Modelling Considerations for the Hydro One Real-time GMD Management System

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Abstract — **Hydro One (Ontario, Canada) has implemented a Geomagnetic Disturbances (GMD) management system in its control centre that combines real-time tracking of GMD events as well as an assessment of Geomagnetically Induced Currents (GIC) on every circuit and transformer in the 230 kV and 500 kV networks from magnetic field measurements. Transformer reactive power loss and hot spot heating due to half-cycle saturation of every transformer with a grounded winding above 230 kV is also estimated. The computational demands in real time required modeling techniques not usually associated with GIC simulations in large networks. This paper describes the modeling approach, capabilities, and usage to make real-time operational decisions during a GMD event.**

Keywords — *Geomagnetism, GIC, Power System Modelling,*

I. Introduction

Power system impacts from Geomagnetic Disturbances (GMD) have been observed since the early 1940's. One of the recent large GMD events in March 13-14 1989 resulted in significant impacts to power grids in North America. On average, heightened solar activities follow the 11-year sunspot cycle. The concern for the power industry regarding GMD has been growing with the increasing size of high voltage networks, narrower operational limits, and complex interconnections of power grids [1 – 4].

During a GMD event, fluctuations in the electrojets (austral and boreal) induce a geoelectric field in the earth. If a closed path though earth is provided in the form of transmission circuits and grounded transformers, Geomagnetically Induced Currents (GICs) will flow. From a GIC modeling point of view, the geoelectric field can be represented as an ideal voltage source in series with transmission lines which acts as the electromotive force that causes GIC flows through the grounded neutrals of wye-connected transformer windings. Since the geoelectric field has a much lower frequency (generally between 0.001 ~ 0.1Hz) than the operating frequency of the power system (50-60 Hz), GIC can be treated as quasi-dc currents. GIC causes a dc bias in the transformer core flux, resulting in half-cycle saturation, which injects significant amounts of even and odd harmonics into the system. The degree of saturation will depend on the transformer's core construction (e.g., single-phase, shell or three-leg three-phase core). A saturated transformer will draw large magnetizing currents and appears as an effective reactive power sink. Hence, during severe GMD events, the power system needs more-than-normal var compensation. On the other hand, devices such as static var compensators (SVCs) and shunt capacitor banks, which are critical for var support are vulnerable to harmonics and may trip [1].

To increase Hydro One Networks' (HON) preparedness for the expected peak of sunspot cycle 24 (2012-2014), a real-time GMD simulator and storm-tracking system (rtGICsim) was developed and underwent commissioning at the HON Grid Control Centre since October 2012 to provide situational awareness to system operators, real time estimates of GIC, transformer heating, transformer var loss in the 230 kV and 500 kV networks, as well as triggers/alarms for pre-defined control actions. The kernel of the rtGICsim GIC computational engine was adapted from the real time GIC simulator originally developed by NRCan in 2005 [5]

In addition to its on-line usage, rtGICsim is also used as an off-line tool to simulate the impact of GMD on the transmission system, evaluate the effect of mitigating measures, and develop action plans and key operating procedures. This application is also used for operator training by playing back previously-recorded and intentionally-scaled events in real time to show the effects of control actions such as removing from service a transformer or a circuit.

This paper describes the modeling approach used in the design and implementation of rtGICsim, as well as its use as a trigger for operational measures in a live control room environment. Section II describes the modeling capabilities of rtGICsim. Section III describes the modeling techniques used to maintain real-time calculation cycles. Section IV describes the integration of rtGICsim with the control room environment and the application of operational measures to manage the adverse effects that an extreme GMD event can impose of the power system

II. Capabilities of the Simulator

The part of the Hydro One HV network simulated with rtGICsim consists of approximately 530 grounded transformers with at least one terminal connected to 230 kV and 500 kV buses. The all-in-service system has 800 circuits and thirty 230 kV shunt capacitor banks. The network configuration is dynamically updated whenever SCADA indicates that there has been a change.

An Oracle database supervises an asynchronous "event bucket". Three types of events are recognized to indicate availability of new input data:

- Magnetic field measurements

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- Network configuration changes
- SCADA and telemetry data

SCADA data consists of:

- Bus voltages (measured where available as well as calculated with the state estimator).
- Power flow through each transformer terminal (measured where available as well as calculated with the state estimator).
- Telemetry from 6 on-line Dissolved Gas Analysis (DGA) monitors.
- HV and LV harmonics (1-13) from 5 transformer differential (digital) relays.
- GIC neutral current measurements from 18 GIC monitoring stations.
- Transformer/station ambient temperature.
- Estimated top oil and winding temperatures for transformers owned by Hydro One. Since this data are not available for non-Hydro One transformers (e.g., generator step-up transformers), a simpler conservative temperature is calculated taking ambient temperature into account.

Magnetic field measurements from the Ottawa magnetometer are polled from the NRCan server. The sampling rate is 1 second. Typical polling cycle is 1 minute.

Notification of network configuration changes is placed in the event bucket by exception. Telemetry data from SCADA is polled every minute. If there is no data to process in the event bucket, rtGICsim idles and checks the contents of the bucket every 20 seconds.

The induced geoelectric field used as the driving function for the calculations performed in rtGICsim is calculated from magnetic field measurements. When the uniform field option is used, a single earth model transfer function is required [6]. The geoelectric field is introduced into the dc network as a voltage source in series with a circuit and proportional to its length. The magnitude depends on the relative orientation of the instantaneous geoelectric field and the transmission circuit. When the non-uniform field option is used, the geographical area of the transmission system is subdivided into as many polygons as needed to characterize the geology of the service territory. In the case of the Province of Ontario a total of 5 polygonal zones are deemed adequate. Geoelectric potentials imposed on circuits that span multiple zones are calculated using the sum of the contributions of each zone. At the time this paper is being written, the magnetic field is assumed to be uniform since the only one magnetometer is being used as input. The integration of input from multiple magnetometers is one of the improvements being planned for the GMD management system.

On output, rtGICsim produces the following:

- Magnitude and direction of the geoelectric field for the operator's display. With the non-uniform field assumption, the display shows the geoelectric field in Zone 1, which has more than 60% of the circuit kilometers of the HV network.
- GIC per phase on every circuit.
- Transformer GIC on every terminal (including neutral).
- Winding and metallic structural part hot spot temperatures.
- Reactive power loss in every transformer as well as the station and system aggregate.
- THD in every transformer.
- Harmonic overcurrents in shunt capacitor banks.
- Storm severity on the basis of peak and 10-minute average GIC measured at key GIC monitoring stations. These "canary" stations have been chosen because they cover the geoelectric field directions that have the largest impact on the system.

  The storm severity display is not directly tied related to K levels but rather GIC and magnetic field measurements (and calculated geoelectric field in V/km) using the March 1989 as the reference value to define a moderate event. Storm levels are:

  - Minor (< 1.5 V/km)
  - Moderate (1.5 V/km - 4 V/km)
  - Severe (4 V/km - 7 V/km)
  - Extreme (> 7 V/km)
- Operator alarms for transformer hot spot overheating. These are used to trigger operational responses
- Capacitor bank overcurrent warning alarms. These are only used for situational awareness.

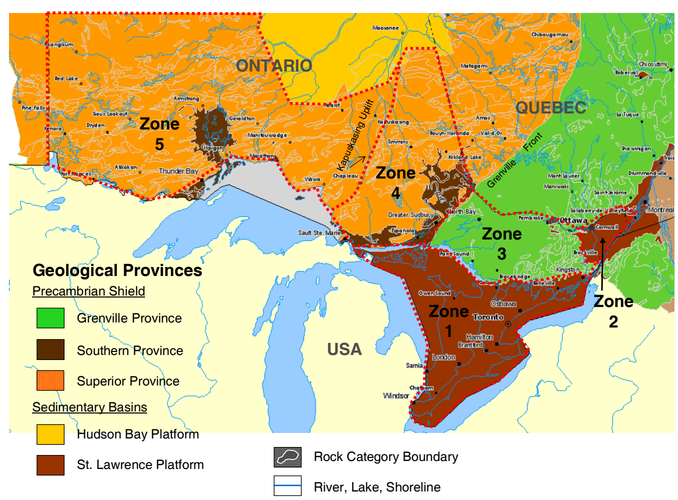

Fig. 1: Distinct earth model zones in Ontario

The time required to perform each calculation cycle is less than 200 ms on a modest laptop computer. The computational time requirements between uniform and non-uniform geoelectric field options are almost identical. Output from rtGICsim is stored into the database. This database is accessed by a graphical user interface for operator's use (see Fig. 2). The graphical user interface is a web-based application, therefore there is a firewall in place between the SCADA sever and rtGICsim, its web server and the graphical user interface. The computational burden of transferring data to the database is relatively high (in the 400 ms to 600 ms range). A complete calculation and data transmission cycle is typically completed in under 800 ms. However, to reduce the volume of stored data, output is only transferred to the database and displayed in the operator's display screen every 15 s even though calculations are carried out every second.

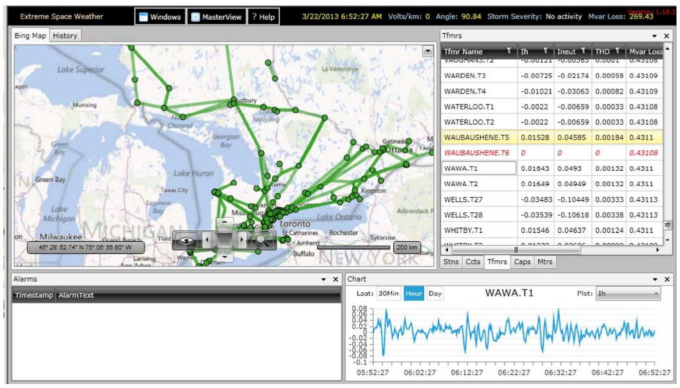

Fig. 2: Graphical user interface and operator's display.

The maximum latency of the system (the time when a change in the magnetic field takes place and the time it is reflected in the display) is typically 1.25 minutes. The display data is refreshed every 15-30 seconds, depending on user interaction.

Most of the output described so far is just for situational awareness. The most critical parts of the application are the alarms that trigger operational responses. These will be discussed in more detail in Section IV.

III. MODELLING CONSIDERATIONS

The modelling techniques used in rtGICsim have been tailored to address the specific challenges posed by data requirements and the real-time environment. Whenever possible, pre-calculation has been used to reduce computational burden inside the time step loop, similar to some of the techniques used in the EMTP family of programs.

A. *Solution of the dc network*

A fairly standard solution technique has been used to solve the dc network

$$[Y_{node}]\cdot[V_x]=[I_x] \tag{1}$$

$$[Y_{node}]\cdot[V_y]=[I_y] \tag{2}$$

In Eq. 1 the current vector $[I_x]$ represents the equivalent current injections of the series voltage sources that represent the contribution of the induced geoelectric field between two nodes when the geoelectric field in the E-W direction is 1 V/km and the N-S field is zero. Similarly E_y represents the contribution when the E-W field is zero and the N-S field is 1 V/km. If the geoelectric field is assumed to be uniform then the voltage on any given bus is simply

$$V_{bus}=E_x\cdot V_x+E_yV_y \quad \text{V/km} \tag{3}$$

The scaling factors E_x and E_y represent the magnitude of the geoelectric field in the E-W and N-S directions, respectively, at any one point in time. V_x and V_y are calculated only once for a given network configuration. If the geoelectric field is assumed to be different in each geographical zone, then E_x and E_y represent the contribution from each zone a given transmission circuit subtends.

Once the bus voltages are known, the calculation of currents in each circuit and transformer is trivial.

B. *Calculation of the geoelectric field*

The calculation of the geoelectric field from the changes in the magnetic field measured in the magnetometer is based on the plane wave method [6]. The transfer function or impedance response of the layered earth Z is calculated in the frequency domain. The relationship between the geoelectric and magnetic fields is given in Equations (4) to (6)

$$E=\frac{Z}{\omega\cdot\mu}\cdot B\cdot\omega=-C(\omega)\cdot G(\omega) \tag{4}$$

In the time domain

$$\begin{aligned}E_x(t)&=c(t)*g_y(t)\\E_y(t)&=-c(t)*g_x(t)\end{aligned} \tag{5}$$

$$\begin{aligned}g_y(t)&=\frac{dB_y(t)}{dt}\\g_x(t)&=\frac{dB_x(t)}{dt}\end{aligned} \tag{6}$$

Instead of using Fourier Transform to calculate the corresponding impulse function c(t) in the time domain and use numerical convolution to calculate the geoelectric field it is more computationally efficient to use techniques similar to those used in frequency dependent line models in the EMTP; that is, to fit C(ω) with rational functions so that Eq. 5 can be solved using numerical convolution [7-8].

The use of recursive convolution is found to be very fast and there is practically no difference between simulation times using a uniform and a 5-zone non-uniform earth models.

C. *Calculation of transformer hot spot temperatures*

The calculation of the temperature increase caused by half-cycle saturation in transformers is numerically more complex than the calculation of the geoelectric field. Nevertheless, some of the same principles apply, namely, to carry out as much pre-processing as possible outside the time step loop.

The process of fitting the hot spot thermal response of a transformer is described in Reference [9]. Of interest in this context is that the fitted thermal response is obtained from either measured or calculated thermal step responses ahead of time and that recursive convolution is used to calculate the temperature increase or decrease as a function of the effective current in a transformer during the time-step calculation [9]. From a practical point of view, obtaining the thermal transfer functions is not trivial. Physical measurements such as the ones shown in Fig. 3, require placing multiple temperature sensors inside the transformer, inject a dc step function into the winding or neutral terminal and measure the winding and metallic part temperature response until it stabilizes (usually in 30-60 minutes). One of the difficulties in carrying out this type of test is that a substantial amount of power is required in order to maintain nominal voltage given the large magnetizing currents that are generated during half-cycle saturation. The problem with calculated thermal responses is that they require internal construction details normally only known by manufacturers. Also, because of the difficulties in carrying out the experimental tests on full-size transformers the validation of manufacturer's models is relatively limited. In some instances a "scale" transformer has been used to validate thermal models. In such cases, scalability of results is sometimes questioned [10-11].

Fig. 4 shows the metallic hot spot temperature of an autotransformer calculated using the magnetic field time series recorded during the March 1989 GMD. In this case the magnetic field was scaled so that temperatures beyond the limits suggested in 200°C short-time emergency overloading limit for metallic hot spot in IEEE C57.91 are exceeded. The thermal transfer functions correspond to a 550/16.5 kV 400 MVA single phase transformer bank

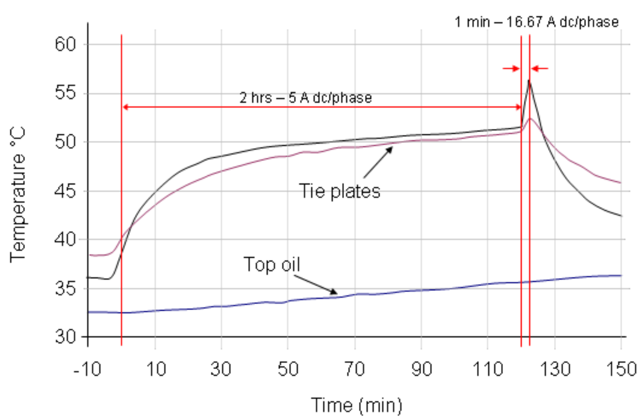

Fig. 3: Measured temperature rise in Transformer B (500/16.5 kV, 400 MVA) during dc injection tests.

When a transformer is taken out of service, rtGICsim assumes it is still connected to the network with a high resistance connection. This effectively forces the current through the windings to zero and allows thermal calculations to continue so that the cooling of transformer can be tracked by the operator. This is a valuable feature to assess when it is prudent to return a transformer back into service after it has been removed from service due to control actions caused by a critical hot spot heating alarm.

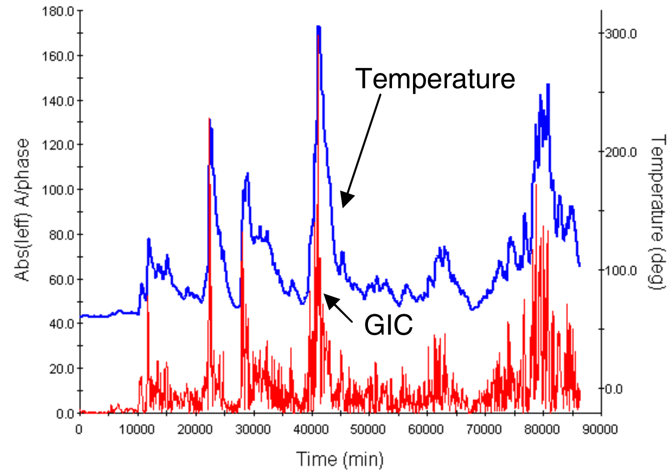

Fig. 4: Single-phase tie-plate hot-spot temperature rise versus time, scaled-up March 1989 GMD event

D. Reactive power loss

Reactive power loss due to transformer half-cycle saturation is calculated using look-up tables of GIC vs. Q evaluated at 0.9, 1.0 and 1.1 pu for different transformer types (single-phase core-type, shell-type, 5 and 3-leg core types). Interpolation/extrapolation is used to account for the actual bus voltage (see Fig. 5). As in the case of hot spot temperature calculations, the effective current in the transformer is used [9].

The bus voltages are obtained from the SCADA data feed and updated at approximately 1 minute intervals. Voltages from the state estimator are used when telemetered measurements are not available.

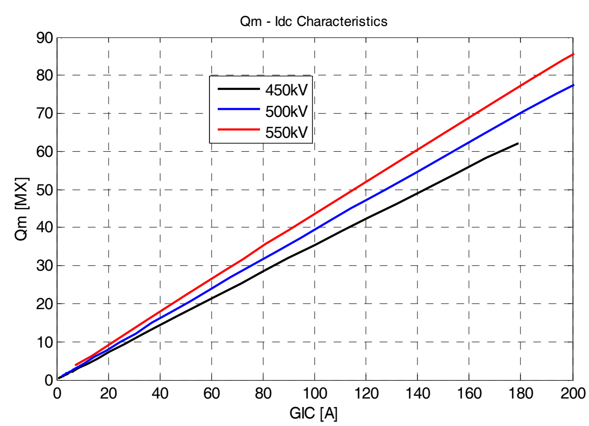

Fig. 5: Variation of reactive power with the transformer voltage versus GIC

Voltage and power flow values from a state estimator are questionable when var loss due to GIC is not taken into consideration in the state estimator's network model (which at this point in time it does not). Therefore var loss will be underestimated where bus voltage is not measured. Alternatively, measured values can be inaccurate within a few percent due to calibration drift. This is a problem to which further consideration will be given after more data is obtained from future GMD events.

E. Harmonics

Harmonics generated by saturated transformers are calculated off-line using harmonic analysis on the magnetizing currents for different values of GIC and stored in look-up tables for bus voltages of 0.9, 1.0 and 1.1 pu. Interpolation/extrapolation is used to adjust values to the measured/estimated voltages (see Fig. 6). Harmonic information is presented to the operator in the form of Total Harmonic Distortion (THD).

The estimated harmonics are used to assess potential shunt capacitor bank harmonic current overloading. When limits are exceeded the operator is presented with a warning alarm for situational awareness.

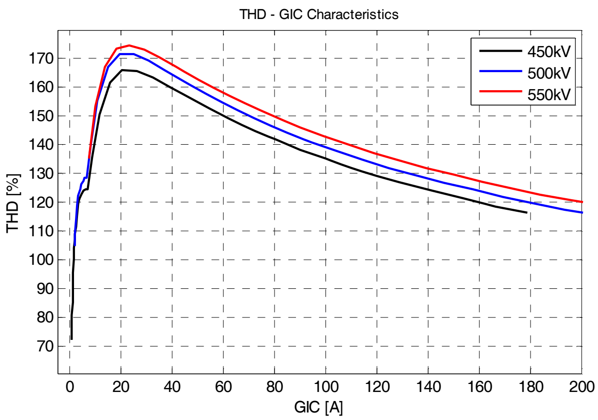

Fig. 6: Variations of THD with the transformer voltage versus GIC. Single-phase core type.

F. Validation

Validation of the modelling assumptions made in this first implementation of rtGICsim will probably benefit from a minor to moderate GMD event. Given the amount of measured information acquired by the GMD management system as well as the availability of cross-validation from direct and indirect sources of measured data, an actual GMD event will make it possible to carry out extensive validation and tune-up of the various models.

Validation efforts have also been carried out using historical data from the March 1989 GMD event. Ontario Hydro had five GIC monitors in service at the time, so it has been possible to gain a fair degree of confidence in the var loss and earth models for northern part of the network [12].

IV. CONTROL ROOM ENVIRONMENT

The effects of a GMD event on var loss take place in a much shorter time frame that the heating effects on HV transformers. The loss of reactive power follows GIC almost instantaneously, even after taking delta winding shielding effects into consideration. Consequently, during a storm peak var loss can reach very severe levels in 4-6 minutes, while transformer hot spot temperatures can take tens of minutes to reach undesirable levels. This suggests that mitigating measures aimed at managing voltage limits and system stability must be defined and implemented ahead of the storm peak, while transformer overheating allows the implementation of control actions on the basis of alarms.

Reacting to transformer alarms during a GMD event must be planned ahead of time on the basis of off-line studies. Not all mitigation measures are intuitively obvious. For instance, in the Hydro One HV network, the presence of series capacitor banks can actually make the injection of GIC into a particular transformer station worse (see Fig. 7). In general, studies for the assessment of mitigating actions under storms of any severity, point to taking key lines out of service, and in fewer cases, to remove transformers from service.

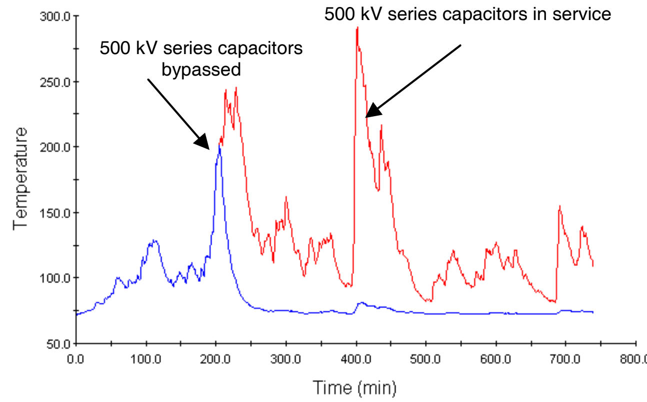

Fig. 7: Flitch plate hot spot temperature before and after mitigating measures. Scaled-up portion of the March 1989 GMD event.

The modelling complexity and volume of information produced by rtGICsim in real time is substantial. However, the amount of critical information presented to a control room operator must be distilled to two types of alarms: transformer hot spot overheating and shunt capacitor bank harmonic overloading. Of these, only transformer alarms require the execution of control actions. Shunt capacitor bank alarms only provide situational awareness. In all cases instructions are unambiguous and since there is very little time for analysis, if any, and all studies to justify the instructions must be done ahead of time. Fallback instructions, in the event that actual events do not match predicted contingencies, must also be backed up with detailed studies as well.

V. CONCLUSIONS

Simulation tools such as rtGICsim can be used for both situational awareness, operational decisions and as part of off-line system studies for the evaluation of the effects of GIC in the power system.

Off-line studies where GIC impacts are combined with load flow calculations are indispensable to develop mitigating measures in the case of severe GMD events. The time frame for GMD-triggered operational decisions is very short: in the order of 4-6 minutes. Therefore, most if not all decisions need to be defined and evaluated ahead of time.

Many of the modelling techniques used in rtGICsim have been adapted from those used in the modelling of frequency dependent lines in the EMTP and have shown to be successful in amply achieving sub-second computation cycles in the Ontario 230 kV and 500 kV network, notwithstanding the large

I/O transactions specified in this implementation of the GMD management system.

In its current implementation, a large amount of non-critical information is transferred from the computational engine to the operator's display application. Information such as the GIC flows in every circuit of the network is not necessary for the operator to carry out required control actions. Should the need to model a larger network arise (e.g., the inclusion of lower voltage networks or neighbouring systems), it would be relatively simply to accommodate the increased network size and still achieve sub-second computational cycles by simply reducing the non-critical I/O flow.

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