Hydro One GMD Preparedness Plan for Cycle 24

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Abstract

This document describes the preparedness plan that Hydro One is implementing to manage the effects of Geomagnetic Disturbances. This effort has built on more than 25 years of in-house experience as well as cooperative efforts with the Geomagnetic Laboratory of NRCAN and the University of Western Ontario. The plan calls for an expanded GIC monitoring network, software tools to assess the distribution of GIC and its effects on major power equipment in the Hydro One 230 kV and 500 kV networks in real time, and off-line analysis tools that integrate load flow analysis with GIC simulations. All these tools and greater visibility into the effects of any given storm will converge into operating measures to protect Hydro One's assets, and ultimately in coordination with the IESO, the security and reliability of supply in the Province of Ontario.

Keywords: GIC, Transformer Saturation, Solar storms, GMD

1 Introduction

Ontario Hydro and its successor transmission company Hydro One have been active in the area of assessment of the impact of Geomagnetic Disturbances (GMD) on the high voltage transmission network since the mid 80's. The degree of engagement has increased over the years, from the installation of a few Geomagnetically Induced Current (GIC) monitors in the early 90's, the installation of 12 new GIC monitoring stations in 2005 [1], to the comprehensive preparedness plan presently being developed for sunspot cycle 24. Along the way Hydro One has maintained a cooperative relationship with the geophysicists at Geomagnetic Laboratory of Natural Resources Canada [2], and has carried out research work with the University of Western Ontario [3-5].

The preparedness plan for sunspot cycle 24, is focused on the protection of major high voltage assets such as transformers, shunt capacitor banks, and Static var Compensators (SVCs), but it has a substantial research component aimed at model tuning and validation with actual measurements.

2 Effects of GIC on High Voltage Transmission Networks

During normal steady-state operation, practically all the magnetic flux of a transformer is contained within its laminated steel core. Electrically, this is equivalent to saying that the magnetizing characteristic of a transformer represented by the nonlinear shunt branch X_{mag} of the simplified representation of Figure 1 is in the linear, high inductance region (see Figure 2 (a)). The flow of quasi-dc currents such as GIC in a transformer winding can introduce dc flux in the core, which effectively shifts the flux-current operating point. In this case, the transformer is operating in the low inductance ($L_{air\text{-}core}$) saturated region for part of the 60 Hz cycle, where flux is not contained in the core and can flow through structural parts such as the transformer tank (see Figure 2 (b)). This is normally called half-cycle saturation. The shift in the operating point depends on the amount of dc current in the winding and on the core design. For the same amount of dc current in the winding, a bank of single-phase units see a larger shift in operating point that a three-phase, three-limb core-type unit.

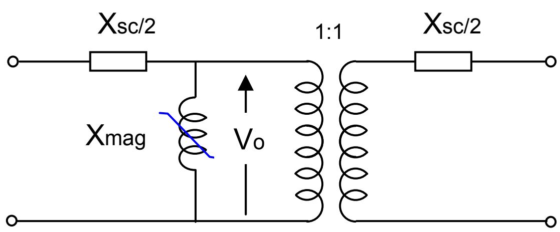
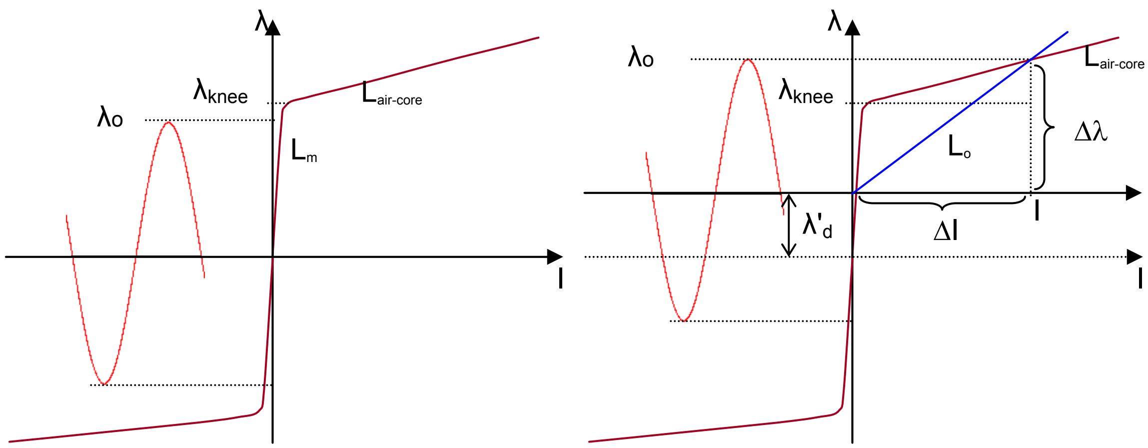
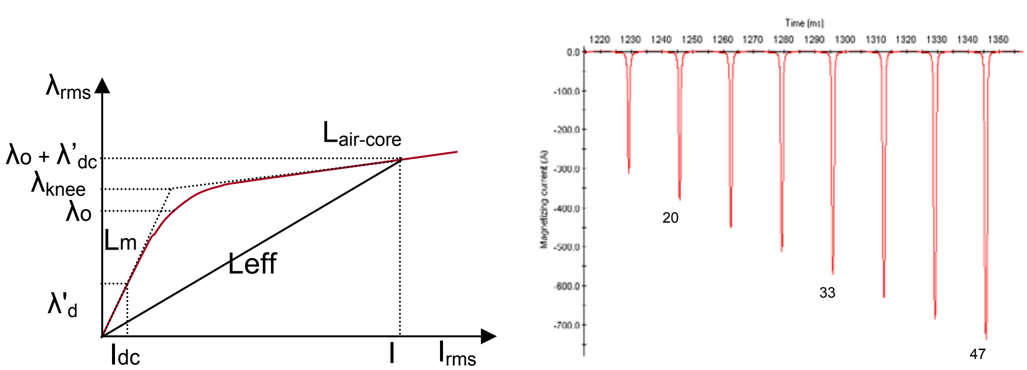


Fig. 1: Simplified representation of a single-phase transformer



(a) (b)

Fig. 2: Flux-current characteristic of a transformer. (a) Normal operation. (b) dc-biased or half-cycle saturation



(a) (b)

Fig. 3: (a) RMS flux vs. RMS current. (b) Magnetizing currents for increasing values of dc flux bias.

The main effects of half-cycle saturation are:

- o Very distorted magnetizing currents (generation of even and odd current harmonics). Increased harmonics in the HV network can cause generator overheating, increased shunt capacitor bank harmonic currents, potential improper operation of protective relays.

- Increased transformer winding and structural hot spot heating because the flux is not contained within the core all the time
- Reduction of the effective magnetizing reactance of the transformer from L_m to L_{eff}, as illustrated in Figure 3. This is equivalent to adding a relatively small inductance across the terminals of the transformer, forcing the voltage across its terminals down, and causing what in power system terms is called drain or loss of reactive power.

These effects are summarized in Figure 4.

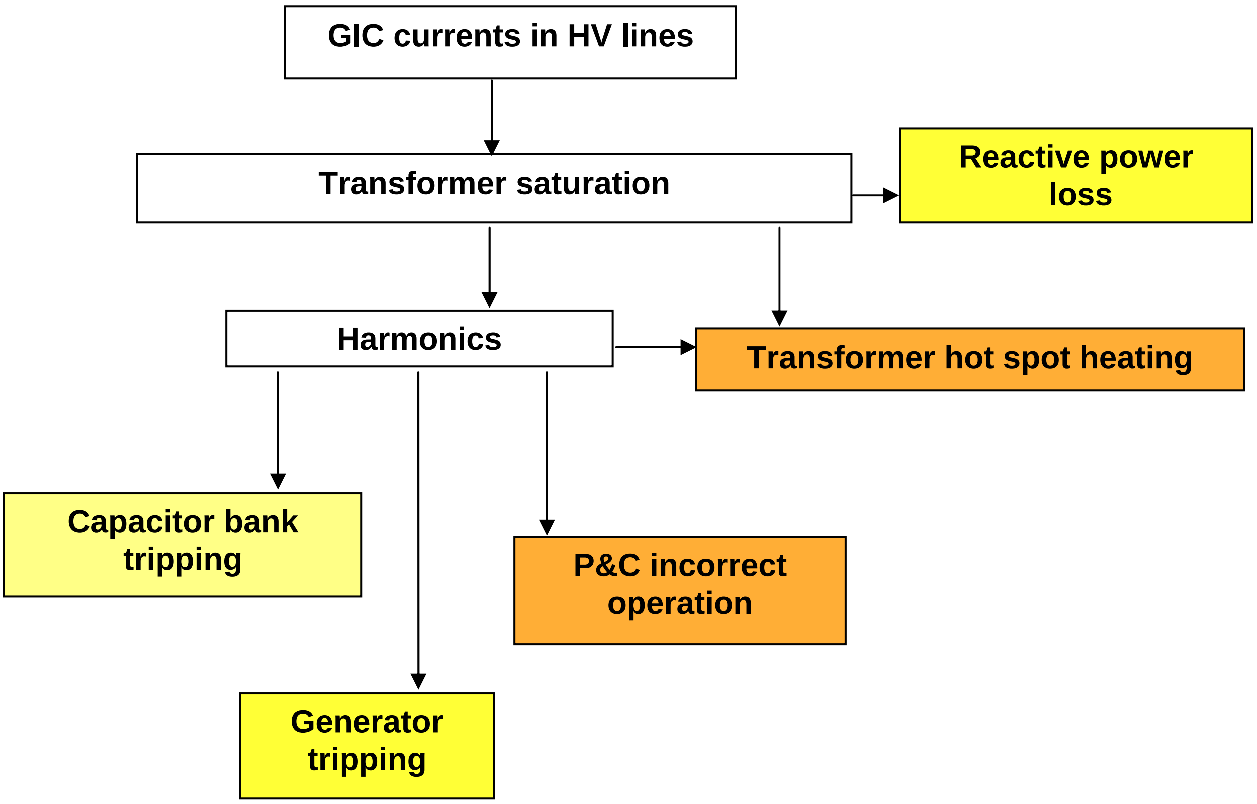


Fig. 4: Effects of GIC on the power system

The relationship between GIC, reactive power loss and voltage can be illustrated by measurements made with Hydro One's GIC detection network during Cycle 23. The event in question was relatively mild from the point of view of the effects on the Ontario system and took place on July 26, 2004. Figure 5 shows the transformer neutral currents recorded in one of the monitoring stations. Of significance is the 17 A per phase (50 A neutral) peak followed by lower magnitude oscillations for approximately 12 hours. Figure 6 shows the solar activity between June and August 2004 with data from NOAA (National Oceanic and Atmospheric Administration). The planetary A index rose sharply to 155 and 190 on July 26 and July 27, respectively.

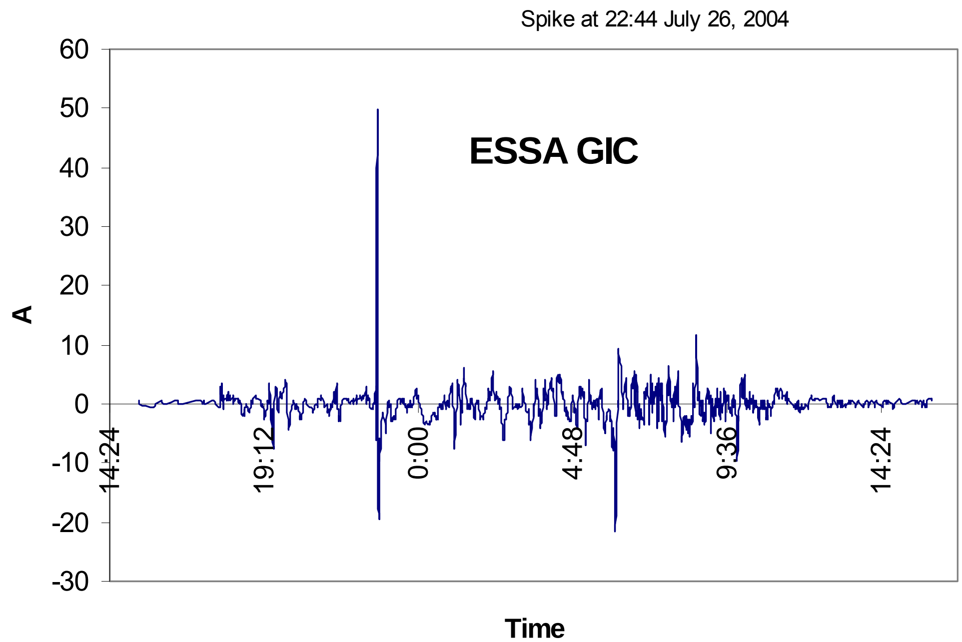


Fig. 5: July 26 2004 GMD event. Measured neutral GIC

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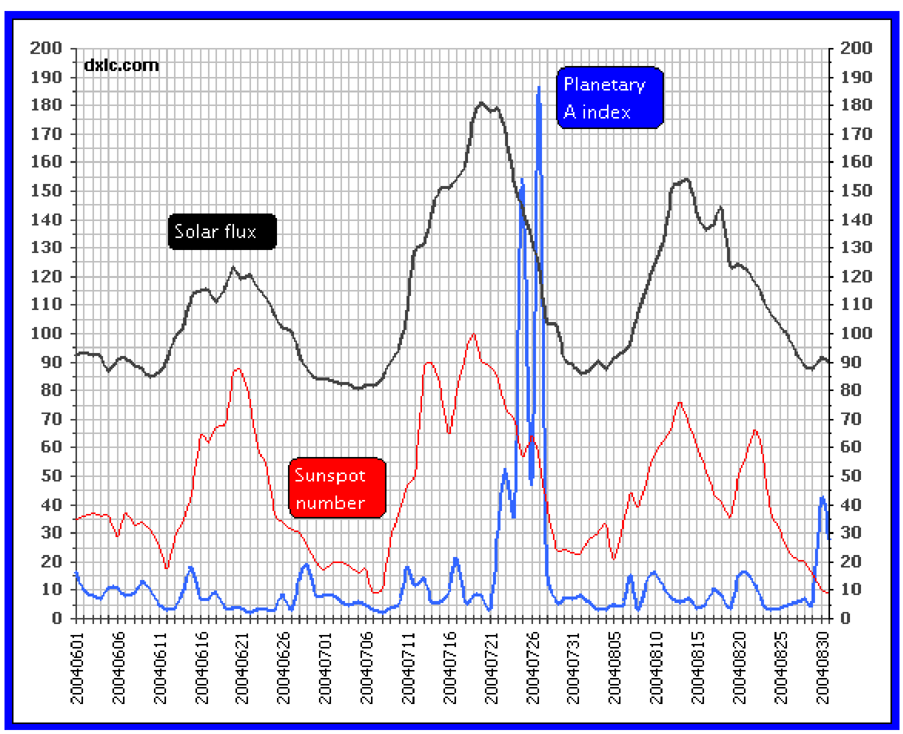

Fig.6: *Solar activity recorded by NOAA/SEC (Time is GMT)*

The effect of the GIC peak was reflected in both the 230 kV and 500 kV networks. Figures 7 and 8 show the recorded voltage drop of more than 1% in some 500 kV and 230 kV buses. Although the voltage drop was observed throughout the network, its magnitude was not uniform through every bus.

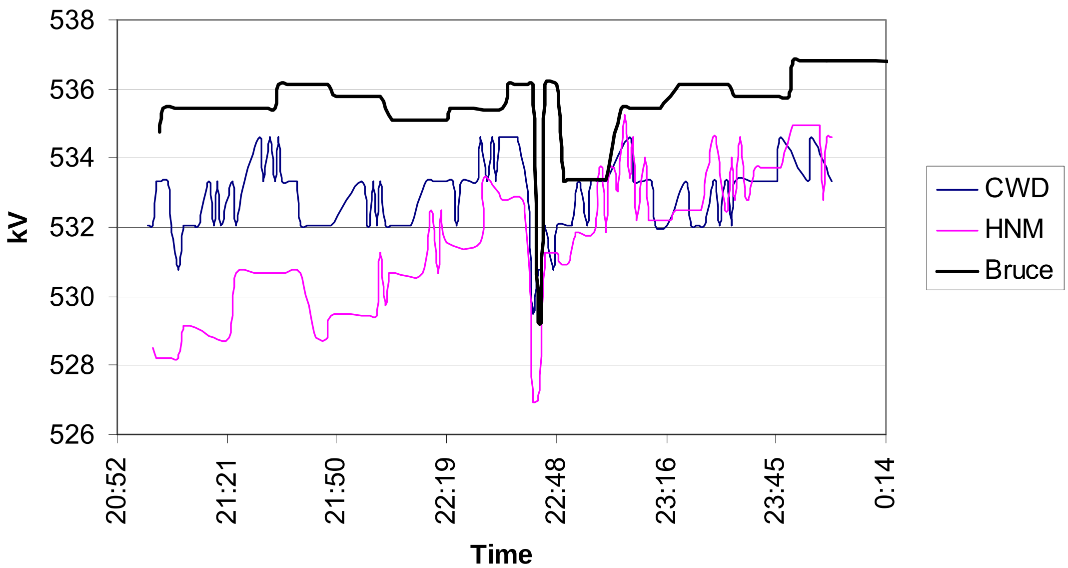

Fig.7: *500kV buses voltage responses to the GIC peak*

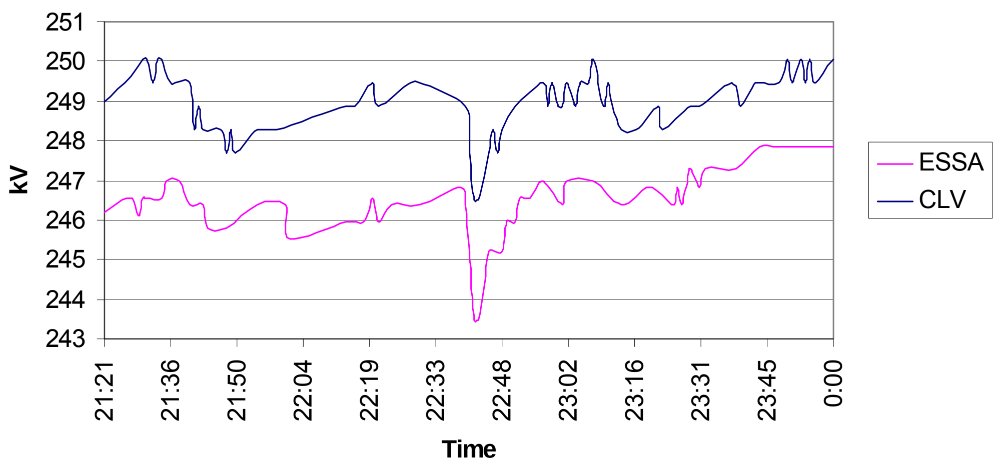

Fig.8: *230kV buses voltage response to the GIC peak*

3 Hydro One's GMD preparedness plans

Hydro One's approach to the management of GMD effects has been an evolutionary process over a number of years. The primary focus has always been increasing the visibility of GIC in the network to allow more informed operational decisions and outage management.

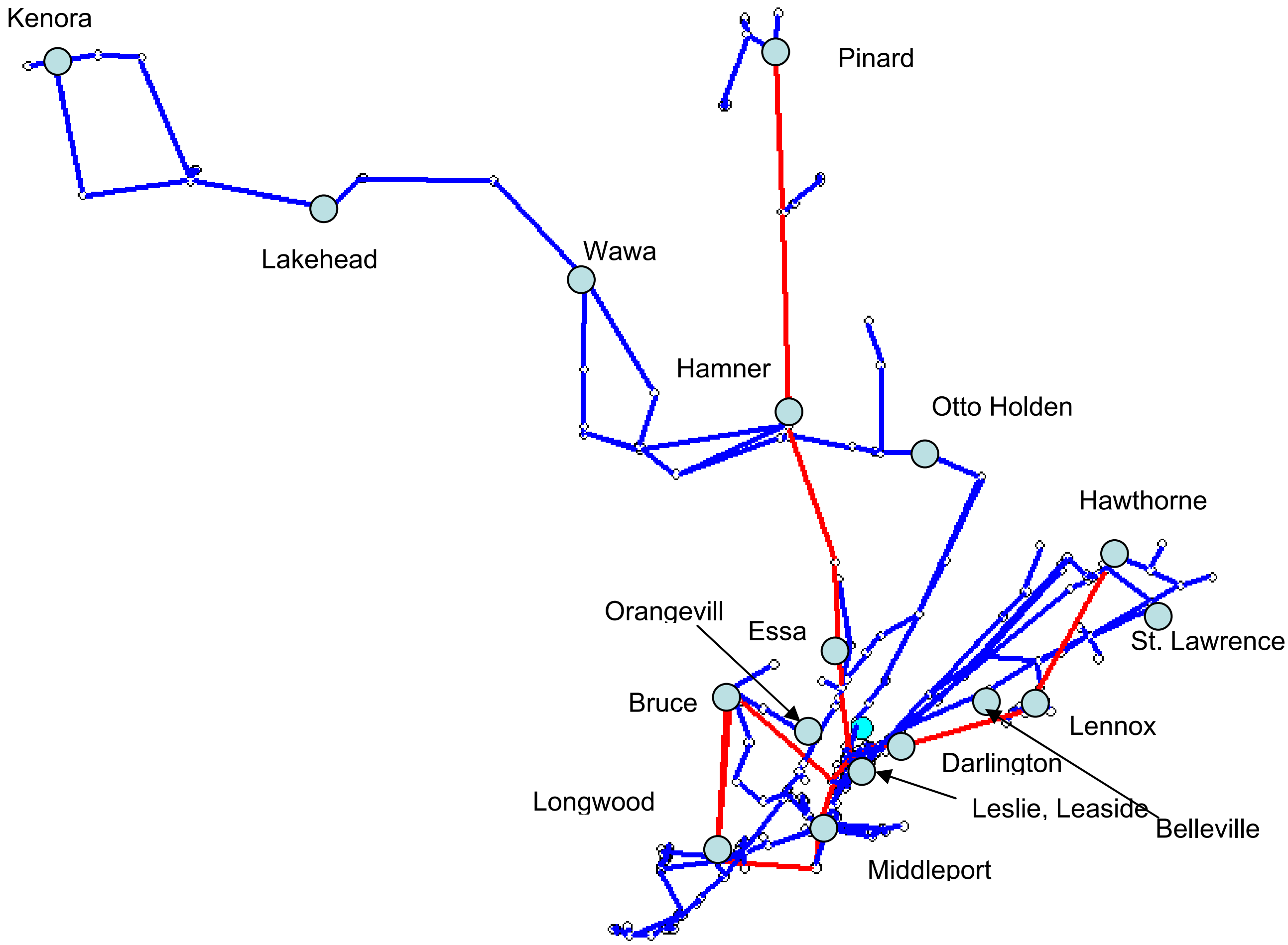

Fig. 9: Hydro One GIC monitoring stations

Preparation for cycle 24 includes:

- Review of protective relaying. This review is carried out every sunspot cycle to assess the impact of changes in relaying technology and protection philosophy. This cycle's review concluded that the replacement of electromechanical relays with IEDs has practically eliminated the impact of GIC on reliability and security of the protection schemes used in Hydro One.
- Increase the size of the GIC detection network to18 monitoring stations (see Figure 9).
- Complement GIC measurements with real-time applications to calculate GIC in every part of the 230 kV and 500 kV network from magnetic field measurements. These applications also estimate harmonic generation, reactive power loss, and hot-spot heating for all HV transformers with a ground connection.
- Estimate in real time the GIC flowing through the windings of the transformer directly from SCADA measurements of reactive power loss
- Estimate in real time GIC flowing through selected transformer from the harmonic currents measured with modern relays (IEDs)
- Measure in real time the rate of change of dissolved gasses in selected transformers to establish correlations with the estimated hot spot heating.
- Integrate the GIC application with standard load flow software to evaluate system contingencies and mitigating measures for any GMD event.

- Set a training environment with the “storm playback” option of the real time applications.

The plan also calls for the tuning and validation of the new applications. This means a staged approach to final “go-live” contingent, of course on measurements and analysis from a couple of moderate GMD events.

4 Incremental innovation

For the most part, the analytical basis of the new applications is well known and mature, albeit applied in real time and on a relatively large scale.

The real-time GIC calculation application is based on the engine developed by NRCAN, and it has been used for a number of years [7]. It has been adapted for the control room environment to handle dynamic network changes and asynchronous data input from SCADA and magnetometer readings. Some of the highlights are:

- The size of the network is defined by the transformers connected to the 230 kV and 500 kV networks that have a path to ground. On average, this subset of the Hydro One network has 500 transformers, 820 circuit segments, 30 shunt capacitor banks, 5 SVCs, and two series-compensation capacitors. The model includes one transformer station past interconnection points with Manitoba, Quebec and the U.S.
- Computational cycle is under 50 ms on an ordinary desktop computer. Access to sixty seconds of magnetic field data is under 400 ms, therefore it can handle a 1 second magnetic field data rate in real time.
- Overall latency due to system data acquisition and output storage is between 1 to 2 minutes. Sixty seconds of magnetic field data are acquired every minute

Some of the modest innovations built into the applications are summarized below:

- Three-way comparison of measured GIC in selected transformers: from direct neutral GIC measurements, from measured reactive power loss, and from GIC calculated from magnetic field measurements.
- Assessment of transformer vulnerability on the basis of winding and structural hot spot heating due to half-cycle saturation. This assessment is based on either measured (see Figure 10) or calculated thermal response of a transformer and it takes into account magnitude and duration of GIC (see Figure 11). These temperatures are compared to either suggested hot spot limits and IEEE C57.91, or to more conservative limits estimated on the basis of transformer age, gas content, moisture, and maintenance history.

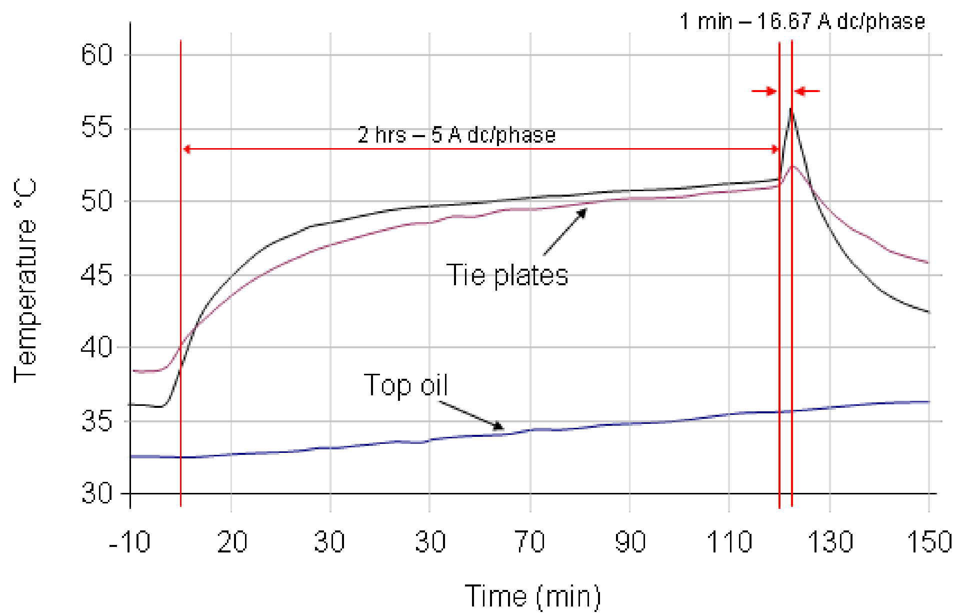

Fig. 10: Thermal response of metallic hot spots in a single-phase 500/16.5 kV 400 MVA *transformer.*

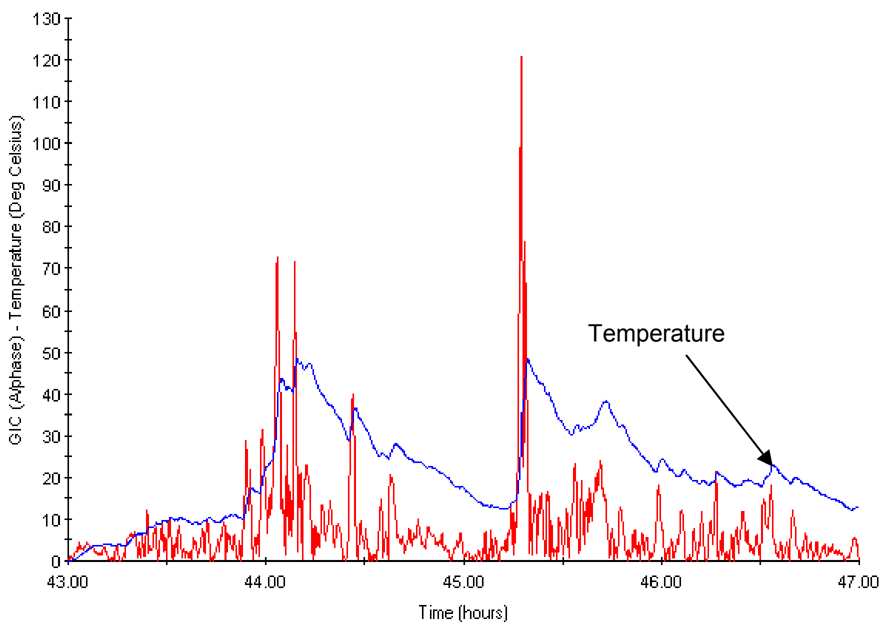

Fig. 11: Incremental temperature rise of the tie plate of a single-phase 500/16.5 kV 400 MVA *transformer under a pre-recorded GMD event. Blue trace is the estimated temperature and the red trace is the absolute value of the GIC in the winding.*

The intent of the study-mode version of the GIC simulator (QSAT) is to assess the effects of reactive power loss on system voltages. The time frame for the effects of reactive power loss is tens of seconds, as opposed to tens of minutes for the effect of half-cycle saturation heating. Therefore, the phase angle of the electric field can be assumed to vary modestly.

Maximum GIC in different parts of the system generally occurs for different orientations of the electric field. We have subdivided the possible number of electric field orientation to six zones (four of which are illustrated in Figure 12).

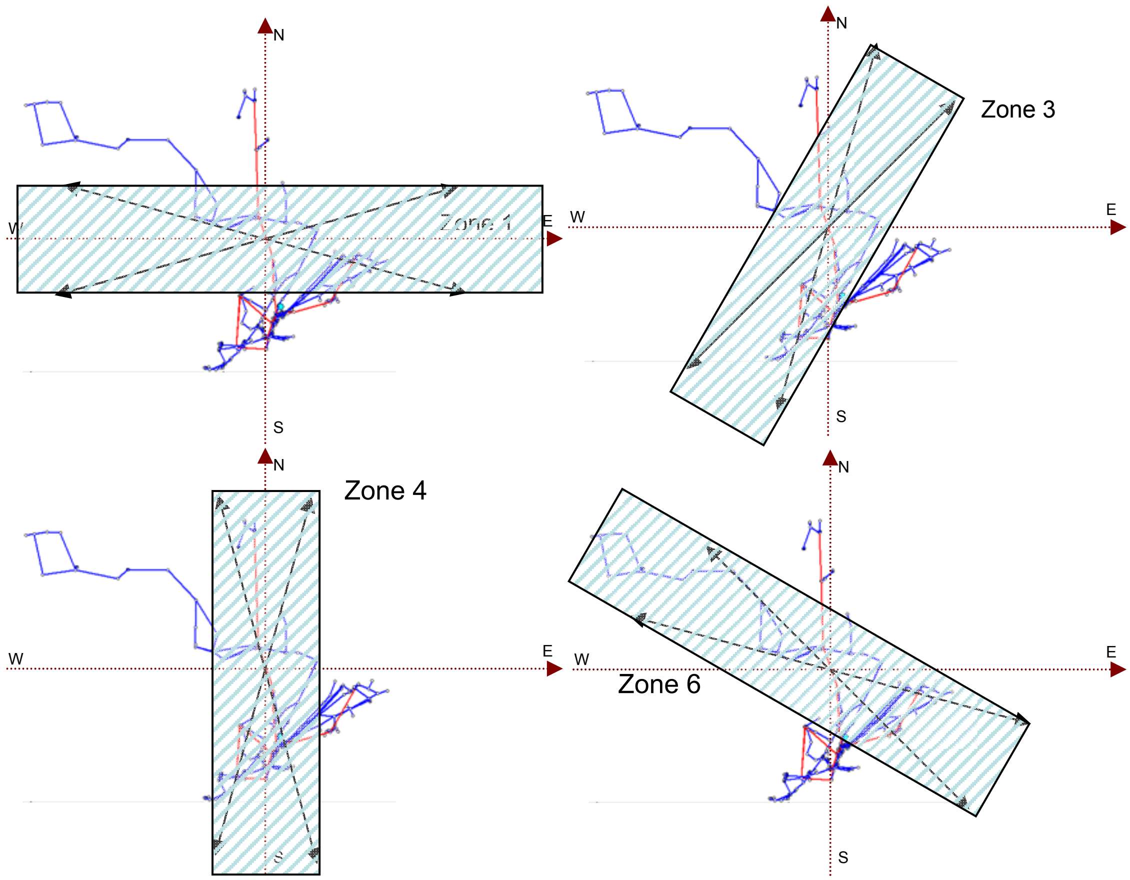

Fig. 12: Off-line study-mode electrical filed zones.

In an off-line system study, an electrical field strength between 1-10 V/km is selected and the distribution of GIC and estimated reactive power loss is calculate for each of the six zones (average over 5° increments) and passed as constant Q sources to the load flow program. If voltages calculated with the load flow program are very different from the voltages assumed in QSAT, the new voltages are passed back to QSAT to estimate the corrected reactive power loss. More than 1 iteration is seldom necessary.

QSAT also produces an estimate of transformer stress based on thermal functions by using a pre-recorded storm such as the one shown in Figure 10, scaled to the V/km assumed in the simulation. This provides an indication of whether transformer vulnerability or voltage issues are the limiting factor in a given simulation.

5 GIC mitigation

For the most part, the effects of GIC on the power system have been understood for decades. Their impact on power system equipment and operation are more than academic speculation. However, utilities usually react to potential GIC consequences according to past operating experience and available resources. Some utilities choose to "ride through" GMD events, while some go to costly measures such as connecting series capacitors on their major lines or transformer neutrals to block dc currents [5].

In Hydro One, the experience with adverse GIC effects has been relatively mild. To-date, Hydro One has followed NERC/NPCC guidelines for severe GMD events, which amount to adopting a "safe system posture", as well as a number of operating/outage management instructions based on studies from earlier cycles. As the new applications and systems are tuned and validated, with real event data, a move towards a more “surgical” response will likely take place. Nevertheless, enough conservatism has been built in the new applications so that they are used today to assess all worst-case scenarios notwithstanding the severity of storm.

The possibility of using GIC reduction/blocking hardware solutions has also been investigated as part of the preparedness activities. EMTP studies were carried out to assess the applicability of resistor-based and capacitor-based transformer neutral devices in two different stations to address very specific issues. In one study, a resistor-based device was considered as a potential option to address asymmetrical fault current issues, and the re-distribution of GIC was investigated. In this case, the main issue from a GIC point of view, was the optimal placement of the devices (number and location) under different operating conditions and contingencies. The study concluded that there was very little room for optimization under all operating conditions and that the devices would have to be installed in practically every transformer in the station. The focus of the study of capacitor-based neutral devices was the potential for linear resonance. Although the study was by no means exhaustive, it showed that resonance would have been an issue in the study system if the bypass mechanism of the GIC blocker were to fail during a line-to-ground fault. The study system focused on a relatively small two-transformer station, so the re-distribution of GIC within the station was not an issue.

Hydro One is not suggesting that there are not instances where the installation of phase or neutral GIC blocking would be a good solution in some specific circumstances. Studies to date, however, strongly suggest that careful system studies are needed for every potential application of a GIC blocking device.

6 Conclusions

In preparation for sunspot cycle 24, Hydro One is putting in place a number of cost-effective GMD management measures aimed at having well-planned and well-informed operating strategies and decisions, as well as unparalleled visibility of GIC and its effects in the system.

Plans for cycle 25 based on lessons learned in this cycle are already being discussed. They include improvements such as the implementation of GIC calculation algorithms based on non-uniform electric fields, integration of hot-spot and dynamic transformer rating algorithms, integration of GIC models of neighbouring utilities, and the expansion of the modeled network below 230 kV, to name a few.

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