Integration of Geomagnetic Disturbances (GMDs) Modeling into the Power Flow

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Overview

• Geomagnetic disturbances (GMDs) have the potential to severely disrupt operations of the electric grid, yet power engineers currently have few tools to help them assess the impact of GMDs on their systems.

• Goal of the this work is to perform the research necessary to help move GMD assessment into the realm of power system planning and operations engineers.

• Guiding motto: “All models are wrong but some are useful,” George Box, 1979
  
  — GIC impact is certainly still an area of research, but power engineers need tools to consider its impact on their systems.
My Background in GMD

• My interest comes from PSERC’s DOE funded “The Future Grid to Enable Sustainable Energy Systems” project
• In June 2011 I attended the JASON GMD briefing
  — Realized GMD calculations could added to power flows
• Implemented these calculations in PowerWorld Simulator while working there full-time in summer 2011
• Presented results in November 2011 at NERC’s Geo-Magnetic Disturbance Task Force; based on feedback changed GMD modeling approach
• NERC Interim GMD Report issued in late Feb 2012
• In 2012 started EPRI large-scale system study and also working with several other utilities for studies
Solar events can cause changes in the earth’s magnetic field (i.e., dB/dt). These changes in turn produces an electric field at the surface.

- Changes in the magnetic flux are usually expressed in nT/minute; from a 60 Hz perspective they produce an almost dc electric field.
- 1989 North America storm produced a change of 500 nT/minute, while a stronger storm, such as the one in 1921, could produce more than 5000 nT/minute variation.
- Storm “footprint” can be continental in scale, for example covering much of the U.S.
- For reference, Earth’s magnetic field is normally between 25,000 and 65,000 nT, with higher values near the poles.

Electric Fields and Geomagnetically Induced Currents (GICs)

- As described by Faraday’s law, changes in the magnetic flux intensity produce a (non-uniform) electric field on the surface; values are impacted by ground conductivity
  - Electric fields are vectors with a magnitude and direction; values are usually expressed in units of volts/mile (or volts/km);
  - A 2400 nT/minute storm could produce 5 to 10 volts/mile.
- The electric fields cause geomagnetically induced currents (GICs) to flow in electrical conductors such as the high voltage transmission grid.
- From a modeling perspective, the induced voltages that drive the GICs can be modeled as dc voltages in the transmission lines.
- The magnitude of the dc voltage is determined by integrating the electric field variation over the line length.
Geomagnetically Induced Currents (GICs)

Earlier approach modeled GMD impact as DC voltage sources in the ground. The newer approach models them as DC sources in the transmission lines.

With pertinent parameters specified, the calculation of the GICs is a straightforward, linear calculation.
The dc GICs are superimposed upon the ac currents. In transformers this can push the flux into saturation for part of the ac cycle. This can cause large harmonics; in the positive sequence (e.g., power flow and transient stability) these harmonics can be represented by increased reactive power losses on the transformer.
Mapping Transformer GICs to Transformer Reactive Power Losses

• Transformer specific, and can vary widely depending upon the core type
  — Single phase, shell, 3-legged, 5-legged
• Ideally this information would need to be supplied by the transformer owner
  — Currently support default values or a user specified linear mapping
• For large system studies default data is used when nothing else is available. Scaling value changes with core type
• Still debate in the industry with respect to the magnitude of damage GICs would cause in transformers (from slightly age to permanently destroy)
The Impact of a Large GMD From an Operations Perspective

- There would be a day or so warning but without specifics on the actual magnitude
- It could strike quickly (they move at millions of miles per hour) with rises times of less than a minute, rapidly covering a good chunk of the continent
- Reactive power loadings on hundreds of transformers could sky rocket, causing heating issues and potential large-scale voltage collapses
- Power system software like state estimation could fail
- Control room personnel would be overwhelmed
- The storm could last for days with varying intensity
- Waiting until it occurs to prepare might not be a good idea

GMD Enhanced Power Analysis Software

• By integrating GIC calculations directly within power analysis software (like power flow) power engineers can readily see the impact of GICs on their systems, and consider mitigation options.

• GIC calculations use many of the existing model parameters such as line resistance. But some non-standard values are also needed; power engineers would be in the best position to provide these values, but all can be estimated when actual values are not available.
  
  - Substation grounding resistance, transformer grounding configuration, transformer coil resistance, whether autotransformer, whether three-winding transformer, generator step-up transformer parameters.
With knowledge of the pertinent transmission system parameters and the GMD-induced line voltages, the dc bus voltages and GIC flows can be calculated by solving a linear equation

\[ I = G V \]

- The G matrix is similar to the \( Y_{bus} \) except 1) it is augmented to include substation neutrals, and 2) it is just conductances
- The current vector contains the Norton injections associated with the GMD-induced line voltages

Factoring the sparse G matrix and doing the forward/backward substitution takes about 1 second for the 62,600 bus Eastern Interconnect Model
Four Bus Example

\[ I_{GIC,3Phase} = \frac{150 \text{ volts}}{(1 + 0.1 + 0.1 + 0.2 + 0.2) \Omega} = 93.75 \text{ amps or 31.25 amps/phase} \]

The line and transformer resistance and current values are per phase so the total. Substation grounding values are total resistance. Brown arrows show GIC flow.
Determining GMD Storm Scenarios

• The starting point for the GIC analysis in the power flow is an assumed storm scenario; this is used to determine the transmission line dc voltages

• Matching an actual storm can be complicated, and requires detailed knowledge of the associated geology

• Feb 2012 NERC report recommended for planning purposes a similar approach could be used
  – Uniform electric field: All locations experience the same electric field; induced voltages in lines depend on assumed direction
  – Maximum value in 1989 was 1.7 V/km (2.7 V/mile)

• We also consider a more detailed non-uniform model
  – Non-uniform electric field: Magnitude of electric field varies according a some function; induced voltages in lines depend on magnitude and assumed direction
Basecase loading is 4700 MW and 1800 Mvar. Transmission voltages are 345 and 500 kV.
Assumed Geographic Location
(Mostly East-West)
GIC Flows with a 1V/km North-South, Uniform Electric Field

Total GIC Losses 528.9 Mvar
GIC Flows with a 1V/km East-West, Uniform Electric Field

Total GIC Losses 758.3 Mvar

The GIC losses are higher with an east-west field since the system mostly goes in that direction.
GIC Flows with a 2V/km East-West, Uniform Electric Field

Total GIC Losses 1474.9 Mvar
GIC Flows with a 2.2V/km East-West, Uniform Electric Field – Approaching Voltage Collapse

Total GIC Losses 1587.5 Mvar
Power Flow Convergence Issues

• Integrated GIC modeling can certainly impact power flow convergence since the GIC induced reactive power losses simultaneously add lots of reactive power.

• Several techniques can help prevent divergence
  – Just calculating the GICs without solving the power flow
  – Not calculating GMD induced voltages for equivalent lines
  – Gradually increasing the assumed electric fields to avoid simultaneously adding too much reactive power
  – Only calculating the GIC transformer reactive power losses for specified areas; reactive power doesn’t travel far
  – Freezing the transformer taps and switched shunts in certain problematic areas
  – Solving in transient stability
Large System Example, Varying Electric Field Magnitude; Max of 4 volts/mile
Voltage Contour with No GIC
Voltage Contour with a 4 Volt/Mile Field GIC
Summary

• Tools now exist to allow the impact of GMDs to be considered as part of the power system planning process
  — Impacts and mitigation strategies can be studied
  — Study results can be used to determine location of GIC monitoring equipment
  — Operations personnel can become familiar with how GICs may propagate through their system, and impact the operating state

• Like many aspects of power systems, this is an area of active research with improved models and understanding coming in the future
Thank You!

Questions?