GIC SIMULATION USING NETWORK MODELING

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Abstract

Electromagnetic disturbances associated with geomagnetic storms can adversely affect the operation of power systems through geomagnetically induced currents (GIC) leading to transformer saturation. Under severe storm conditions, Canadian power utilities are particularly vulnerable to simultaneous system-wide transformer saturation leading to equipment damage, depressed voltage levels and unwanted tripping of relays. A significant incident in 1989 led to a voltage collapse on the Hydro-Quebec power system resulting in a complete blackout.

In order to better address this risk, a power system simulation for geomagnetically induced transformer saturation has been developed. The model comprised three components covering the induced electric field, the induced currents across a transmission network and the induced flux offset in transformers.

Analysis showed that the substations most likely to experience high GIC corresponded to where the greatest variation in overhead line conductivity in the direction of the electric field occurred, such as at the periphery of the network. Shell-type, banked single-phase, or 4/5 limb core-type transformers are the most vulnerable to high flux offsets on account of their high zero sequence magnetizing inductances, but are afforded some protection from the long inductive lag associated with high winding L/R ratios.

Preliminary model validation was undertaken using data for the Ontario transmission system. The simulation has been incorporated into the Canadian Space Weather Forecast Service, and also as a stand-alone Excel/VBA application to provide a risk assessment screening tool for Canadian power utilities.

Keywords: *Geomagnetically Induced Currents (GIC), Power System, Simulation, Transformer Saturation.*

1 Introduction

Electromagnetic disturbances associated with geomagnetic storms can adversely affect the operation of power systems by inducing slowly varying currents leading to transformer saturation. In order to better address this risk, a power system simulation was sought to extend work previously undertaken by Natural Resources Canada (NRCan), in collaboration with Canadian power utilities [1, 4-7]. The objectives of the simulation were:

- to calculate and display geomagnetically induced currents and transformer saturation levels over a transmission network
- to identify the most critical locations, conditions and data sensitivities
- be readily applicable to any Canadian power utility
- be able to be integrated into the Canadian Space Weather Forecast Service.

Simulation begins with an understanding of the physical process to be modeled.

Charged particles, emitted from the sun during solar storms, are guided by the Earth's magnetic field into regions of the upper atmosphere where they produce the aurora (northern lights) and an intense electric current in the ionosphere, called the auroral electrojet. The electrojet occupies an oval-shaped band around the magnetic pole and is typically 100 km above the surface of the earth and several hundred kilometers wide. During severe disturbances, the auroral oval expands, typically reaching 45 degrees north over North America [5].

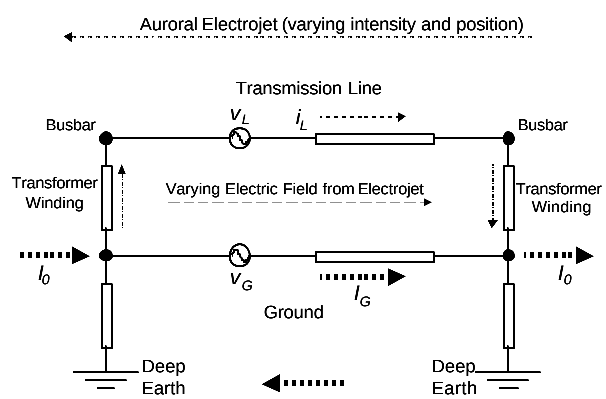

Figure 1: Induced Voltages and Currents

As the electrojet intensity and position varies it produces a varying electro-magnetic field that induces low frequency currents and voltages in conductors at the surface of the earth. Power transmission lines, in view of their high conductivity, can experience significant induced currents . At power system transformers, a proportion of this current passes to ground via the transformer windings and neutral point connections (see Figure 1). The induced currents are sufficiently slowly varying that the transformers experience them as slowly-varying d.c. currents.

Their effect therefore is to create slowly-varying uni-directional magnetic flux in the transformer core which is superimposed on the normal 60Hz pattern. Transformers are generally designed to operate on the linear part of the transformer core B-H characteristic in order to prevent the undesirable effects of magnetic flux saturation. The combination of GIC and the normal 60 Hz sinusoidal currents leads to saturation of the magnetic core during the portion of the 60Hz cycle in which both currents are in the same direction. This is called half-cycle saturation. The induced d.c. current can be considered to offset the normal operating range of the transformer by the amount of d.c. induced flux. Half-cycle saturation distorts the magnetizing current waveform producing large current peaks during the saturated portion of each cycle. The effects of half-cycle saturation include transformer hot-spots, increased reactive power consumption and the increased production of harmonics.

2 Model Description

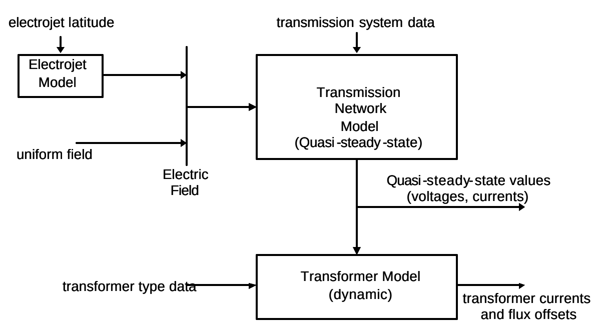

Figure 2: Model Structure

The model comprises three main analytical components covering the Electrojet Electric Field, the Transmission System and the Transformers (see Figure 2). The following initial modeling assumptions were made:

- the ground is of uniform lateral conductivity with a surface conducting layer and deep earth at 0V
- the presence of the transmission line does not effect the electric field in the ground induced
- the transmission line and the ground are sufficiently close that they experience the same induced electric field
- the electric field variations are sufficiently slowly varying that the only significant dynamic effect is the inductive lag of the transformer windings

2.1 Electric Field Model

Several options were modeled including a uniform constant electric field, a uniform rotating electric field, a uniform field based on a recorded time-series dataset, and that due to an east-west electrojet [1,6].

2.2 Transmission System Model

As GICs are low frequency, the reactance of a transmission line is sufficiently small that it can be considered as purely resistive. Hence, a transmission network can be modeled as a d.c. network of resistances, with no time lag between a change in electric field and the induced current.

2.2.1 Single Transmission Line Model

For a steady electric field **E**, the induced voltage in the transmission line is:

$$v_L = \int \mathbf{E} . \mathbf{dl}$$

where the integration is along the line-route. For the case of a uniform field, the induced line voltage equates to:

$$v_L = \mathbf{E} . (\mathbf{p}_2 - \mathbf{p}_1)$$

where $\mathbf{p}_1$ and $\mathbf{p}_2$ are the position vectors of the line end-points. As the ground and transmission line are spatially close, they experience the same electric field and thus the same induced voltage for a uniform field, i.e. $v_L = v_E$ and $v_G = v_E$. For a single straight transmission line, the induced voltage and line resistance vary in proportion with length. Thus, if the line resistances are significantly larger than the shunt resistances at the transformer neutrals, the induced current approximates to the **Long Line Current**:

$$I_L = E \ . \ s \ . \ \cos a$$

where E is the electric field strength, a is the angle between the directions of the electric field and the transmission line, and s is the unit length circuit conductivity. For two long transmission circuits with a high conductance shunt connection at their common busbar, the shunt current is approximately equal to the difference in their directional conductivities times the electric field strength, i.e.

$$I_S = E \ . \ (s_1 \ \cos a_1 - \ s_2 \ \cos a_2)$$

Thus, in an area where the line conductances are significantly less than the transformer winding conductances, the busbar shunt current is approximately equal to the electric field strength times the change in circuit conductivity in the direction of the electric field. At locations where there are relatively few transformers to share the total shunt current, a high per unit transformer current can be obtained. Hence, the periphery of a system is often the most vulnerable to high transformer shunt currents.

2.2.2 Transmission Network Analysis

Networks with branch series voltages can be analyzed by using the method of equivalent current injection. This substitution preserves the network topology, impedances and voltage pattern.

Applying this to the system in Figure 1, the induced ground voltage can be equivalenced by currents into and out of the ground connection points which exactly back off the nominal external ground current. Thus the effect of the transmission line can be considered as circulating an induced current with a ground return path.

Next, we assume that the ground resistance associated with the transformer substation grounding connections, dominates the resistance of the ground return path. Thus the shunt resistance can be considered as having two contributions due to the transformer windings and the grounding connection. Assuming further that the ground resistance is small will result in the highest transformer shunt currents.

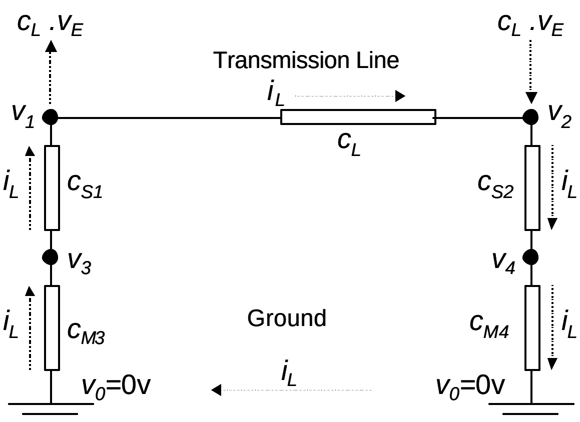

Figure 3: Equivalenced System

Now applying the equivalent current substitution to the voltage induced in the transmission line results in the single line model shown in Figure 3. This representation, with nodal current injections instead of branch series voltages is suitable for solution using standard network analysis algorithms. The method of solution is:

1. Calculate the induced series d.c. voltage in each transmission line branch due to the electric field.
2. Express the induced series voltage as equivalent nodal current sources.
3. Calculate the network admittance matrix based on component and ground resistances.
4. Calculate the induced busbar dc voltages from the equivalent nodal currents and the network admittance matrix.
5. From the busbar voltages, solve for the branch and transformer shunt currents.

2.3 Transformer Model

The flux offset in the transformer core caused by an induced d.c. winding current i is:

$$f_{OFFSET} = (L_o / N) \,.\, i$$

where L_o is zero sequence magnetizing inductance and N is the number of turns on the winding. The per unit (p.u.) value of L_o varies enormously with transformer type [2], with the key attribute being whether there is an iron path for d.c.-induced flux:

- Shell-type, banked single-phase, or 4/5 limb core-type transformers contain an iron path for d.c.-induced flux. These can have zero sequence magnetizing inductances of 100-1000pu, making them vulnerable to significant flux offset. However, their long inductive lag time-constant (L_o/R ~ 140-270 seconds) attenuates flux levels due to higher-frequency geomagnetic disturbances. To accommodate this effect, the transformer is modeled as a steady-state characteristic with a first-order lag.
- Three-limb core-type transformers do not contain an iron path for d.c.-induced flux. These have zero sequence magnetizing impedances around 1 pu, and are generally not vulnerable to significant flux offset. Their inductive lag time-constant is generally around 3 seconds.

Flux-offset contributions can potentially come from either winding of a transformer, for instance:

- Grounded-Wye/Delta : No d.c. current in delta windings, only the HV windings contribute
- Grounded-Wye/Grounded-Wye: The HV winding contribution is generally dominant as LV d.c. current is generally less due to a higher resistive system, and with fewer turns.
- Transmission Auto-transformer: Contributions to flux offset from both windings need to be considered as both the d.c. currents and the number of turns on the series and common windings are similar, i.e.

$$f_{OFFSET} = L_o \,.\, \left((i / i_R)_{COMMON} + .(i / i_R)_{SERIES} \right)$$

where L_o is the per unit (pu) magnetizing inductance and i_R is the rated peak current.

3 Implementation and Validation

The simulation was initially implemented as a FORTRAN program and a series of IDL macros for time-series and dynamic analysis. Particular effort was put into ensuring that the data interface was compatible with typical industry-standard formats, and that the results could be displayed on a geographic power network diagram. It was incorporated as a real-time GIC simulator within the Canadian Space Weather Forecasting Centre in Ottawa. Subsequently, the simulation was implemented as an Excel/VBA application with a view to providing a risk assessment screening tool for Canadian power utilities (see Figures 4). Of particular value was its ability to produce an ordered list of the most vulnerable transformers across a network.

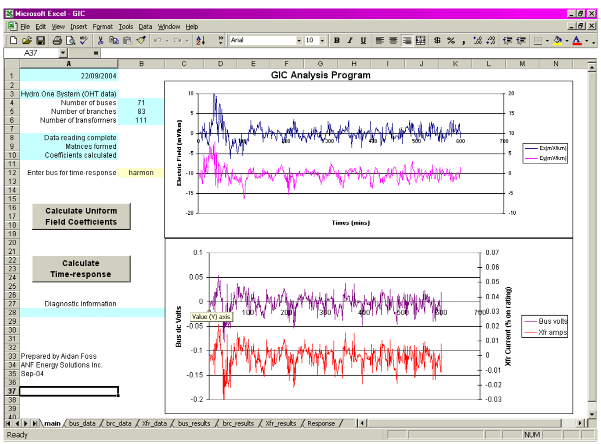

Figure 4: Excel/VBA Risk Assessment Tool

The model was initially exercised using data for the Ontario 500/230kV transmission system supplied by Ontario Hydro Technologies [2]. Preliminary model validation was undertaken by comparing measured and modeled transformer d.c. currents at four locations across Ontario during the geomagnetic storms of 22/23 September 1999 and 21/22 October 1999 [3]. Ongoing validation of the simulation is currently in progress in association with Hydro One [8].

4 Conclusions

A power network simulation for geomagnetically induced currents and transformer saturation has been developed and implemented. The simulation has been incorporated into the Canadian Space Weather Forecast Service, and also as a stand-alone Excel/VBA application to provide a risk assessment screening tool for Canadian power utilities.

Analysis showed that the substations most likely to experience high GIC corresponded to where the greatest variation in overhead line conductivity in the direction of the electric field occurred, such as at the periphery of the network. Shell-type, banked single-phase, or 4/5 limb core-type transformers are the most vulnerable to high flux offsets on account of their high zero sequence magnetizing inductances due to a complete an iron path for d.c.-induced flux. However, the long inductive lag associated with high winding *L/R* ratios attenuates the flux offset levels from higher-frequency geomagnetic disturbances.

Preliminary model validation was undertaken using data for the Ontario 500/230kV transmission system, and is currently in progress in association with Hydro One.

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