System Planning Studies to Determine Impacts of Geomagnetic Disturbances

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Overview

• GMDs have the potential to severely disrupt operations of the electric grid, yet power engineers have had few tools to help them assess the impact of GMDs on their systems

• This presentation will show a tool to calculate the impact of GMDs on the power grid in the power flow time frame, and then show example study results

• Input is an assumed electric field variation, the tool then calculates the geomagnetically induced quasi-dc currents (GICs), and then (optionally) solves the power flow including the impact of the GICs on transformer’s reactive power consumption
Geomagnetically Induced Current (GIC)

The impact of the electric field variation is modeled as dc voltages superimposed on the transmission lines. The GIC calculation then just involves solving a linear dc circuits problem.

\[ V_{dc} = \oint \vec{E} \cdot d\vec{l} \]
Four Bus Example

\[
I_{GIC,31} = \frac{150 \text{ volts}}{1 + 0.1 + 0.1 + 0.2 + 0.2} = 93.75 \text{ amps or } 31.25 \text{ amps/phase}
\]

The line and transformer resistance and current values are per phase so the total resistance is 1/3 this value and total line current is 3 times this value. Substation grounding values are total resistance. Brown arrows show GIC flow.
A GMD-enhanced Power Flow

• 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 auto-transformer, whether three-winding transformer, generator step-up transformer parameters
GIC G-Matrix

• With knowledge of the pertinent transmission system parameters and the GMD-induced line voltages, the dc bus voltages and flows are found by solving a linear equation

\[ \mathbf{I} = \mathbf{G} \mathbf{V} \]

– The G matrix is similar to the \( \mathbf{Y}_{\text{bus}} \) except 1) it is augmented to include substation neutrals, and 2) it is just resistive values (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
GMD-enhanced Power Flow Simulations

• Results presented here were calculated using PowerWorld Simulator with the GIC add-on
• GIC model is determined with 1) data from the power flow such as system topology, transmission line resistance, and series capacitor locations, 2) estimates/user entered data for GIC specific fields such as transformer coil resistance, transformer grounding/whether it is an auto-transformer, and substation grounding resistance
• GIC flows can be calculated independently or as part of an integrated power flow solution
• A number of options are included for improved power flow solution with high levels of GIC induced reactive losses
Goal: To Integrate GMD Assessment into Planning Process

• Overall goal is to make GMD assessment a standard part of the power system planning process
  – Ignorance is not bliss
  – The amount of risk can be assessed, and appropriate plans, including operating procedures, can be developed
  – Initial plans may involve the installation of monitoring equipment at locations identified by studies as having high GMD potential
• Tools could also help operations engineers better understand GIC flows
• Tools to do this exist now!
• “All models are wrong but some are useful” George Box, 1979
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 rise 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
Parameter Sensitivity: Changing Four Bus Assumed Substation R from 0.2 to 0.1 Ω

\[ I_{GIC,3Phase} = \frac{150 \text{ volts}}{\left(1 + 0.1 + 0.1 + 0.1 + 0.1\right) \Omega} = 107.1 \text{ amps or 35.7 amps/phase} \]

In this example the GIC flow calculation is mostly dominated by the resistance of the 765kV line.
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
• Transformer reactive power losses are modeled as a shunt reactive current (i.e., the reactive power losses vary linearly with the bus voltage)
Changing Assumed Transformer Mapping in Four Bus Example

• Mapping for left transformer was changed from 1 to 0.5, matching value for the right transformer
Determining GMD 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; line voltages depend on assumed direction
  – Maximum value in 1989 was 1.7 V/km (2.7 V/mile)

• We will also consider a non-uniform model
Integrated Geographic Information

• The potentially time-varying GMD induced dc voltages are determined by knowing the latitude and longitude of the transmission lines
  – Just knowing the geo-coordinates of the terminal buses should be sufficient
• Hence buses need to be mapped to substations, and substations to their geo-coordinates
• Note, the numbers assigned to buses can vary from case to case
• Assigning a bus to the wrong substation can result in significant dc voltage errors!
Basecase loading is 4700 MW and 1800 Mvar. Transmission voltages are 345 and 500 kV.

Contour shows the ac, per unit bus voltage magnitudes
Assumed Geographic Location (Mostly East-West)
GIC Flows with a 1V/km East-West, Uniform Electric Field

The GIC losses are higher with an east-west field since the system mostly goes in that direction.

Total GIC Losses 758.3 Mvar
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
GIC Flows with a 2.22V/km East-West, Uniform Electric Field – On Verge of Voltage Collapse

Total GIC Losses 1598.3 Mvar
Getting Access to the Results

• GIC studies involve the traditional power system results (voltages, flows, etc.), along with a new set of variables such as
  – Estimated parameters, such as substation grounding and transformer coil resistance
  – Substation neutral dc voltages
  – Bus dc voltages
  – GIC flows in branches
  – GIC induced reactive power losses in transformers

• Providing easy access to the results/data is key to making the solution transparent, as is good wide-area visualization
### Example of Power Flow List with DC GIC Flows

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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
Determining Mitigation Strategies

- With the ability to simulate the impact of GICs on the power system, mitigation strategies can be studied.
- Planning horizon (long-term) options might include the installation of monitoring equipment and/or GIC reduction devices (such as capacitors in the transformer neutral).
- Operations horizon (short-term) options could include generation re-dispatch to reduce voltage collapse vulnerability, and/or selectively opening devices to reduce the GICs.
EPRI 20 Bus Example: GIC Reduction at Substation 6: Blocking One Generator

Total GIC Losses 1555.5 Mvar

When only one generator is blocked the reactive losses are only reduced slightly, from 1587 to 1555 Mvar.
Reactive power losses are substantially reduced when the GICs at both generators are blocked.
EPRI 20 Bus Example: GIC Reduction at Substation 4: Increases GIC Losses at Sub 3

Blocking all four transformers at Sub 4 does reduce the Mvar losses slightly but increases them at Sub 3 (from 200 to 256 Mvar)
The total reactive power losses can be changed operationally by opening various devices.

Green arrows show the direction of real power flow.
EPRI 20 Bus Example: GIC Reduction by Operational Mitigation: Redispatch, Open Sub 5

GIC losses are reduced by redispatching 400MW to right side, and opening the Sub 5 transformers.
Large Case Examples: MMWG Case

• The next slides demonstrate GIC calculations on a large example, using the 62,605 bus MMWG 2010 Series Summer 2012 Peak Case

• Results presented here use estimated values for GIC specific fields (i.e., those not in the power flow case)

• Therefore results presented here are for educational purposes only and do NOT represent an engineering study about the response of the actual system
  – We are involved in doing these studies, but are not presenting the results here
  – Part of this study process is determining the actual GIC specific fields, like substation grounding, transformer coil resistance, and mapping GICs to transformer Mvar losses
Large Case General Observations

- High GICs in transformers tend to appear at locations of network “discontinuities” because the GICs from lines in one direction tend to be canceled by those in the other direction.

In 345/138 kV sub on left about 242 amps are coming in from the east, yet only 46 amps are going to neutral in the two auto transformers.

Images blurred for confidentiality.
High Transformer GICs at Network Discontinuity for an East-West field

- Below image shows an example of a “source” substation for an east-west field. A total of 195 amps are coming up from ground into the transformers, while 215 amps are exiting (20 amps are coming into the sub)
Location is Not a Discontinuity for an North-South Field

- Image shows same substation, but now for a north-south field it is no longer a source (52.5 amps are coming into the sub and 54 amps are going out; 8.2 are coming up from ground on the 138 kV and 6.8 amps into ground at 345kV)
Large System Study Fields and GICs

• The determination of the GICs themselves just requires solving a linear system, so it is fast, even for large systems
  – Takes about 1 second for the 62,000 bus MMWG when matrix must be factored, much faster if not
• Solving the power flow, with high reactive power loadings, is another matter
• Therefore limiting the locations in which the GICs are calculated can be helpful
  – A uniform field across the entire grid would be unrealistic
• Also, limiting regions in which GIC losses are calculated can be helpful
These flows are relatively easy to calculate, but studying such a GMD is probably not that realistic.
ATC Footprint Example

• Next several slides provide an “educational” example considering the GMD impacts on the ATC System (primarily much of Wisconsin and Northern Michigan)
  – Again, since many values are defaults this should not be considered to be an actual, engineering study

• A uniform electric field is considered over the ATC footprint; in an actual study a number of directions could be considered. Here we just consider an 4.0 volt/mile east-west field.

• GICs will scale linearly with the assumed field magnitude; transformer reactive power losses are mostly linear; system ac voltages will be non-linear
Wisconsin GICs; Contour Shows Assumed Electric Field Magnitude; max of 4 volts/mile
Transformer GICs and Mvar Losses

• For simplicity the transformer Mvar losses were just calculated for the areas in the ATC footprint; highest transformer neutral currents were mostly along Lake Michigan.
Voltage Contour with No GIC
Voltage Contour with a 4 Volt/Mile Field GIC
Voltage Contour with a 4 Volt/Mile Field GIC Bus
Now Including ComEd GIC Induced Mvars

Including GIC reactive power losses in ComEd increases WEC’s reactive generation from 853 to 941 Mvar
Blocking the two GSUs with the highest GICs did reduce reactive consumption, but also transferred much to a nearby generator.
Zoomed View of Blocking Area
Blocking Just the GSUs at One Substation
Blocking All Transformers at Both Substations

WEC’s reactive power generation is reduced by 60 Mvar, while WPS’s does not change significantly; GIC flows are partially reduced and partially diverted.
A Large System Study Procedure

- To rapidly determine areas of particular concern, an interconnect can be studied with a uniform field, just solving the linear GIC equations
  - Different electric field magnitudes could be used for different geographic regions
- Transformers with high GICs can be identified, with more detailed studies conducted in those areas
- Results are direction dependent, but varying direction in 30 degree increments is probably sufficient (0 to 150 degrees)
- “Discontinuities” are certainly not just associated with bodies of water
Central US Example: NE 4 Volt/Mile Field
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?
Together…Shaping the Future of Electricity