Methods to detect transformer saturation due to Geomagnetic Induced currents (GIC)

Nuwan Perera and René Midence
ERLPhase Power Technologies

ABSTRACT

The GMD (Geo Magnetic Disturbance) activity, which causes GIC (Geomagnetic Induced Current) and its impact, has been seriously looked into in many geographical areas across the globe. Specifically, the North American continent has more probability of impact with GIC as per the calculations and as well as the events that have happened in the past. It is clear that the GIC phenomenon causes widespread effects throughout the electrical grid. The electric field gradient and the induced current can flow over wide areas of power systems. This includes the entire possible closed electric circuit path between grounded points. This technical paper provides general information on GIC in power systems and describes the causes and sources of GIC and touch on the consequences on power transformers. In addition, it provides information on how to apply a power system monitoring device to monitor for the negative effect of GIC on power transformers.

INTRODUCTION

Geo Magnetic Disturbance (GMD) activity, which causes Geomagnetic Induced Current (GIC), has been seriously studied in many geographical areas across the globe. Specifically, North America probably has greater impacts from GIC, according to calculations and judging by past events [1]. To monitor and mitigate GMD effects, the North American Electric Reliability Corporation (NERC), the commission-certified electric reliability organization, submitted a reliability standard in response to FERC Order No. 779 [2]. This reliability standard is designed to mitigate the effects of geomagnetic disturbances (GMD) on the bulk power system by requiring responsible entities to implement operating plans, procedures and processes.

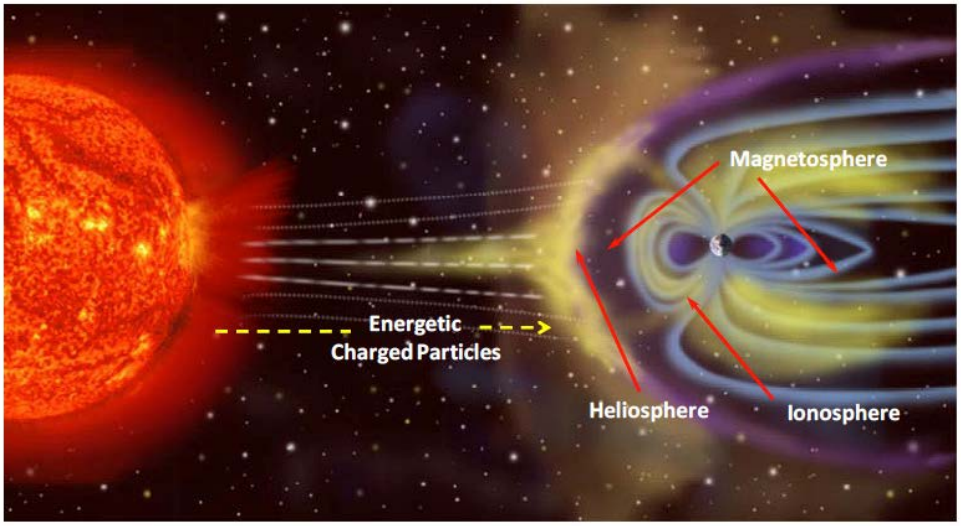

Figure 1: Solar storm activity [1]

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On March 10, 1989, a strong wind left the sun, heading for Earth. On March 12, the first voltage fluctuations were being seen on the Hydro Québec transmission grid [3]. The system control center was doing what it could to maintain stability. However, on March 13 at 2:44 a.m., the Earth's magnetic field was fluctuating violently. The grid's protection system was triggered, and a blackout occurred in less than a minute! The province was submerged in darkness for more than nine hours. Later, Hydro Québec reviewed the protection and control procedures to adapt to GIC impacts.

In 2006, notable GIC activity was reported in China [4]. These types of electric field gradients and their induced currents can flow over wide areas, sometimes including the entire possible closed electric circuit path between grounded points in a power system. Many simulation techniques and tools are available for power system planners to estimate GIC impact on power systems. Due to the complex nature of the GIC phenomenon, it is important to validate these simulation models from time-to- time with the help of real time measurement of the GIC. Specifically, the impact of GIC on power transformers is paramount.

SYSTEM IMPACT OF GIC EVENTS

This section describes the impact of GIC on various components in the power system including power transformers.

Power Transformers (neutral grounded)

When GIC flows through the ground into a closed circuit path, the most affected power system component is the grounded station power transformers (due to the very nature of the non-linear magnetic circuit, as well as its design, construction, type and saturation characteristics). GIC impact on transformers is discussed in more detail later in this paper.

Generators

Generators are not directly affected by GIC, but due to the transformers' saturation effect, harmonics (odd and even) will be generated from the transformers, and nearby generators connected through the GSUs (generator step-up transformers) are affected by the negative sequence current overheating. Harmonic currents also affect the rotor of the generator [5]. Even though the GIC's frequency of oscillation is between 0.001 to 0.1 Hz, one must also consider interaction from the mechanical natural modes of the turbine and generator rotor systems.

Current Transformers (CTs) and Potential Transformers (PTs)

A CT's time-to-saturate is, by design, higher than that of a power transformer since it has more "iron" available to deal with the DC offsets during fault conditions. Therefore, solar storms with lesser GIC may not impact power transformers more than CTs. On the other hand, during fault, when a CT is driven to near saturation, moderate GIC current is enough to drive the CTs to saturate quicker and hence the secondary current is not reproduced faithfully.

Protection will be impacted, but most modern microprocessor-based relays effectively deal with the CT saturation. Another important parameter to watch is the burden on the secondary, which also plays an important role in CT saturation. Wound PTs usually respond to GIC like power transformers do, and their time-tosaturate depends on the PT's design and construction. However, at the transmission level, voltage measurement is generally done through CCVTs (Capacitive Coupled Voltage Transformers), therefore relatively unaffected by the GIC flow. Side effects from harmonics and overheating due to nearby transformers are a concern.

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Shunt Capacitors

Capacitors themselves are not impacted directly by the GIC quasi DC current, but distorted voltages due to nearby transformer saturation can adversely affect capacitor bank protection. For example, an incident in the Hydro Québec system resulted in over voltage relays operating due to distorted voltage [3].

Series Capacitors

In fact, series capacitors block GIC and are considered GMD reduction devices. Series capacitors have several advantages, but their interaction with distributed resources on the grid can cause sub harmonics and require attention. Also, installing new series capacitors (even with less capacity) into existing networks is not economically justified solely on the basis of blocking GIC.

Shunt Reactors

Shunt reactors with iron cores and grounded neutrals saturate like power transformers unless utilities use specially designed shunt reactors to withstand DC. Air-core shunt reactors are not directly affected by GIC, although harmonics may cause extra heating from nearby transformer current distortion.

Static Var Compensators (SVCs)

GIC caused many misoperations of the SVCs during the 1989 Hydro-Quebec blackout [3]. The Hydro Québec study also showed SVC resonance at 120 Hz, which further caused operation of the SVCs protection. Depending on SVC design, if the reference control signal uses true RMS voltage values, performance can be affected during GIC. The impact will be severe if the nearby transformer is highly saturated and is consuming more reactive power.

HVDC Systems

The continuous adjustment of firing angle control on both the rectifier and invertor will take care of GIC effect. Therefore at moderate GIC levels, little or no effect is felt (terminal voltage at both ends may vary by a small percentage). Convertor transformers are affected by GIC. Overloading of filter banks due to harmonics is a concern, and commutation failures may happen in line-commutated convertors.

Communication Systems

PLC (Power Line Carriers), Ethernet switches, telecommunication systems and, to an extent, the fiber-optic networks are all impacted directly or indirectly by GIC.

Impact on Power Transformers

Power transformers are the most affected component in a power system [6,7,8,9,10,11,12]. Power transformers with grounded neutrals are impacted by GIC as follows:

Half cycle saturation due to GIC offset

The following illustration depicts the effect of half-cycle saturation. There are several references available that help estimate the approximate closed solution and simulation modeling of the

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transformer impact during GIC. Measurement done during a GIC event can be used to verify the transformer used in simulations.

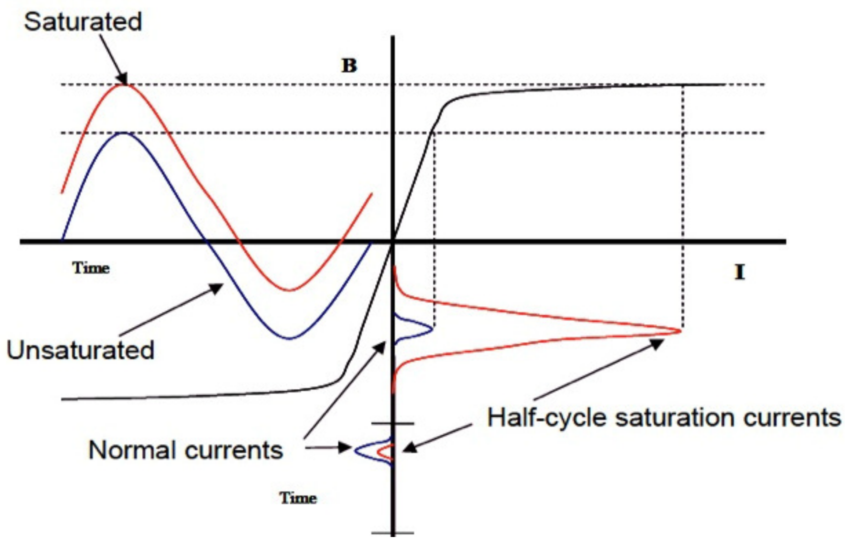

Figure 2: The half-cycle saturation due to typical GIC offset [1]

Reactive power consumption

GIC half-cycle saturation draws more exciting current, which lags the supply voltage by 90 degrees in phase due to the inductive properties of the magnetizing component. Since the amount of excitation current can be very high (depending on saturation severity), more reactive power will be consumed by the transformer. For mathematical illustration [6], a simplified case of fundamental reactive power and its relation during severe saturation is illustrated below.

Q = m x GIC + Q0

where, m = slope, GIC = magnitude of the GIC current, Q0= initial reactive power.

The above equation is derived with the assumption that during the start of a GIC event, the voltage V at the transformer terminal will try to maintain its value to "one per unit" as long as the generator or the in-feed network supplies the extra reactive power demand during the GIC event. Also, as is close to 90 degrees, and as the GIC amplitude increases, the excitation current will also increase linearly; therefore for low to moderate GIC currents, reactive power varies linearly with respect to the GIC current. The following diagram shows reactive power for a typical autotransformer.

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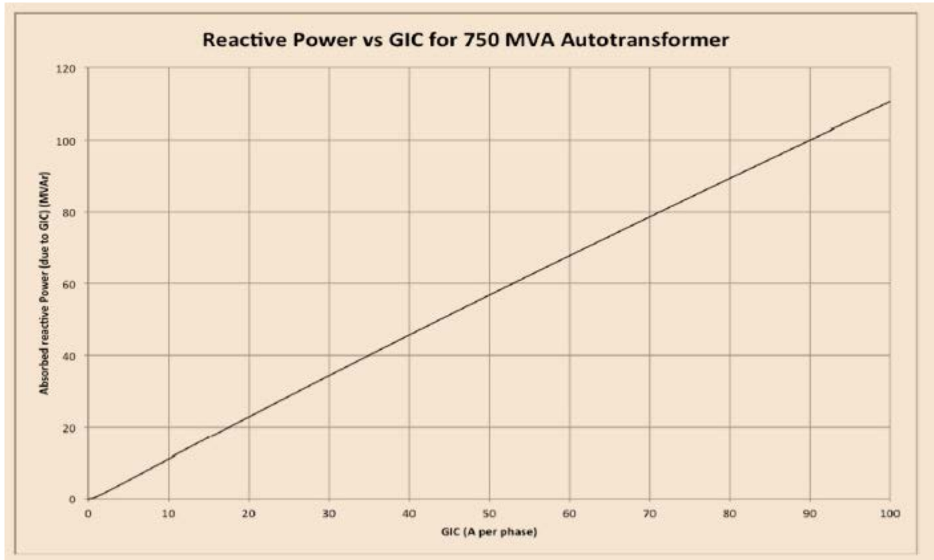

Figure 3: Reactive power absorbed versus the GIC current for 750 MVA autotransformer [6]

In practice, due to harmonic currents, the reactive power estimates should also consider harmonic effects. For severe solar storms, the reactive power versus GIC relationship will become non-linear.

Harmonics

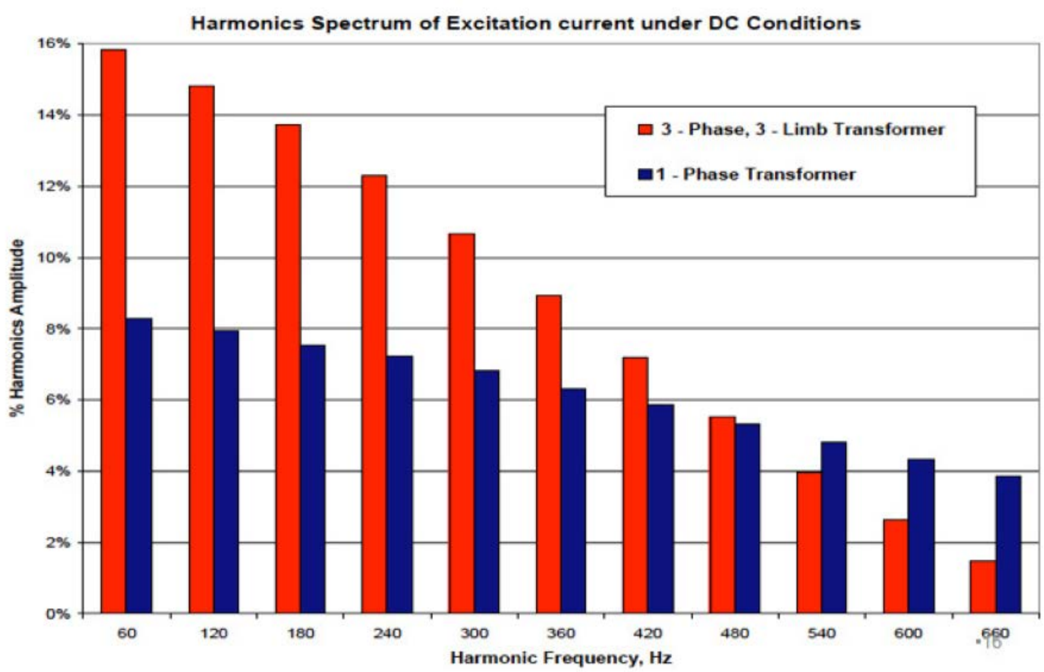

Figure 4: Illustration of the odd and even harmonics during DC excitation [1]

Transformers become a source of harmonics due to half-cycle saturation, which has a number of impacts on connected components. Since the waveform is asymmetrical, there will be significant odd and even lower order harmonics generated. Typical harmonic waveforms are shown above.

Stray or air-core flux

When a transformer is subjected to saturation, the flux through the "iron" or "magnetic" path must find a non-magnetic path (the tank, the plates, the bolts,and the nuts etc.) to maintain constant maximum flux. Stray flux causes eddy currents in several metallic parts that contribute to additional heating on the transformer tank (Figure 5). These eddy currents are another effect of constant DC excitation, caused by moderate to severe GIC conditions.

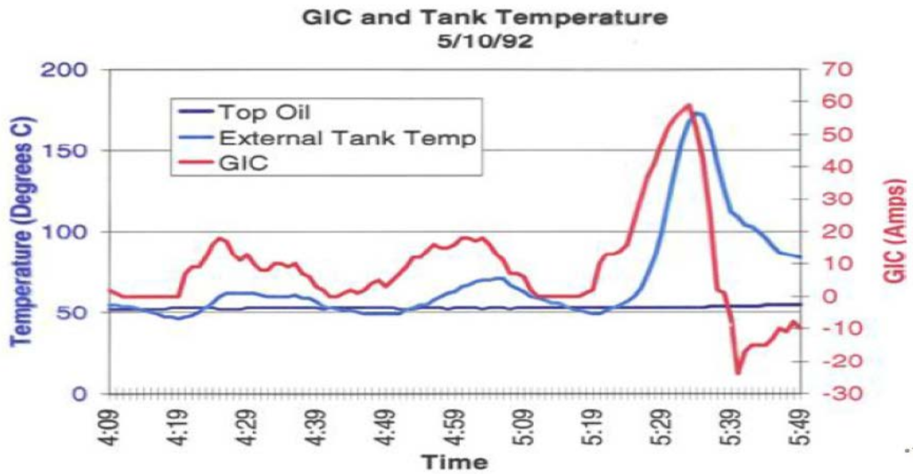

Figure 5: Illustration of GIC impact on transformer temperature profile [1]

Significant acoustic noise

When a quasi-DC excitation from GIC flows through a transformer, the magnetostriction effect and Lorentz force effect can create highly audible noise. Especially in certain types of transformer construction, the level of noise can reach up to 100 dB or higher, depending on the strength of the GIC. Similar noise has also been observed in transformers when HVDC systems [7] are operating in mono-polar mode with the ground return path (Figure 6).

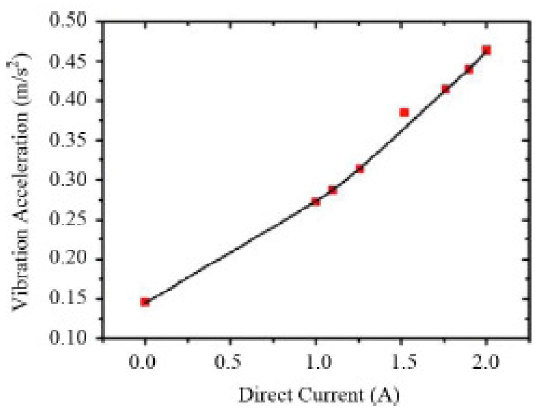

Figure 6: Vibration during DC excitation through a transformer model [7]

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GIC MONITROING AND DETECTION

This section provides information on typical GIC monitoring and detection methods applied in the field using a typical disturbance monitoring system.

Localized Measurements

During a solar storm, there are a number of symptoms (named in the sections above) that can be used to authenticate the existence of the GIC. The TESLA DFR has flexible analog input modules to connect to AC, DC, or any sensor which gives 4 - 20 mA output and +/- 2.5, 5, 10 V with suitable shunts (need proper isolation).

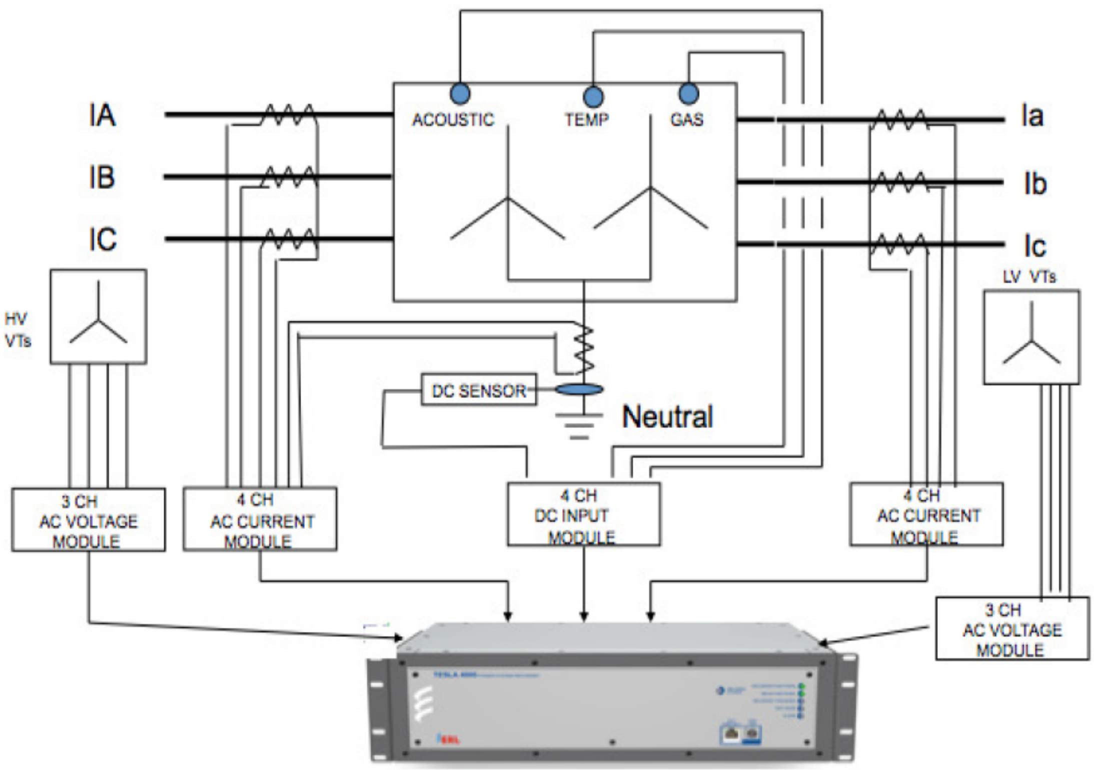

Figure 7: Typical quantities measured by the GIC monitoring and detection device (TESLA DFR).

Figure 7 shows the applicability of TESLA DFR for GIC monitoring. Key functions are listed below.

- Monitor the DC current through the transformer's neutral connection. This could be done by measuring the voltage across a suitable shunt or by using a suitable current monitoring device. Suitable DC Hall sensors with 4 – 20 mA analog output along with the TESLA DC module can measure the GIC neutral current.
- Monitor transformer tank temperature using a suitable 4 – 20 mA RTD (Resistance Temperature Detector) sensor or equivalent.
- Monitor the transformer tank's acoustic sound via a suitable sensor (4 –20 mA).

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- Monitor the reactive power of the transformer primary and secondary derived channel (can be configured using TESLA Windows software).
- Monitor the THD on transformer input currents and voltages. TESLA can measure this using AC voltage and current modules. TESLA can also measure individual harmonics. Care should be taken to supervise the fundamental voltage or current quantities in setting THD. Loading (fundamental frequency quantities) severely impairs THD ratios, and we recommend a supervised THD that can be configured through TESLA logics.
- Measure transformer tap positions using digital input status.

Figure 8 shows the measurements captured during a GIC event injected into the TESLA monitoring system.

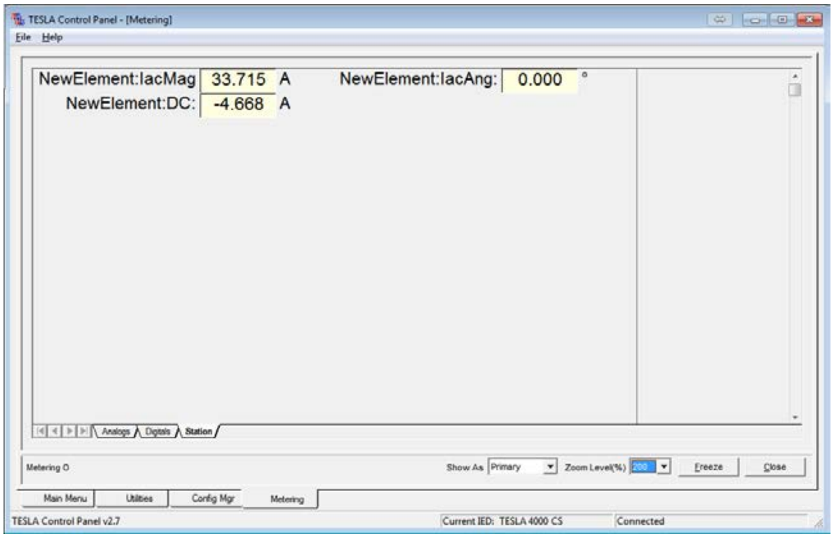

Figure 8: Neutral measurement on TESLA

Wide Area Measurements

As mentioned at the beginning of this paper, GMD activity is not a local phenomenon. Disturbances have wide area impact. In fact, the direction of the GIC flow also reverses from time to time, depending on the electric field direction. Wide area real time measurement of GIC activity is very helpful in managing related contingencies, depending on the solar storm severity. For example, to access the GIC with confidence, if wide area data is measured at different substations and collected at a central location, the data can be aggregated and analyzed from the wide area perspective to arrive at a better estimation of the GIC effect using synchrophasor (PMU) data.

CONCLUSION

The operation of a transformer subjected to GIC can be unpredictable because of the various factors in place. A monitoring, detection and warnings can be provided using a TESLA recorder measuring various quantities such as reactive power consumption, THD of the transformer voltages and currents, neutral dc currents, etc. These warnings can be provided to control center personnel who may be able to reduce risk of tripping by lowering loads to reduce the heating effect. Measurement techniques proposed in this paper are very useful to monitor wide area GIC events and compare the performance of the power

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system using simulation models. These real time measurements provide extra confidence and visibility to handle system contingencies during a wide area GIC event.

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BIOGRAPHY

Nuwan Perera (IEEE SM’2017) earned his BSc Electrical Engineering in 2003 from the University of Moratuwa, Sri Lanka and the M.Sc. and Ph.D. degrees from the University of Manitoba in 2007 and 2012 respectively. He is a Professional Engineer with 15 years of industrial and academic experience in power system protection. He joined ERLPhase Power Technologies in 2011 and currently holds the position of Product Manager for the recording products. He is a senior IEEE member, actively involved with various

IEEE Power Systems Relaying Committee (PSRC) working groups. He is also involved in academic research activities as an adjunct professor at the University of Manitoba. He has published over 25 papers in various IEEE/IEC journals and conferences, and is an innovator of patents.

René Midence (IEEE M'2007, IEEE SM'2009) is a 1983 graduate from the University of Honduras with a Bachelor of Applied Science degree in Electrical and Industrial Engineering, and with over 30 years of experience in power systems, protection & control, SCADA, substation automation and substation LAN systems. His well-rounded experience covers the fields of consulting and engineering, construction and commissioning, manufacturing, strategic marketing, technical support and training. He has contributed to the development and successful introduction to market of new state-of-the-art protection and control microprocessor based relays, and Ethernet switches and routers. He is a Senior Member of the IEEE with active participation in the development of IEEE Standards. He joined ERLPhase Power Technologies in 2010 and currently holds the position of Director of Technical Services.

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