager, the historical data was analyzed for key gas increases. See Table 12 in Appendix C for more information on what causes key gases in power transformers. Figure 24 shows the DGA recordings from April – August 2015. Any key gases released in the transformer may take a week or two to circulate through to the DGA device. The results do not indicate that any Partial Discharge or thermal damage from harmonics occurred from the result of the GIC.

Although tripping a transformer offline may cause outages, it is the best way to protect transformers from internal damage from GIC. Due to the varying degrees of susceptibility, age, location and importance of the asset, the tripping trigger can vary greatly. If the asset is declared a critical infrastructure piece of equipment, than greater care must be taken to comply with the North American Electrical Reliability Corporation's Critical Infrastructure Protection program.





**Figure 24 Transformer T1 DGA Recording after GIC Event**

The bulk power system is operated using what is termed the N-1 operation criterion. This N-1 criteria deems that the system must always be operated to withstand the next credible disturbance contingency without causing a cascading collapse of the system as a region or whole. GIC events cause almost simultaneous events that impact the bulk power system over a wide area.

Tripping from just high current values from GIC events will protect the asset. When tripping from current over time or current combined with thermal and other sensor inputs, the asset experiencing GIC will be able to remain in service as long as possible prior to any damage occurring. This is a key factor for preventing nuisance alarms, and causing unnecessary outages breaking the N-1 operation criteria.

## Chapter 7 Conclusion

This thesis intends to raise the issue of geomagnetic phenomenon as a potential disturbance to the bulk power system. A systematic approach was used to bring notice of how susceptible the system actually is and how many different ways it can be effected from one GIC event. This was achieved by studying the events that cause GIC, mathematically modeling GIC, simulating GIC and discussing monitoring and investigating real world data from a local event. If proper monitoring and mitigation techniques are not rolled out system wide, we will see cascading outages like we have in the past.

More field research must be conducted to come up with a valid monitoring and mitigation process for each case. Contingency plans must be developed to maintain the N-1 operation criteria. NERC and IEEE have all identified the issues discussed in this thesis and are actively developing new guidelines so new products are designed with GIC failure modes identified and lessened as much as possible. Guides for assessing susceptibility of assets will be published by IEEE in the near future. Hopefully NERC CIP will eventually publish regulations that must be abided by to prevent GIC events causing large scale outages in the future, but until then any utility can actively create their own monitoring and mitigation programs to prevent damage to their costly assets.

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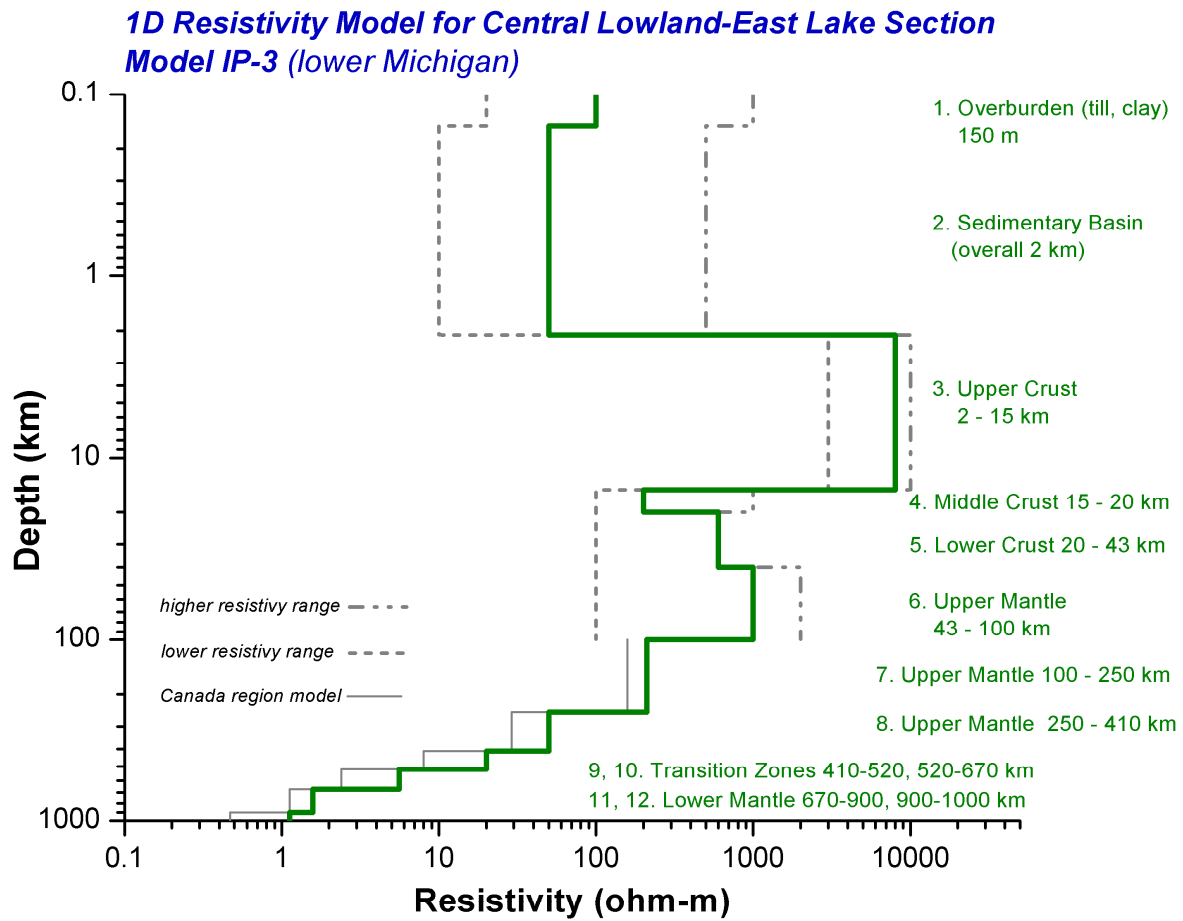
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## Appendix A

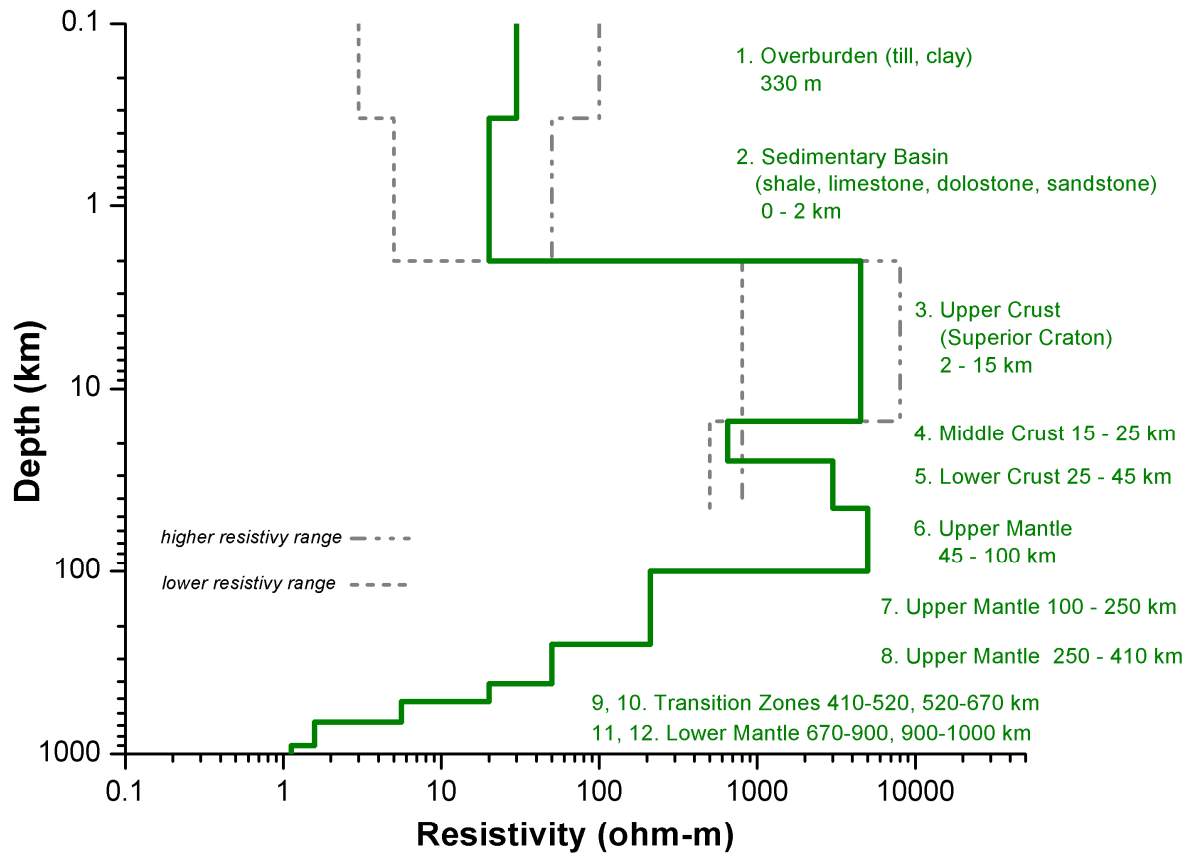


Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

**Figure 25 Interior Plains IP-3 Resistivity Graph [10]**

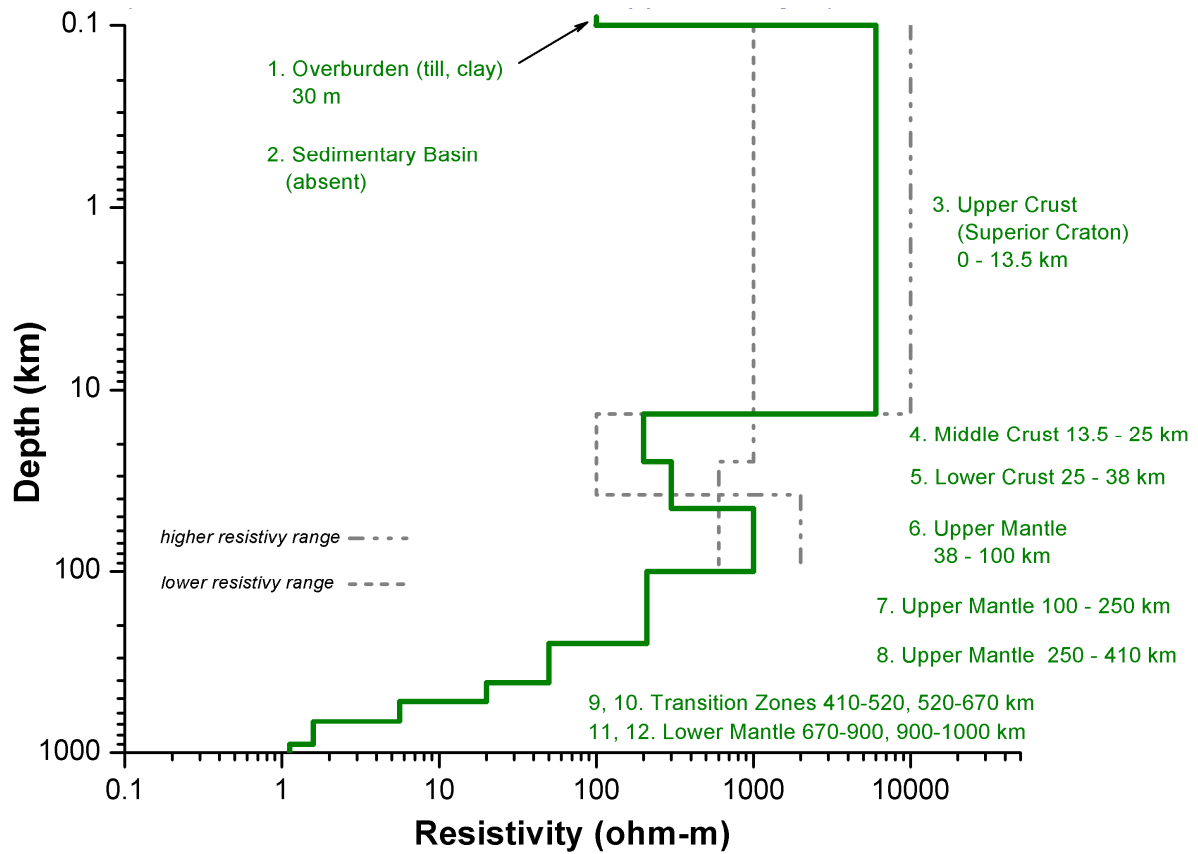


### 1D Resistivity Model for Interior Plains (North Dakota) Model IP-1



Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

**Figure 26 Interior Plains IP-1 Resistivity Graph [10]**



**Figure 27 Superior Upland SU-1 Resistivity Graph [10]**

## Appendix B

### OpenDSS code for simulation;

Clear

New circuit.GICtest

!GIC Line Data

New GICLine.1 bus1=1 bus2=2 R=4.334 Lat1=46.554666 Lon1=-90.990730 Lat2=43.113731  
Lon2=-89.232048 EE=10.00 EN=0.00

New GICLine.2 bus1=3 bus2=4 R=4.028 Lat1=43.113731 Lon1=-89.232048 Lat2=43.019590  
Lon2=-88.040024 EE=10.00 EN=0.00

!GIC Transformer Data

New GICTransformer.T1 busH=1 busNH=1.4.4.4 R1=0.5 type=GSU

New GICTransformer.T2 busH=3 busX=2 busNX=3.4.4.4 R1=0.2 R2=0.2 type=Auto

New GICTransformer.T3 busH=4 busNH=4.4.4.4 R1=0.5 type=GSU

!Substation Ground Grid Data

New Reactor.SUB1gnd phases=1 bus1=1.4 R=0.200 X=0

New Reactor.SUB2gnd phases=1 bus1=3.4 R=0.200 X=0

New Reactor.SUB3gnd phases=1 bus1=4.4 R=0.200 X=0

!Perform analysis

Set frequency=0.1

Solve

!Load file with bus coordinates, used for plotting

LatLongCoords LatLonFile.csv

Show Current Elements

Show Transformer Elements

plot circuit Current Max=70 dots=y labels=y subs=n C1=\$00FF0000

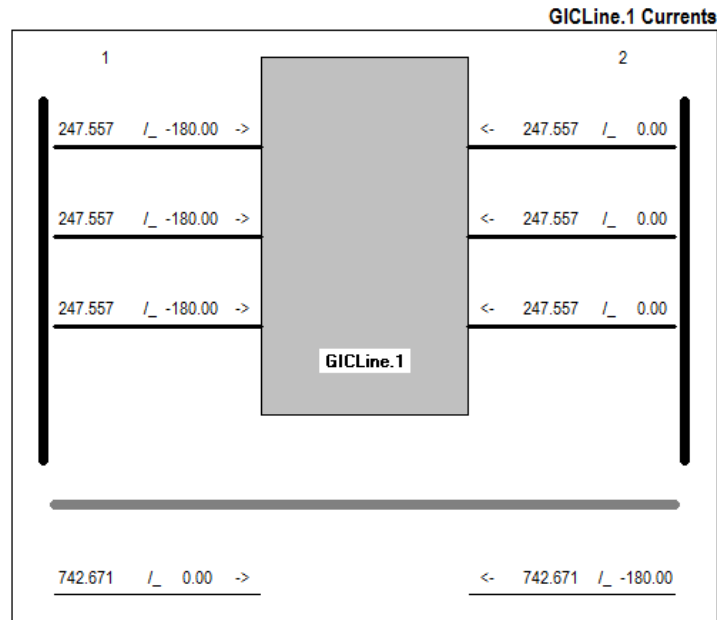
## OpenDSS simulation generated results;

### SYMMETRICAL COMPONENT VOLTAGES BY BUS (for 3-phase buses)

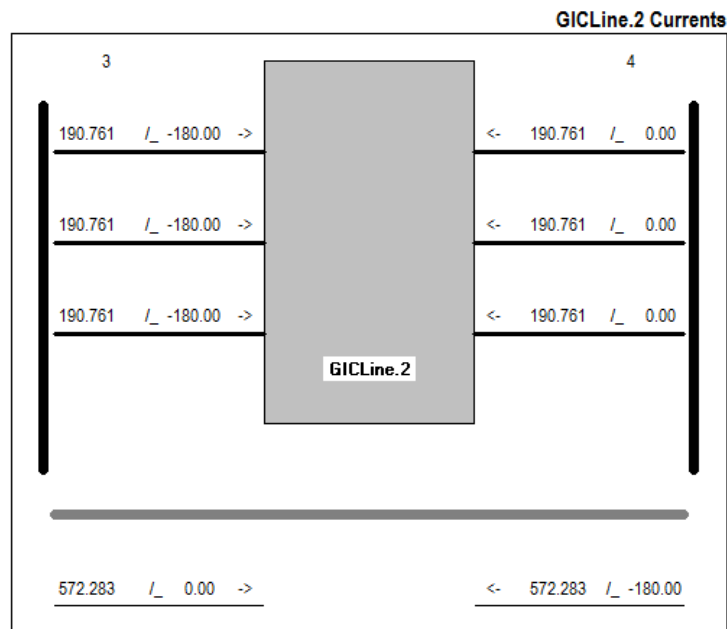
Bus	Mag:	V1 (kV)	p. u.	V2 (kV)	%V2/V1	V0 (kV)	%V0/V1
sourcebus		0	0	0	0	0	0
1	1.421E-017		0	2.842E-017	200	0.2723	1.916E018
2	4.783E-018		0	3.553E-018	74.28	0.04544	9.5E017
3	4.379E-018		0	4.003E-018	91.4	0.007284	1.663E017
4	7.105E-018		0	7.105E-018	100	0.2098	2.953E018

### Power Conversion Elements

Bus	Phase	Magnitude, A	Angle	(Real)	+j (Imag)
ELEMENT = "GICLine.1"					
1	1	247.56 /_	-180.0 =	-247.56 +j	-8.3678E-008
1	2	247.56 /_	-180.0 =	-247.56 +j	-8.3678E-008
1	3	247.56 /_	-180.0 =	-247.56 +j	-8.3678E-008
-----					
2	1	247.56 /_	0.0 =	247.56 +j	8.3678E-008
2	2	247.56 /_	0.0 =	247.56 +j	8.3678E-008
2	3	247.56 /_	0.0 =	247.56 +j	8.3678E-008
ELEMENT = "GICLine.2"					
3	1	190.76 /_	-180.0 =	-190.76 +j	-6.448E-008
3	2	190.76 /_	-180.0 =	-190.76 +j	-6.448E-008
3	3	190.76 /_	-180.0 =	-190.76 +j	-6.448E-008
-----					
4	1	190.76 /_	0.0 =	190.76 +j	6.448E-008
4	2	190.76 /_	0.0 =	190.76 +j	6.448E-008
4	3	190.76 /_	0.0 =	190.76 +j	6.448E-008



**Figure 28 OpenDSS Simulation GICLine1**



**Figure 29 OpenDSS Simulation GICLine2**

# CIRCUIT ELEMENT CURRENTS

(Currents into element from indicated bus)

## Power Delivery Elements

Bus	Phase	Magnitude, A	Angle	(Real)	+j	(Imag)
ELEMENT = "GICTransformer.T1"						
1	1	247.56 /_	0.0 =	247.56 +j	8.3678E-008	
1	2	247.56 /_	0.0 =	247.56 +j	8.3678E-008	
1	3	247.56 /_	0.0 =	247.56 +j	8.3678E-008	
-----						
1	4	247.56 /_	-180.0 =	-247.56 +j	-8.3678E-008	
1	4	247.56 /_	-180.0 =	-247.56 +j	-8.3678E-008	
1	4	247.56 /_	-180.0 =	-247.56 +j	-8.3678E-008	
ELEMENT = "GICTransformer.T2"						
3	1	190.76 /_	0.0 =	190.76 +j	6.448E-008	
3	2	190.76 /_	0.0 =	190.76 +j	6.448E-008	
3	3	190.76 /_	0.0 =	190.76 +j	6.448E-008	
-----						
2	1	190.76 /_	-180.0 =	-190.76 +j	-6.448E-008	
2	2	190.76 /_	-180.0 =	-190.76 +j	-6.448E-008	
2	3	190.76 /_	-180.0 =	-190.76 +j	-6.448E-008	
-----						
2	1	56.796 /_	-180.0 =	-56.796 +j	-1.9198E-008	
2	2	56.796 /_	-180.0 =	-56.796 +j	-1.9198E-008	
2	3	56.796 /_	-180.0 =	-56.796 +j	-1.9198E-008	
-----						
3	4	56.796 /_	0.0 =	56.796 +j	1.9198E-008	
3	4	56.796 /_	0.0 =	56.796 +j	1.9198E-008	
3	4	56.796 /_	0.0 =	56.796 +j	1.9198E-008	
ELEMENT = "GICTransformer.T3"						
4	1	190.76 /_	-180.0 =	-190.76 +j	-6.448E-008	
4	2	190.76 /_	-180.0 =	-190.76 +j	-6.448E-008	
4	3	190.76 /_	-180.0 =	-190.76 +j	-6.448E-008	
-----						
4	4	190.76 /_	0.0 =	190.76 +j	6.448E-008	
4	4	190.76 /_	0.0 =	190.76 +j	6.448E-008	
4	4	190.76 /_	0.0 =	190.76 +j	6.448E-008	
ELEMENT = "Reactor.SUB1GND"						
1	4	742.67 /_	0.0 =	742.67 +j	2.5103E-007	
-----						
1	0	742.67 /_	-180.0 =	-742.67 +j	-2.5103E-007	
ELEMENT = "Reactor.SUB2GND"						
3	4	170.39 /_	-180.0 =	-170.39 +j	-5.7593E-008	
-----						
3	0	170.39 /_	0.0 =	170.39 +j	5.7593E-008	
ELEMENT = "Reactor.SUB3GND"						
4	4	572.28 /_	-180.0 =	-572.28 +j	-1.9344E-007	
-----						
4	0	572.28 /_	0.0 =	572.28 +j	1.9344E-007	
=====						

## Appendix C

INDICATION / FAULT GAS	CO	CO <sub>2</sub>	CH <sub>4</sub>	C <sub>2</sub> H <sub>2</sub>	C <sub>2</sub> H <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	O <sub>2</sub>	H <sub>2</sub>	H <sub>2</sub> O
Cellulose aging	●	●							●
Mineral oil decomposition			●	●	●	●		●	
Leaks in oil expansion systems, gaskets, welds, etc.		●					●		●
Thermal faults – Cellulose	●	●	●				●	●	
Thermal faults in Oil @ 150°C - 300°C			●		TRACE	●		●	
Thermal faults in Oil @ 300°C - 700°C			●	TRACE	●	●		●	
Thermal faults in Oil @ >700°C			●	●	●			●	
Partial Discharge			●	TRACE				●	
Arcing			●	●	●			●	
Guidelines for surveillance range <sup>1</sup> for Type 1 transformers (IEEE PC57.104 D11d)	N <350 C 350 - 570 W >570		N <120 C 120 - 400 W >400	N <2 C 2 - 5 W >5	N <50 C 50 - 100 W >100	N <65 C 65 - 100 W >100		N <100 C 100 - 700 W >700	
<sup>1</sup> ppm for Normal (N), Caution (C), Warning (W) – alarm thresholds									

**Table 12 DGA Gas Interpretation [25]**

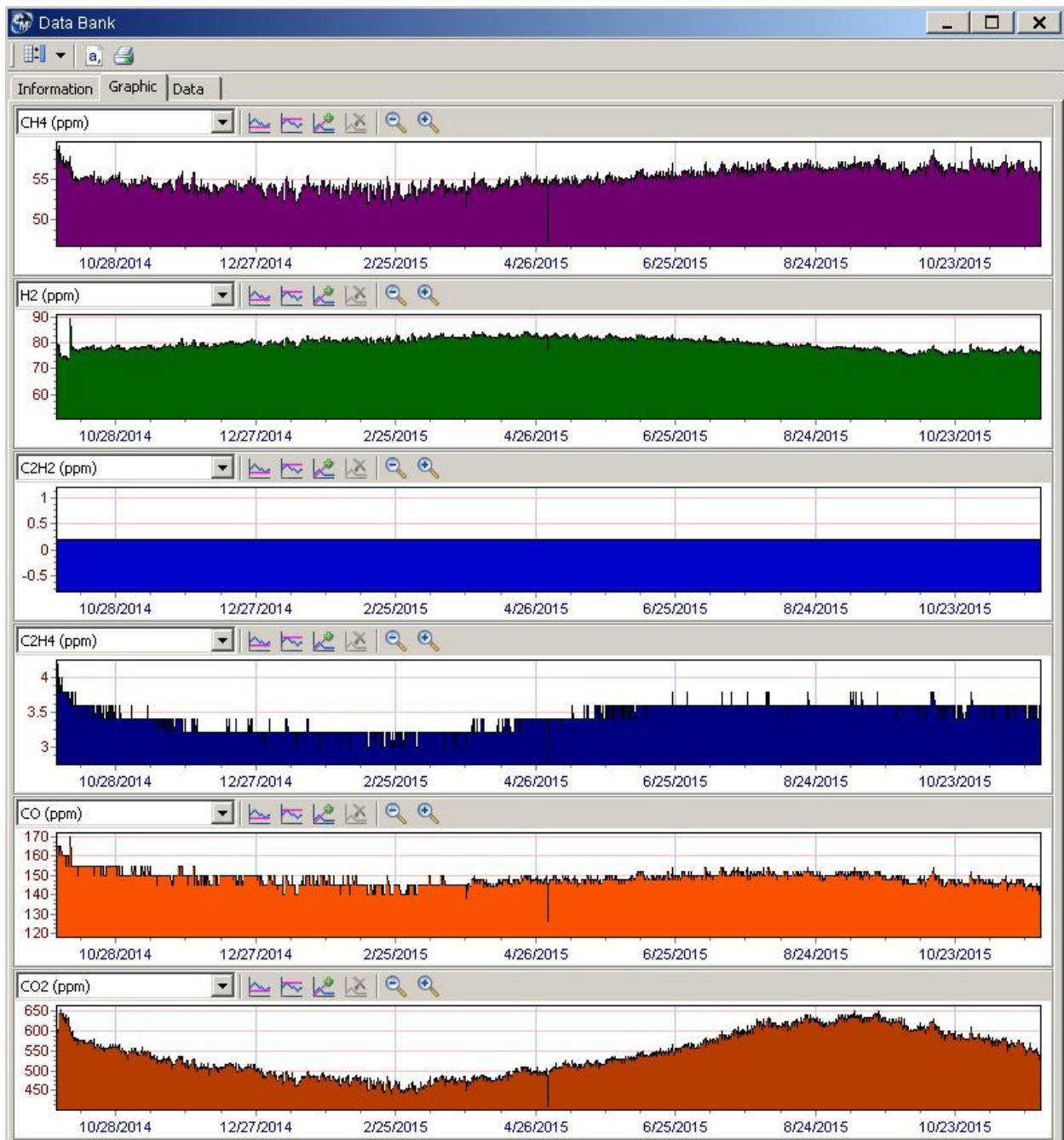


Figure 30 T1 Transformer DGA History Long