The Use of Intensity Modulated Optical Sensing Technology to Identify and Measure Impacts of GIC on the Power System

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ABSTRACT
This paper describes the phenomenon of geomagnetically induced currents (“GIC”), a geomagnetic disturbance’s potential impact on transformers and the electric power system, and FERC/NERC regulation regarding utility responsibility. The paper then introduces intensity modulated optical sensing technology, explains how this technology has been adapted to measure voltage, current, phase and other characteristics of electric phenomena, and answers why this adaptable core technology provides a comprehensive solution to identifying and measuring the impacts of GIC.

INTRODUCTION
The phenomenon of geomagnetically induced currents (“GIC”) has been well documented[1] and is summarized herein. Because of the catastrophic impacts a major solar storm, which precipitates GIC flow, can have on electric power grid operations and its components, the Federal Energy Regulatory Commission (FERC) issued an order in May 2013 requiring the North American Electric Reliability Corporation (NERC) to create reliability standards to address the Geomagnetic Disturbance (GMD) threat.

This paper reviews the mechanism by which the loss of reactive power occurs due to GIC and how it could lead to system voltage collapse, which is central to FERC’s concerns. However, the main impetus for writing this paper is to introduce a technology that brings true system visibility within reach of utility asset managers and system operators. This visibility is paramount to the success of managing GIC effects. Practically, it is impossible to manage something you cannot measure; for example, how can you know whether the reaction is appropriate for the problem if the latter is not quantified? Increase system visibility also validates the effectiveness of strategies to block GIC.

Managing and blocking are the two mitigation approaches for dealing with GIC. Managing GIC in real time involves fast, responsive operating procedures. While modeling efforts will aid in predetermining operating steps that will help to minimize outages and limit damage to critical equipment in the presence of GIC, accurate, real-time system visibility reveals the necessity of these operating steps or need for more during each unique GMD event and guide the operator (manual or automatic) with respect to when these steps must be implemented (and when the danger is gone). Afterwards, this increased visibility will help improve the predefined thresholds of system switching and VAR support components used during GIC induced events.

Alternatively, blocking GIC can be done through several means, including the installation of a GIC neutral blocking capacitor on the neutral of a susceptible transformer, resistive grounding of the transformer (although this will require a higher surge arrester rating), and series capacitor in transmission lines.

[1] *W.Hagman, “Space Weather in Solar Cycle 24: Is the Power Grid at Risk?,” IEEE PES Boston Chapter & IEEE Comp Society Boston Chapter Joint Lecture, April 16, 2013, references.*

The technology that delivers the system visibility required to effectively manage and mitigate the threat of GMD is called Intensity Modulated ("IM") Optical Sensing. It was developed by the Naval Research Laboratory for use by the United States Navy in mission-critical applications, which presented with very hostile measuring environments. IM optical sensing devices solve the measuring challenges to which other optical devices and traditional instrument transformer devices succumb, including those present during geomagnetic storms. Furthermore, the measuring capabilities of IM optical sensing devices transcend the capabilities of traditional devices. The remarkable stability of an IM optical monitoring systems in harsh measuring conditions, its higher accuracy, broadband measuring capabilities, and its real-time delivery power system information are key to delivering a more resilient electric power grid, even and particular in the grips of such High Impact Low Frequency events as GMD.

GEOMAGNETICALLY INDUCED CURRENTS

Geomagnetic storms are associated with activity on the sun's surface, namely sunspots and solar flares. Solar flares result in electromagnetic radiation (coronal mass ejections (CME), x-rays and charged particles) forming a plasma cloud or "gust of solar wind" that can reach earth in as little as eight minutes. Depending on its orientation, the magnetic field produced by the current within the plasma cloud can interact with the earth's magnetic field, causing it to fluctuate, and result in a geomagnetic storm.

Geomagnetically induce currents ("GICs") are caused when the "auroral electrojet", currents that follow high altitude circular paths around the earth's geomagnetic poles in the magnetosphere at altitudes of about 100 kilometers, becomes 'energized' and subjects portions of the earth's nonhomogeneous, conductive surface to slow, time-varying fluctuations in Earth's normally unchanging magnetic field. [1][2] By Faraday's Law of Induction, these time-varying magnetic field fluctuations induce electric fields in the earth which give rise to potential differences (ESPs – earth surface potentials) between grounding points. The distances over which a resulting electric field's effects may be felt can be quite large. The field, then, essentially behaves as an ideal voltage source between rather remote neutral ground connections of transformers in a power system, causing a GIC to flow through these transformers, connected power system lines and neutral ground points.

A power system's susceptibility to geomagnetic storms varies and is dependent upon several contributing elements, including:

- The characteristics of the transformers on the system, which serve as the entry (and exit points) for GIC flow, such as:
    - Transformer winding construction: Any transformer with a grounded-wye connection is susceptible to having quasi-DC current flow through its windings; an autotransformer (whereby the high- and low-voltage windings are common, or shared) permits GIC to pass through the high-voltage power lines, while a delta-wye transformer does not [Figure 1].
    - Transformer core construction: The core design determines the magnetic reluctance of the DC flux path which influences the magnitude of the DC flux shift that will occur in the core. A 3-phase, 3-legged core form transformer, with an order of magnitude higher reluctance to the DC Amp-turns in the 'core-tank' magnetic circuit than other core types, is least vulnerable to GIC. Most problems are associated with single-phase core or shell form units, 3-phase shell form designs or 3-phase, 5-legged core form designs.[3]

- Transformer ground construction: Transformers on extra high voltage (EHV) transmission systems are more vulnerable than others because those systems very solidly grounded creating a low-resistive, desirable path for the flow of GIC. Incidentally, many EHV transformers are not 3-phase, 3-legged core form designs.

The geographical location, specifically the magnetic latitude, of the power system; The closer the power segment is to the earth's magnetic poles generally means the nearer it is to the auroral electrojet currents, and consequently, the greater the effect.[4] Note, however, that the lines of magnetic poles are offset from Earth's spin axis poles. Therefore, the East coast geographic mid-latitude is more vulnerable than the West coast geographic mid-latitude as the former is closer to the magnetic pole.[4]

Earth ground conductivity: Power systems in areas of low conductivity, such as region of igneous rock geology (common in NE and Canada), are the most vulnerable to the effects of intense geomagnetic activity because: (1) any geomagnetic disturbance will cause a larger gradient in the earth surface potential it induces in the ground (for example: 6 V/km or larger versus 1-2 V/km)[5] and (2) the relatively high resistance of igneous rock encourages more current to flow in alternative conductors such as power transmission lines situated above these geological formations (current will utilize any path available to it but favors the least resistive).[5] Earth's conductivity varies by as much as five orders of magnitude.[5] [Reference Figure 2.] Orientation of the power system lines (E-W versus N-S): The orientation of the power lines affects the induced currents. The gradients of earth surface potential are normally, though not always, greater in the east-west direction than in the north-south direction.[6]

The length and connectivity of the power system lines: The longer the transmission lines the greater the vulnerability. Systems dependent upon remote generation sources linked by long transmission lines to deliver energy to load centers are particularly vulnerable. This is characteristic of Hydro Quebec's system in Quebec where much of its power is produced far from where it is consumed; for example, its James Bay generators are 1,000 km away from any populated load center.[7] Since the GMD event that ravished their system in March 1989, Hydro Quebec has installed series capacitors on transmission lines which will block GIC flow. The strength of the geomagnetic storm: A more powerful solar storm increases the intensity of the auroral electroject currents and can move these currents towards the earth's equator.

FIGURE 1
Conducting Path for GICs[8]

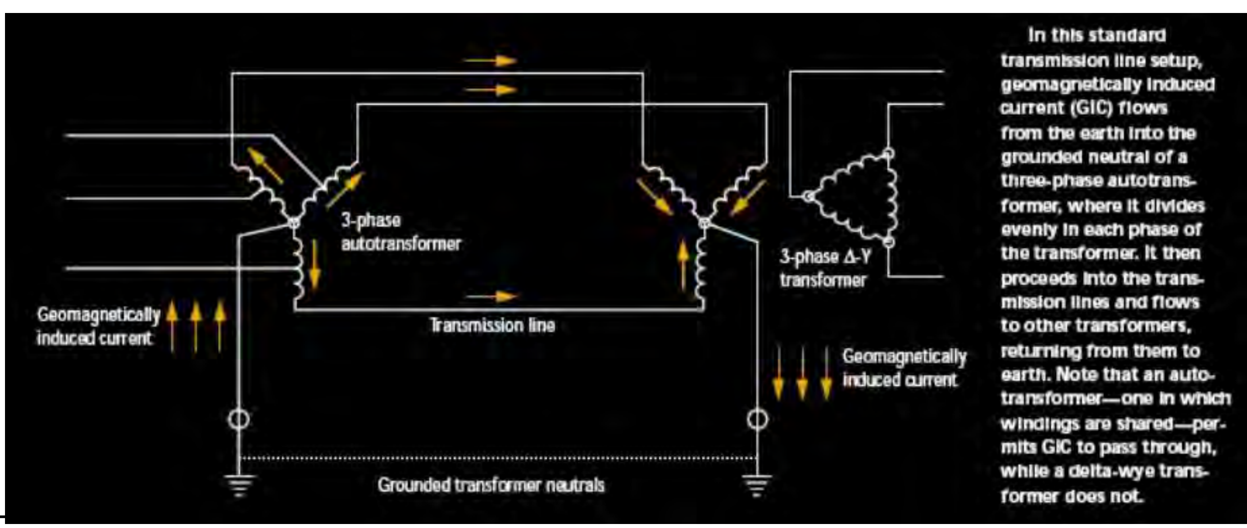
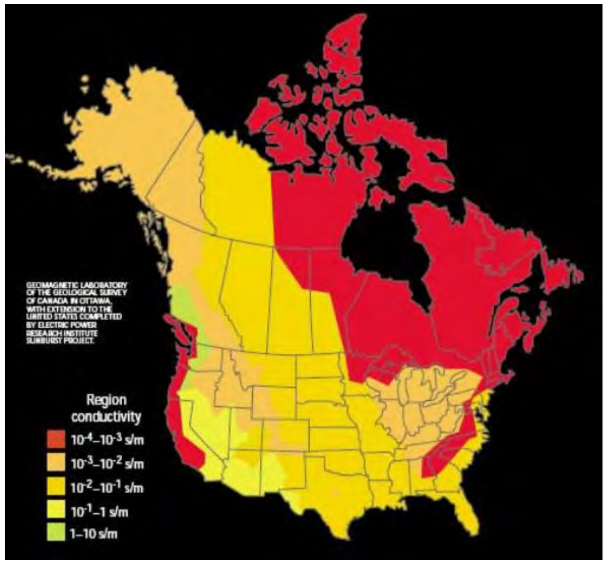


FIGURE 2
Earth Conductivity in US & Canada[8]



The impact of GIC on afflicted transformers and corresponding electric power systems is generally understood but the many variables that influence vulnerability and therefore the inconsistency in the resultant singular manifestations of GIC lends to a near impossible cumulative quantification of a geomagnetic storm's impact on power systems. Most impact quantifications up to now have been anecdotal.

POTENTIAL IMPACT OF GIC ON TRANSFORMERS AND ELECTRIC POWER SYSTEMS
The source of nearly all of the operating and equipment problems attributed to a geomagnetic disturbance is the reaction of susceptible transformers in the presence of GIC. Therefore, the first order effects of GIC are those on the transformer and the second order effects of GIC are those on the power system.

[3] *R. Girgis and K. Vedante, "Effects of GIC on Power Transformers and Power Systems," 2012 IEEE PES Transmission and Distribution Conference and Exposition, Orlando, FL, May 7-10, 2012.*

[4] *James A. Marusek, "Solar Storm Threat Analysis", Impact 2007, Bloomfield, Indiana*

[5] *John G. Kappenman, 'Geomagnetic Disturbances and Impacts upon Power System Operation,' The Electric Power Engineering Handbook, Chapter 4.9, 4-151., 2001.*

[6] *P.R. Barnes, D.T. Rizy, and B.W. McConnell, "Electric Utility Experience with Geomagnetic Disturbances," Oak Ridge National Lab, Nov. 25, 1991.*

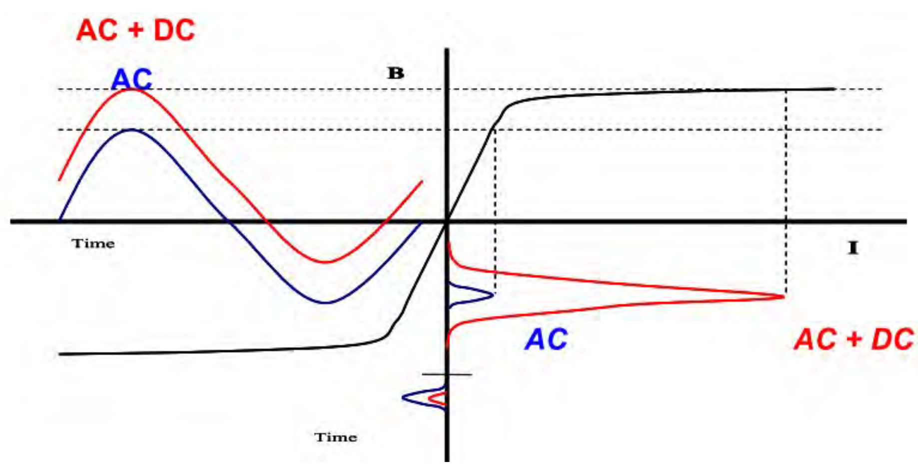
[7] *M. Corey Goldman, "How one power grid kept lights on", Toronto Star, September 8, 2003, http://www.ontariotenants.ca/electricity/articles/2003/ts-03i08.phtml*

[8] *Tom S. Molinski, William E. Feero, and Ben L. Damsky, "Shielding Grids from Solar Storms", IEEE Spectrum, November 2000, pp. 55-60.*

First Order Effects of GIC

The exciting current of a transformer represents the continuous energy required to force "transformer action", in other words, make the transformer behave as a transformer. It is largely a reactive current (usually dominated by an inductive contribution known as the magnetizing current) and typically very small as transformers are very efficient devices, usually less than 1% of the transformer's rated operating current. Under normal, steady state conditions, the exciting current of a transformer is symmetrical (balanced between the positive and negative peaks of its waveform) as shown in Figure 3; the exciting current is shown in blue on the bottom vertical axis.

FIGURE 3
Part Cycle Semi Saturation of Transformer Cores[9]

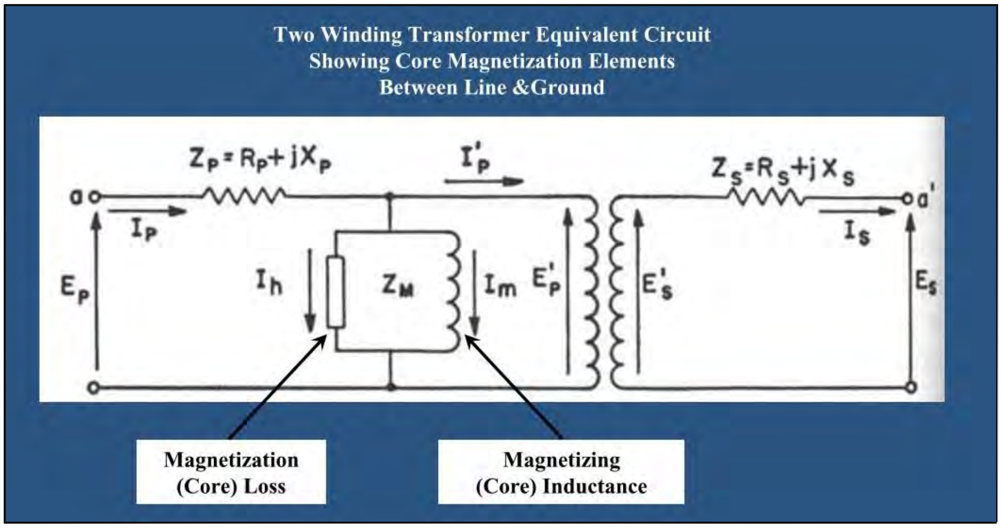


For economic motivations, the peak ac flux in the power transformer (given by the blue waveform on the left side of Figure 3) is designed to be close to the knee (or magnetic saturation point) of the magnetization curve (shown by the black curve in Figure 3) so that nearly the full magnetic capabilities of the transformer's core is used during operation. When a core operates below its saturation point, practically all of the magnetic flux created by the exciting current is contained in the core. The magnetic reluctance of the core is low because the core steel is an excellent conduit for magnetic flux.

Accordingly, the magnetization losses are low (i.e., a small I_h in Figure 4) and the (shunt) magnetizing inductance is high, resulting in a very small magnetizing current, I_m. The exciting current is the vector sum of these current contributions, I_h and I_m. The inductive volt-amperes-reactive (VAR) requirements of the transformer are very low. Moreover, with non-saturated core magnetization, the transformer voltage and current waveforms contain very low harmonic content.

[9] *R. Girgis and K. Vedante, "Effects of GIC on Power Transformers and Power Systems," 2012 IEEE PES Transmission and Distribution Conference and Exposition, Orlando, FL May 7-10, 2012.*

FIGURE 4
Transformer Equivalent Circuit[10]



During a GIC event, a quasi-dc current enters the ground-connected neutral of the transformer and splits equally between phase windings (on multiple phase winding transformers). If the zero sequence reluctance of the transformer is low, the GIC biases the operating point on the magnetization curve to one side (see the top black dashed line in Figure 3). The bias causes the transformer to enter the saturation region in the half cycle in which the ac causes a flux in the same direction as the bias. This effect is known as half-cycle saturation[11]. When the core saturates, it has reach the limit of its ability to carry a magnetic field and any field beyond the limit "leaks" out of the core and passes through the space around the core (air/oil) as "leakage flux". While the magnetic reluctance of the core is still low, the reluctance of the portion of the magnetic circuit outside the core is high. This results in a much-lowered value of shunt inductance and a large shunt current (I_m) flows through the magnetizing branch. The inductive volt-amperes-reactive (VAR) requirements of the transformer can become very high (see the red exciting current pulse given a DC offset on the bottom vertical axis in Figure 3). With saturated core magnetization, the transformer voltage and current waveforms contain very high harmonic content.

Problems can occur with differential protective relays that are looking to see balanced primary and secondary currents, i.e., the transformer may trip as the primary current becomes disproportionately large (drawing increasingly more reactive current) compared to its secondary current.

Leakage flux is always present in a transformer that is carrying load. Because of the problems that it can otherwise cause, transformer manufacturers design and build their transformers such that the anticipated leakage flux is "managed" and has minimal impact on the long-term operation and survivability of the transformer. Leakage flux, however, is never anticipated from the excitation of the transformer. The high peak magnetizing current pulse (red in Figure 3) produces correspondingly higher magnitudes of leakage flux (as given by the red waveform on the left side of Figure3) that is also rich in harmonics.[12]

[10] *W. Hagman, "Space Weather in Solar Cycle 24: Is the Power Grid at Risk?", IEEE PES Boston Chapter & IEEE Comp Society Boston Chapter Joint Lecture, April 16, 2013.*
[11] *W. Chandrasena, P.G. McLaren, U.D. Annakkage, R.P. Jayasinghe, "Modeling GIC Effects on Power Systems: The Need to Model Magnetic Status of Transformers", 2003 IEEE Bologna Power Tech Conference, June 23-26, 2003, Bologna, Italy.*

The influence of excessive leakage flux on the transformer is generally thermal. Leakage flux in transformers that links any conductive material (including transformer windings and structural parts) will cause induced currents, which will result in almost immediate localized, unexpected, and serve heating due to resistive losses. Paint burning off transformer tank walls might be considered an asset owner's best news case example. Transformer designs that implement core bolts are a concern because should the stray flux link such bolts located at the bottom of the windings and cause the surrounding oil to heat to 140°C, this could result in bubble evolution that ultimately fails the transformer. For any given design, a finite element analysis will reveal the leakage flux paths and weaknesses, if any, in the design. If a transformer is lightly loaded, and therefore its operating leakage flux is light as compared to its full load rated flux, the unit may be able to handle the additional leakage flux introduced by GIC.

In summary, a saturated transformer becomes a reactive energy sink, an unexpected inductive load on the system, and behaves more like a shunt reactor.[13] Transformer differential protective relays may trip and remove the transformer from service. Excessive leakage flux can result in detrimental overheating, or in some designs, winding damage due to resulting high winding circulating currents. Separately, the magnetizing current pulse of a GIC inflicted transformer injects significant harmonics into the power system. The resultant impact of these changes in the transformer(s) constitutes the second order effects of GIC.

Second Order Effects of GIC

Many agree that the more concerning impacts of GIC are its indirect effects on the power system and its components. The influence of a transformer morphing into a shunt reactor on the power system is best understood after a review of shunt reactors and capacitors.

Shunt capacitor banks are used to offset inductive effects on the power systems (to support voltage) while shunt reactors are used to offset the effects of capacitance on the system (to lower voltage). Typically shunt capacitors are switched in during periods of high load and shunt reactors are switched in during periods of light load. The same effects can be achieved, within rating limits, by varying the excitation of generators, i.e., operating them as "synchronous condensers." Statics VAR compensators (SVC's), which combine capacitor banks and reactors also provide similar compensation and voltage support, with very fast automated controls. Many power systems had dedicated synchronous condensers (rotating machines). However, capacitor banks are cheaper and capacitor technology advanced to the point where reliability became excellent, so synchronous condensers were retired.[14]

Inductive reactance, which is expressed by, $X_L = 2fL$, indicates that as inductance, L, goes down, inductive reactance drops. Saturated transformers have low shunt magnetizing inductance so they draw high currents; they look like shunt reactors on the system, dragging down the system voltage. Capacitive reactance is expressed by, $X_C = 1/(2fC)$. From this, it is easy to see that a capacitor presents as an open circuit (infinite impedance) to DC current; thus the effectiveness of series capacitor blocking in very long transmission lines as a GIC mitigation strategy. Alternatively, as frequency goes up, capacitive reactance drops so capacitor banks have lower impedances to harmonics and draw larger currents when harmonics are present.

[12] *R. Girgis and K. Vedante, "Effects of GIC on Power Transformers and Power Systems," 2012 IEEE PES Transmission and Distribution Conference and Exposition, Orlando, FL, May 7-10, 2012.*

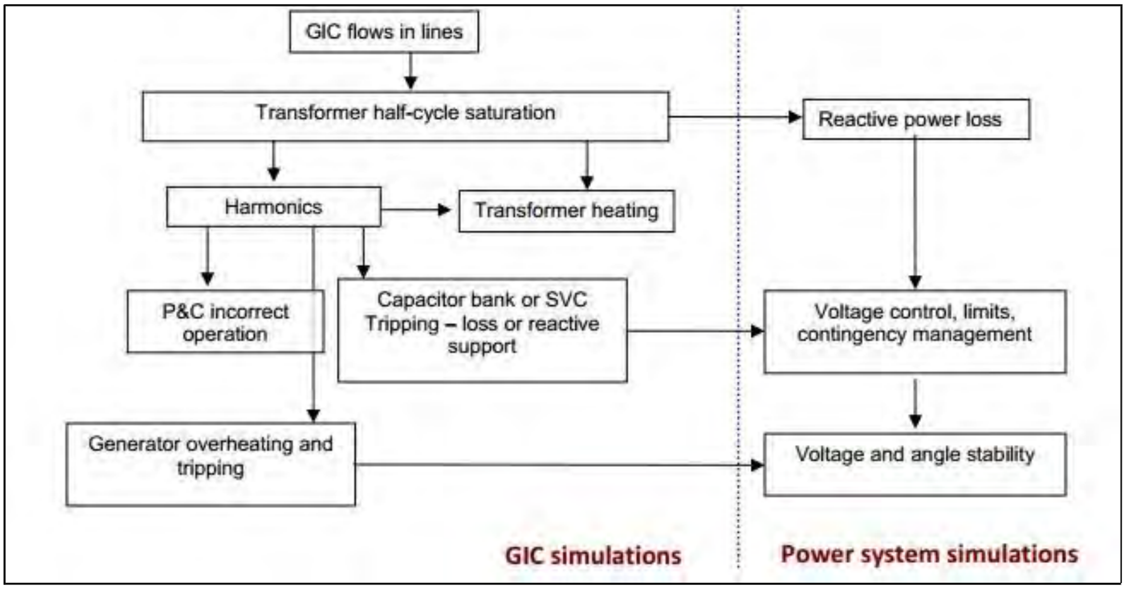
While saturated transformers draw large currents, forcing system voltage down (and potentially overloading long transmission lines), capacitor banks also draw large currents due to the presence of resultant harmonics, partially offsetting the inductive effects. Essentially, the saturated transformers are in a tug-of-war with the capacitors on the system. Modern shunt capacitors have very low loss and are therefore less susceptible to transient heating damage due to excess current. However, large currents may affect other components in capacitor bank installations, resulting in damage and unwanted tripping.[15] Voltage imbalance and overvoltage protection may also be "fooled" by harmonic voltage spikes and cause unwanted trips. Finally, overcurrent protection may also operate spuriously in the face of harmonic currents.[16] Similar issues may apply to SVC's. Harmonic filters for SVC's banks create parallel resonances, which can exacerbate voltage disturbance issues and result in tripping of the protection devices.[13]

Rotating machines have fairly high thermal inertias, so generators operated as synchronous condensers have a higher probability of staying on line.[13] However, generators can also be affected by GIC currents. These effects include additional heating, damage to rotor components, increased mechanical vibrations and torsional stress due to oscillating rotor flux caused by increased negative sequence harmonic currents. The harmonic content of negative sequence currents can also cause relay alarming, erratic behavior or generator tripping.[17] If VAR resources are exhausted during a GMD event, specifically capacitive voltage support, voltage collapse can occur.

NERC's 2012 Special Reliability Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System provides a block diagram that illustrates the effects of GIC, culminating in a threat to system voltage and angle stability (Figure 5).

[13]It should be noted that upon removal of the DC current, a core will not remain in its saturated state while energized.
[14]W. Hagman, "Space Weather in Solar Cycle 24: Is the Power Grid at Risk?", IEEE PES Boston Chapter & IEEE Com Society Boston Chapter Joint Lecture, April 16, 2013.
[15]W. Hagman, "Space Weather in Solar Cycle 24: Is the Power Grid at Risk?", IEEE PES Boston Chapter & IEEE Com Society Boston Chapter Joint Lecture, April 16, 2013.
[16]B. Bozoki et al., Working Group K-11 of the Substation Protection Subcommittee of the Power System Relaying Committee, IEEE PES, "The Effects of GIC on Protective Relaying," IEEE Transaction on PowerDelivery, Vol. 11, No. 2, April 1996, pp. 725-739.
[17]D. Wojtczak and M. Marz, "Geomagnetic Disturbances and the Transmission Grid"
http://www.cce.umn.edu/documents/cpe-conferences/mipsyconpapers/2013/geomagneticdisturbancesandthetransmissiongrid.pdf

FIGURE 5
From NERC: Effects of GIC in a High Voltage Transmission Network[18]



<u>A Special Dispensation About the Effects of GIC on CTs (and protective relays)</u>

It is important to have accurate measurements of system state during abnormal operating conditions. For these purposes, the industry has predominantly relied upon conventional instrument transformers (such as a current transformer ("CT"); a potential (or voltage) transformer, which may be inductive ("PT"/"VT") or capacitive ("CCVT"); or a combined current and voltage instrument transformer). An instrument transformer ("IT") is "intended to reproduce in its secondary circuit, in a definite and known proportion, the current or voltage of its primary circuit with the phase relations and waveforms substantially preserved."[19] The electromagnetically induced current or voltage waveform(s) in the secondary circuit(s) of the instrument transformer (IT) should then be of an easily measurable value for the metering or protective devices that are connected as the load, or "burden", on the IT.

In as much a traditional, "ferromagnetic" IT has a magnetic core; instrument transformers are subject to influence from the presence of GIC much like a power transformer (discussed in the preceding sections). If an IT is pushed to a non-linear region of its saturation curve (i.e., its operating curve), due, for example, to a DC flux shift, the accuracy of the IT will significantly decline. While it is true that it's typically operate at lower magnetization levels than power transformers because reading accuracy must be maintained in the face of large fault currents (i.e., they have more "built-in margin" on the curve), there is no way of knowing whether the magnitude of GIC in the system is yet enough to saturate the core (despite its margins), or if remanence was pre-existing in the core and already compromising the IT's performance.

[18] *North American Electric Reliability Corporation (NERC) Geomagnetic Disturbance Task Force (GMDTF) Interim Report, "Effects of Geomagnetic Disturbances on the Bulk Power System," February 2012, page 62. http://www.nerc.com/files/2012GMD.pdf*

[19] *"C37.110-2007 IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes", IEEE, New York, NY April 7, 2008.*

In short, there will always be uncertainty about the reliability of system state measurements provided by ferromagnetic instrument transformers during a GIC event. Moreover, when currents and voltages become rich in harmonics, even if the IT is not operating in a saturated state, the accuracy of the measurements will decline. Unfortunately, there is no on-line method of validating whether the instrument transformer is operating in a non-saturated state and, therefore, within its "window of accuracy" (i.e., the pseudo-linear region of its saturation curve at 60Hz) or in a saturated state and, therefore, outside the realm in which it can accurately reproduce measurements.
Reference 20 provides more details about the variables that impact the performance of conventional instrument transformers.[20]

It is lastly noted that protective relays operate based only on their inputs. If a CT, for example, is supplying a distorted waveform due to the effects of harmonic saturation, the relay may respond in a different, and unwanted, way than it does to nearly sinusoidal inputs.[21]

<u>FERC/NERC Regulation</u>
Federal regulations designed to protect the nation's electric grid from the potentially server and widespread impact of a geomagnetic disturbance (GMD) are in the process of being adopted. Following several years of study, the Federal Energy Regulatory Commission (FERC) initiated a rulemaking in 2012, the first of its kind directing NERC to develop and submit for approval Reliability Standards to protect the grid from the impact of GMDs.

In Order No. 779, FERC determined that the rise posed by GMD events, and the absence of Reliability Standards to address GMD events, posed a risk to system reliability that justified its precedent-setting order directive to NERC to develop Reliability Standards to address the issue. In order to expedite the standards-setting process, FERC ordered NERC to develop mandatory standards in two stages, both of which are now underway.

In the first stage, FERC directed NERC to submit Reliability Standards that required owners and operators of the bulk-power system to develop and implement operational procedures to mitigate the effects of GMDs to ensure grid reliability. These operational procedures were considered a "first step" to address the reliability gap and were approved by FERC in June 2014. These standards become mandatory on January 1, 2015.

In the second stage, FERC has directed NERC to provide more comprehensive protection by requiring entities to perform vulnerability assessments and develop appropriate mitigation strategies to protect their facilities against GMD events. These strategies include blocking GICs from entering the grid, instituting specification requirements for new equipment, and isolating equipment that is not cost effective to retrofit. In subsequent orders, FERC has reiterated its expectation that the second stage GMD standard include measures that address the collection, dissemination, and use of GIC data, by NERC, industry, or others, which may be used to develop or improve GMD mitigation methods or to validate GMD models.

[20]*J. Duplessis and J. Barker, "Intelligent Measurement for Grid Management and Control", PACWorld Americas Conference, Raleigh, NC, September 2013.*
[21]*W. Hagman, "Space Weather in Solar Cycle 24: Is the Power Grid at Risk?", IEEE PES Boston Chapter & IEEE Com Society Boston Chapter Joint Lecture, April 16, 2013.*

Thus, FERC's forthcoming standard is likely to require or strongly encourage the installation of GIC monitoring equipment as a means of assessing vulnerability and as the data source by which GIC blocking or other protection schemes are to be implemented. The second stage standards including equipment-based GMD mitigation strategies are due to be filed by NERC in January 2015 and are likely to be approved by FERC in mid-2015.

Intensity Modulated Optical Sensing Technology

Intensity modulated optical sensing technology provides the full system visibility; accuracy and stability required to effectively mitigate GIC effects. This cannot be done with the grid's present information infrastructure comprised primarily of ferromagnetic type instrument transformers.

The fundamental solution to accurate information is to find a physical solution that can observe the system without being electrically coupled to the system, or measurand. This concept precludes any of the IT products either currently available or under development. Instead, it requires a completely new approach to measurement.

Starting in the late 90's, the electric power industry began to experiment with optical techniques that used interferometric wave and phase modulation as the physical underpinnings of an electrically decoupled measurement system. Unfortunately, this equipment has generally failed in field applications due to its extreme sensitivity to temperature and EMI.

To solve this problem, a new approach based on recently declassified military applications has now been adapted to the needs of the electric power grid – thus achieving the objective of a highly accurate and reliable measurement device that is electrically coupled to the measurand.

How the technology works:

The U.S. Naval Research Lab (NRL) has been a leader in optical sensing research for over 50 years. Similar to the power industry's experience with interferometric sensors[22], the Navy found that the acute temperature and EMI sensitivity of these devices caused them to fail in mission critical, field applications. To solve these problems, the NRL ultimately developed a highly stable, intensity modulated optical sensor that has no temperature sensitivity, no susceptibility to EMI, no frequency modulation, and has been proven to operate accurately in very harsh conditions for long periods of time. This technology, vetted over decades, has now been adapted to measure voltage, current, phase and other characteristics of electric phenomena, and can deliver accurate, stable and reliable performance in rigorous field applications on the power system.

An intensity modulated optical monitoring system consists of a transducer that is located within the force field it is measuring, a light source located some distance away, a fiber optic transmitted cable, at least on fiber collector or return cable, and power electronics.

A sensing element is held securely within the transducer; this is a material that is deliberately selected based upon the measuring application and which responds to changes in the force to which it is subjected.

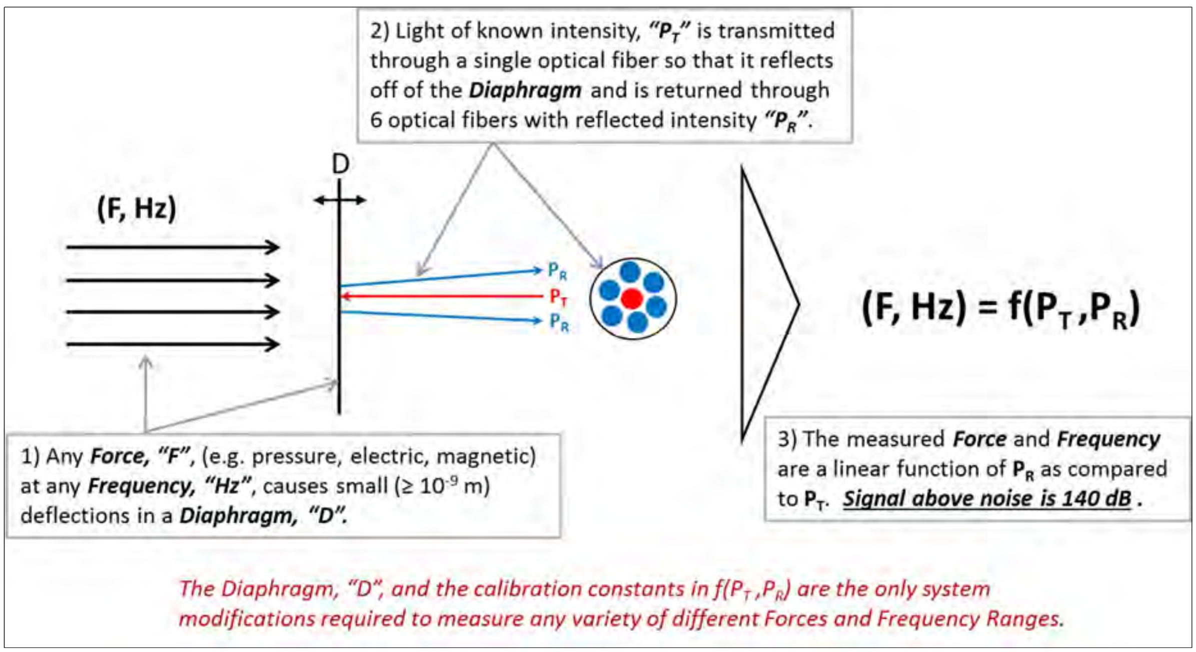
[22] *As Gauged by General Polled Feedback*

This force is characterized by a magnitude and frequency. In the case of acoustic measurements, and as shown in Figure 6, this material is a diaphragm. Physical displacement of the sensor is being directly measured but this movement is ultimately a function of the force (i.e., the measurand) acting upon it.

Light of a known intensity (P_T) from a light-emitting diode (LED) is coupled into an optical fiber for transmission to the sensing element where it is modulated in accordance with the state of the measurand.

Reflected light of a varying intensity (PR) is collected by at least one return fiber for transmission back to a photo-detector.

FIGURE 6
Intensity Modulated Optical Sensing – Fundamental Concept



The intensity of the light returned through the fiber correlates to the force exerted on the sensing element and the frequency with which it is changing. As an example, consider an acoustical measurement. As sound changes, the diaphragm moves and the resultant distance between the fiber probe and the diaphragm changes. Note that the fiber probe is stationary. It is the movement of the sensing element that alters the distance between the probe and the sensor. If the distance becomes smaller by way of displacement of the diaphragm towards the fiber probe, the reflectance changes and the intensity of the reflected light captured by the return fibers decreases (Figure 7). As the distance increases, more reflected light is captured by the return fibers, and consequently, P_R increases (Figure 8).

One transmits fiber and only one return fiber is depicted in Figure 7 and 8. The use of multiple return fibers amplifies the sensitivity of this intensity-modulated technology, resulting in the ability to detect displacement changes of the sensing element on the order of 10^{-9} meters.

FIGURE 7[23]
P_R Decreases as Displacement Between Probe and Diaphragm Decreases

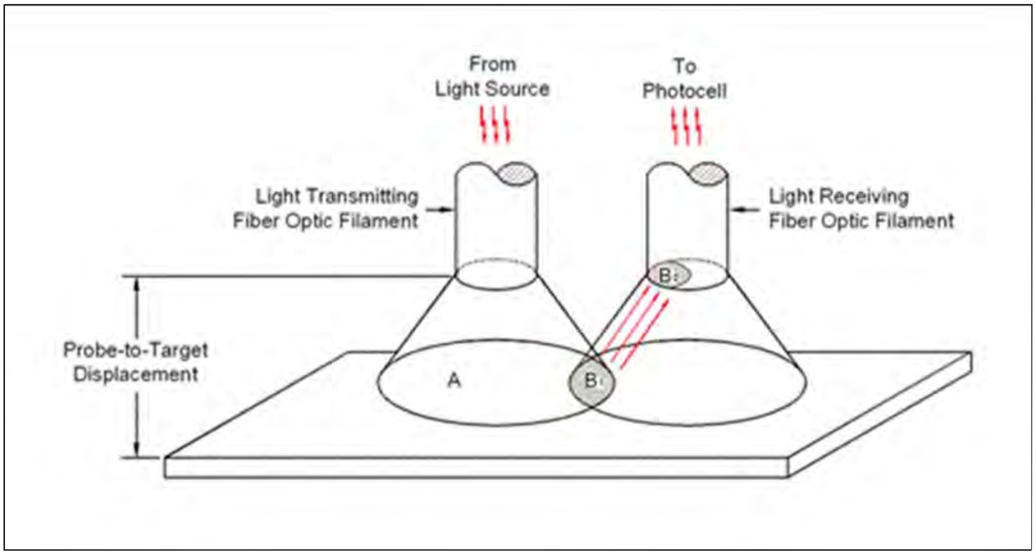
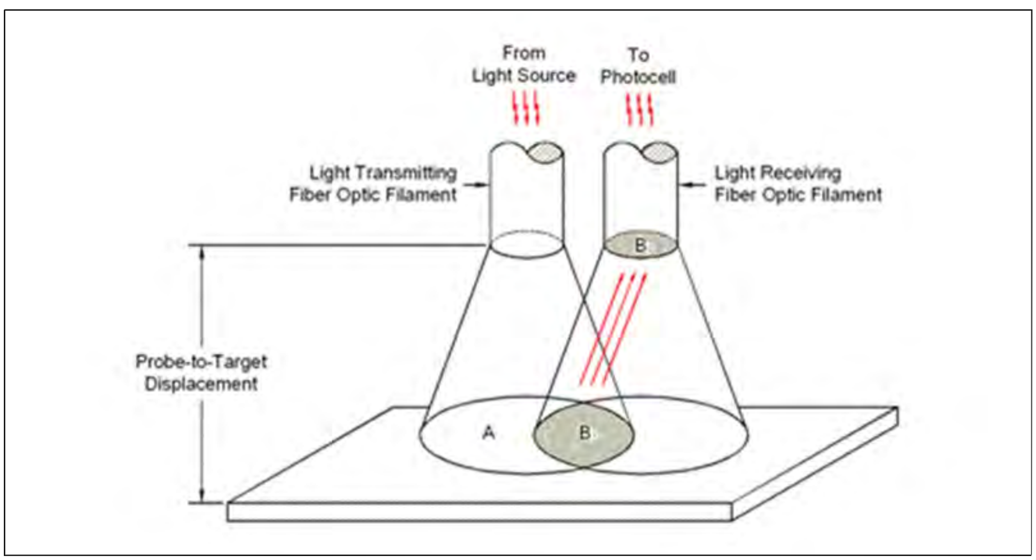


FIGURE 8[24]
P_R Increases as Displacement Between Probe and Membrane Increases



[23] *Yury Pyekh, "Dynamic Terrain Following: NVCPD Scanning Technique Improvement", Fig. 3.7, Thesis Presented to the Academic Faculty of Georgia Institute of Technology, August 2010.*
[24] *Yury Pyekh, "Dynamic Terrain Following: NVCPD Scanning Technique Improvement", Fig. 3.8, Thesis Presented to the Academic Faculty of Georgia Institute of Technology, August 2010.*

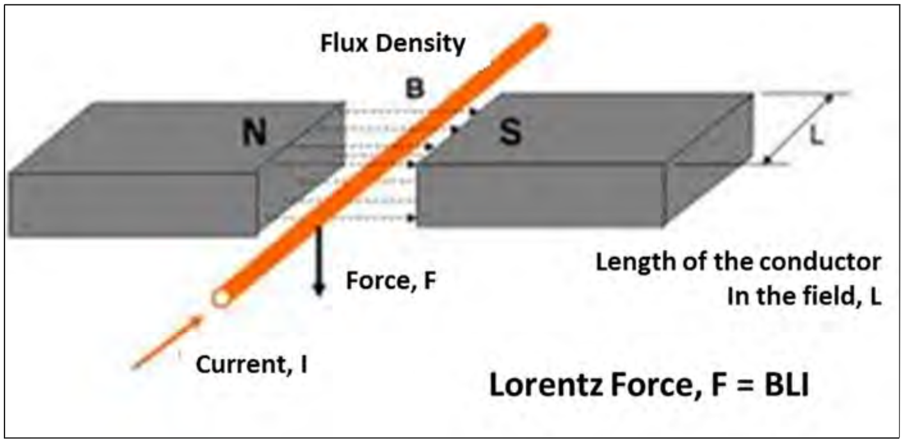
ADAPTATION

Adapting Intensity Modulated Optical Sensors to Measure Electrical Phenomena:

Laws of physics are used to adapt the intensity modulated (IM) optical sensors to measure current and voltage. For example, principles of Lorentz's Force are applied to build the IM optical (AC) current sensor.

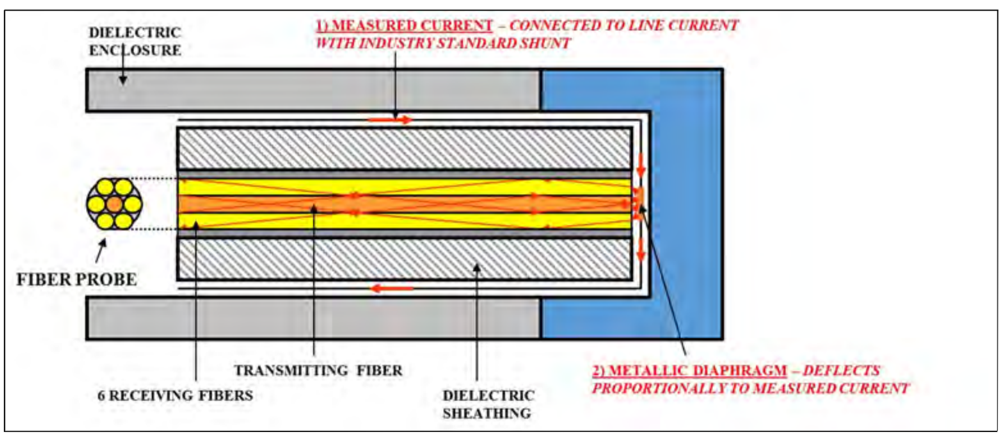
A Lorentz Force, given by F = BLI and illustrated in Figure 9,will result when a current (I) carrying conductor passes through a non-varying magnetic field with flux density, B for some length, L.

FIGURE 9
Lorentz Law



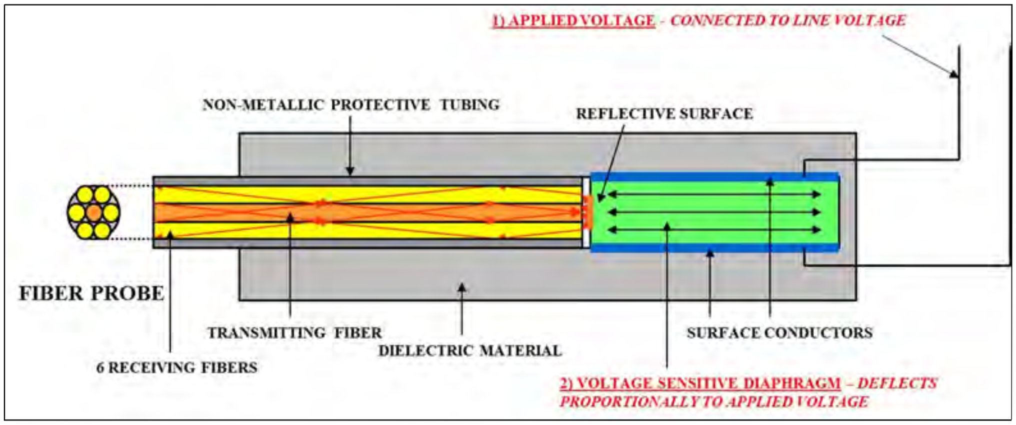
Accordingly, the current sensing element (Figure 10) connects to the line conductor; as current changes, variations in the Lorentz Force will result in the physical displacement of the sensing element. The intensity of light reflected back will therefore alter proportionally to the changes in the current.

FIGURE 10
Intensity Modulated Fiber Optic Current Sensor



For voltage measurements, the selection of the sensing element is key. Here, a piezoelectric material is selected that has very stable physical characteristics that vary in a known way as the electric field in which the material is placed varies. A reflected surface affixed to the end of the sensing element will physically displace, therefore, as the material deflects relative to changes in the electric field.

FIGURE 11
Intensity Modulated Fiber Optic Voltage Sensor



The IM optical current and voltage sensors are housed in a common transducer. The physical dimensions of these sensors are very small; the length of a sensor, its maximum dimension, is typically shorter than a few inches. This makes it possible to hold several sensors within one transducer, including IM optical temperature sensors.

IM optical sensing technology is adapted differently to measure DC current and voltage but is no discussed in this paper.

ADVANTAGES

Accurate, Repeatable Measurement Over an Extremely Wide Range of Values and Frequencies

The fact that Intensity Modulated (IM) optical sensing is passive, non-ferromagnetic and non-interferometry based in central to why this technology delivers a step-change improvement in performance over both conventional instrument transformers and interferometry-based optical equipment.

First, because of its passivity, an IM optical transducer does not disturb the (power) system it observes. The sensing element is non-conductive and the transducer is electrically decoupled from the grid; light is the 'exchange medium' of the transducer and an electrical system is not altered by light. The transducer therefore 'sees' exactly what exists on the power system and this creates notably higher accuracy than what can be achieved by even the most accurate of metering class instrument transformers.

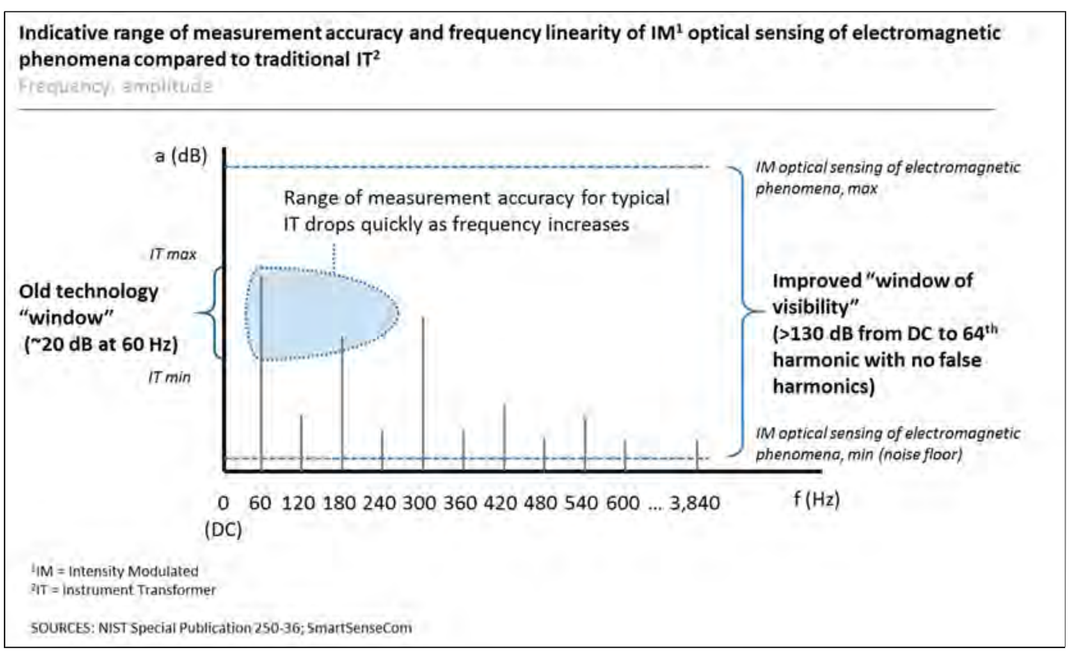
Second, because IM optical sensing is electrically de-coupled and is not ferromagnetic, traditional burdens have no influence on the transducer and the power system cannot negatively impact is measuring capability. IM optical sensors have no saturation curve; their equivalent operating "curve", and therefore performance, is perfectly linear throughout their wide measurement range. By removing variables introduced by system and burden influencers, which have plagued the performance of conventional IT's in unpredictable ways for decades, the industry gains automatic assurances that the IM optical transducer is maintaining the accuracy it should at all times. This creates consistent accuracy and therefore, repeatability.

A third advantage of IM optical sensors' non-ferromagnetic based operation is that frequency has no influence on its measuring capabilities. While varying the frequency does alter the shape of a saturation curve that defines the operating characteristics of a conventional IT, it has no effect on the linear operating curve of an IM optical sensor. IM sensors can measure voltage and current at frequencies from quasi-DC to several thousand Hertz. There are no concerns about resonant frequencies associated with inductive and capacitive voltage transformers. This measuring technology therefore affords the power industry the opportunity to view a broad range of non-fundamental frequency components with the same accuracy as measurements at the fundamental frequency (50/60 Hz) and therefore, to perform incredibly insightful power quality studies.

While the pseudo-linear range of a conventional IT's saturation curve is not large, affording only an approximate 20 dB dynamic range, the linear range of operation of an IM optical sensor delivers an approximate >130 dB dynamic range. This means that a single IM optical current sensor, for example, can measure an extremely large fault current, and at once, an exceptionally small harmonic current with identical accuracy. An IM system's measuring range is only limited by its noise floor, which is much lower than any other conventional or non-conventional field measurement device that is currently available.

Figure 12 gives a visual representation of the range of (current/voltage) magnitudes over which a conventional IT will yield accurate measurements (the vertical height of the blue shaded area at (60 Hz) and the limiting influence of frequency on a conventional IT's accurate measuring capabilities (as given by the diminishing height of the blue-shaded area as the frequency decreases/increases). In contrast, the much broader, frequency independent, and notably more accurate measuring capabilities of an IM monitoring system are indicated by the encompassing white backdrop that frames the graph in Figure 12.

FIGURE 12
Accuracy/Linearity as a Function of Frequency
(For an IM Optical Monitoring System vs. a Conventional IT)



SAFETY AND RISK REDUCTION

A separate, but equally important, advantage of passive IM optical sensors is safety and risk reduction in the unlikely event of the IM optical system's failure. With a conventional IT, the electrical grid extends all the way to the meter or protective device and the possibility exists for workers to be injured or even killed if they were to inadvertently come into contact with an open-circuited CT secondary. In contract, the equivalent "secondary" side of an IM optical transducer is fiber optic cable carrying light. It presents no safety hazard. Moreover, should a conventional IT fail, it typically brings the circuit down with it, either due to catastrophic fire or a fault that trips the breaker. In comparison, the IM has no influence on the power system it is observing, and if it should fail, the power system would typically continue to operate as usual.

An additional benefit of being non-ferromagnetic is the periodic field-testing to verify operating characteristics and insulation integrity is not necessary for an IM optical transducer. In fact, because an IM optical transducer is electrically decoupled from the grid, there is no requirement for the use of dielectric materials such as oil or SF6 in the device. The combination of these factors reduces O&M costs and expedites safe system restoration after outages.

"IM" OPTICAL SENSING AS A COMPREHENSIVE SOLUTION TO IDENTIFITYING AND MEASURING IMPACTS OF GIC

The concerns about GIC are justified and the effects of GIC well documented. The path forward becomes clear after reflection upon just a few of the industry comments about GIC:

- "Accurate estimation of the VAR consumption of the transformer during a GMD event is critical for proper mitigation of effects of GIC on power system stability."
- "Increase in VAR demand is one of the major concerns during a GMD event. The loss of reactive power could lead to system voltage collapse if it is not identified and managed properly."
- "The magnetizing current pulse injects significant harmonics into the power system which can have a significant impact on shunt capacitor banks, SVCs and relays and could compromise the stability of the grid."

The GIC mitigation solution lies in the ability to quantify its effects in real time. The industry has not been able to do that up to now with the measuring devices available. IM optical monitoring systems change this.

An AC current and voltage IM optical transducer must be installed on the high-voltage side of a susceptible transformer. This will measure the VAR consumption of the transformer as well as any harmonics generated given the operating state of the transformer, well in the kHz range. A DC change IM optical transducer would be installed on the grounded neutral connection of the transformer. IM optical technology provides for accuracies of approximately one percent at low magnitude DC currents, 1-25A, allowing exacting correlation between DC currents and concurrently observed effects on the transformer (reactive energy consumption and harmonic profile).

Because of the many variables that contribute to the vulnerability of the transformer and connected power system, even given the same GIC magnitude, the transformer/system response is expected to be different. For this reason, it is not enough to install a simple DC current monitor, such as a Hall Effect Sensor, on the neutral ground connection of a transformer. Even if one were to look past the instability of such devices, particularly at low DC current levels (<25), a DC measurement alone does not afford reliable predictability about the associated power system impact.

CONCLUSION

The negative impacts of geomagnetically induced currents (“GIC”) are understood at a high level. GIC flow negatively impacts certain power transformers causing half-cycle saturation that leads to increase demand for reactive power, generation of harmonics, and transformer heating. This in turn negatively impacts electric power transmission systems; at its worse, causing grid instability due to voltage collapse, mis-operation of protection equipment (e.g., capacitor banks, overcurrent relays), damage to sensitive loads due to poor power quality, and/or thermal damage to the transformer. However, better system visibility is required to develop effective GIC mitigation strategies. For example, what is the actual change in reactive power and the harmonic generation profile at a specific location when GIC is present? How will the surrounding transmission system actually respond to these changes?

It is important to have accurate measurements of system state during abnormal operating conditions. Unfortunately, traditional ferromagnetic-type instrument transformers are at risk of being affected by GIC conditions too. There is no way of validating, in real time and while energized, whether an instrument transformer is saturated or not, so it is possible that information provided to protective devices may be riddled with error on the magnitude of over 12 percent. Moreover, classical instrument transformers do not have the ability to reproduce harmonics with any guaranteed accuracy (even when demagnetized) much beyond the 3rd harmonic.

The GMD/GIC phenomenon is a prime example where the industry’s inability to sufficiently measure will leave it struggling to manage unless we embrace change. A solution to gain full (and stable!) system visibility was introduced. It is an optical solution called Intensity Modulated (IM) optical measuring; it resolves the grid’s present-day measuring inadequacies and is different than earlier optical techniques, which while promising, have proven to be unstable under field conditions due to extreme temperature instability and electromagnetic interference. An IM optical system was described along with some example adaptations for its use in measuring electrical phenomena. Advantages of IM optical transducers, rooted in their passivity and non-ferromagnetic characteristics, were enumerated. These include a step-change improvement in accuracy; hardening to otherwise influencing ‘environmental’ variables resulting in stability and consistency in measurements, and therefore, repeatability; the ability to observe the power system more comprehensively than ever before through one transducer; and significant enhancement in personnel and system safety.

The GIC mitigation solution lies in the ability to quantify its effects in real time. This can be accomplished through intensity modulated optical monitoring systems.