Assessing and Mitigating the Risk of Carrington-Type Events with PowerModelsGMD.jl

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Motivation: Risk of GMDs to the Bulk Power System

Figure 1: Loss of power leads to industrialized nations becoming failed states[1]

- Geomagnetic Disturbances (GMDs) resulting from solar events can have adverse imparts on the bulk electric system by causing geomagnetically induced currents (GICs)
- Impact could be blackouts or destruction of grid components with long lead times such as large power transformers (LPTs)
- Will civilization collapse?
- Do you need to keep your electronics in a Faraday box?

[1] https://en.m.wikipedia.org/wiki/File:Ajdabiya_technical_-_Flickr_-_Al_Jazeera_English.jpg

How do GMD Events Work?

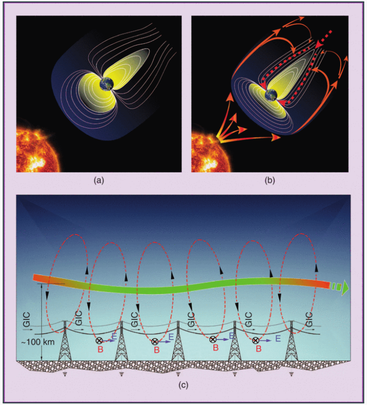


Figure 2: (a) Earth's normal magnetosphere, (b) Earth's substorm magnetosphere, and (c) The electrojet current (green arrow) producing a magnetic field (B) and inducing a geoelectric field (E) on power network. This generates a flow of geomagnetically induced current (GIC) in transmission lines. (Courtesy of Hydro-Québec.) [1]

- Coronal mass ejection (CME) results in a flow of charged particles above the surface of the Earth
- This flow results in a changing magnetic field
- Changing magnetic field in turn results in low-frequency electric field at the surface of the Earth
- This electric field couples into electric transmission lines

What do These Fields Look Like?

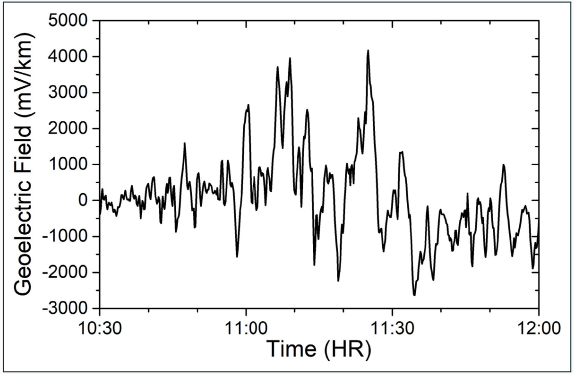


Figure 3: Ground electric field magnitude on 13 March 1989 [2]

- Magnetic field variation at the Earth's surface has significant content from 10^{-5} to 1 Hz
- The Earth behaves as a high-pass transfer function in terms of the relationship between the magnetic and electric fields at the surface
- The significant frequency content in the electric field is still significantly lower compared to the electrical time constants within a power transmission system - this will be important later

How do GMD Events Impact Electric Power Systems?

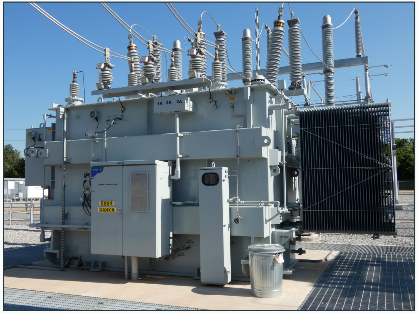
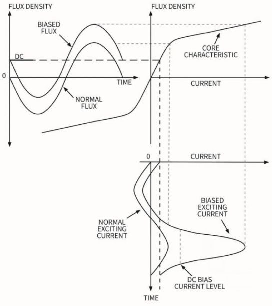


Figure 4: Large power transformer[a]

[a] https://commons.wikimedia.org/wiki/File:Substation_Power_Transformer_1.jpg



- Silicon steel is expensive so large power transformers operate at the edge of saturation
- Quasi-dc currents will push transformers into half-cycle saturation
- This causes harmonic current injection plus an increased current at the fundamental frequency *90 degrees out of phase with the voltage*
- Ultimate result is increase in reactive power draw

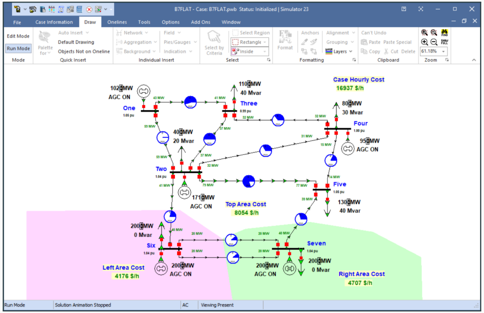


Figure 5: PowerWorld Simulator B7Flat Case[a]

- SPICE-type software isn't suitable for analysis of multiconductor power systems
- Calculating impedances for multiconductor lines is non-trivial

- Types of solvers
  - Transient (EMTP)
  - Steady-state
    - balanced (positive-sequence)
    - unbalanced
  - Dynamic - positive-sequence power flow with generator/load dynamics
- Types of problems
  - Load flow
  - Optimal power flow
  - Maximum loadability
  - Optimal transmission switching

[a] https://www.powerworld.com/training/quick-start-guides

GMD Analysis/Mitigation Workflow

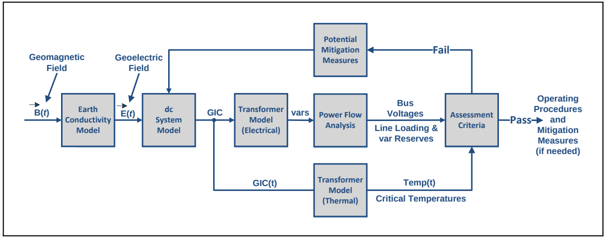


Figure 6: NERC GMD assessment procedure[1]

1. Generation of the dc network given the ac network
2. Line coupling calculations to determine the induced voltages along transmission lines
3. Calculations of the "effective" GICs (I_{eff}) on transformers
4. Calculations of the transformer reactive power losses (q_{loss})
5. Solving the ac power flow problem.
6. Applying mitigation

Depending on the problem specification, some steps may be coupled (typically 3 – 5)

[1] "Application Guide: Computing Geomagnetically-Induced Current in the Bulk-Power System," NERC, 2013. [Online]. Available: `https://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx`

AC and DC Representation for GMD Analysis

Conventional power systems problems can use positive-sequence representation:

- AC load flow (PF)
- Optimal power flow (OPF)
- Optimal line switching (OTS)
- Maximum loadability (MLD)

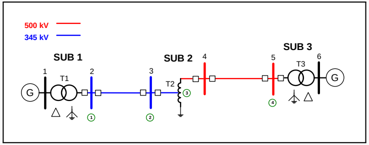


Figure 7: B6GIC ac positive-sequence representation[3]

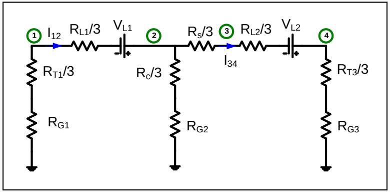


Figure 8: BGIC quasi-dc representation[3]

Modeling GICs requires a multi-network representation as the physics of GICs are different from ac power flow:

- Similar to the zero-sequence representation of the ac network but only real-valued
- Inductances assumed short-circuits, capacitances assumed open-circuits

[3] "Application Guide: Computing Geomagnetically-Induced Current in the Bulk-Power System," NERC, 2013. [Online]. Available: https://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx

Why Use Transformer Neutral Blockers?

Options for mitigation include:

- Load-shedding
- Transmission line switching
- Generating switching and re-dispatch
- Shunt/series capacitor switching
- Transformer neutral blocking devices

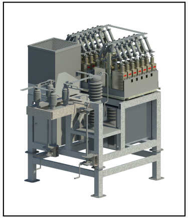


Figure 9: GIC blocker construction[4]

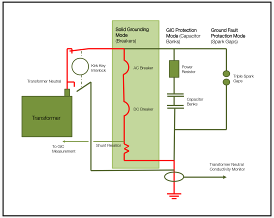


Figure 10: GIC blocker schematic[4]

- Neutral blockers do not reduce the power-carrying capacity of the grid
- But...not guaranteed to reduce GICs to zero so 100% placement doesn't guarantee feasbility
- Forcing GICs to zero will require series capacitors

[4] ABB Tech Rep. 2GNM110098

PowerModelsGMD.jl

Analysis

- GIC
- GIC $\rightarrow$ AC-PF
- GIC $\rightarrow$ AC-OPF
- GIC $\rightarrow$ AC-OPF time-extended
- GIC $\rightarrow$ AC-MLD
- GIC $\rightarrow$ AC-Cascade
- GIC + AC-PF
- GIC + AC-OPF
- GIC + AC-MLD

Mitigation

- GIC + AT-OTS
- GIC + AC-OTS time-extended
- GIC + AC-MLD blocker placement

Formulations

- ACP
- SDP
- SOC

Solvers

- JuMP Interface
- Matrix Solve

PowerModelsGMD.jl Data Model

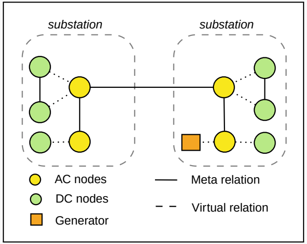


Figure 11: Relationship between and and dc components [3]

GIC Quasi-DC Components

- GMD Bus
- GMD Branch
- Transformer Neutral Blocker

AC Components

- Bus
- Branch
  - Transmission Line
  - Transformer
  - Three-Winding Transformer
  - HVDC Line
  - Switch
- Generator
- Load

PowerModelsGMD.jl Data Inputs

Extended MatPower

- MatPower format contains tables for Buses, Branches, Generators
- Add additional tables for DC network: GMD Buses, GMD Branches, Transformer winding configurations

RAW + GIC

- CSV-like format with multiple tables concatenated into a single file
- Developed by PSS/E
- RAW - AC components: Buses, Transmission Lines, Transformers, Three-Winding Transformers, Generators, Loads, HVDC Lines
- GIC - Supplementary information: Substations, Bus-Substation mapping, Transformer winding configurations
- GIC doesn't provide the dc equivalent circuit, this is constructed on the fly

GIC Data Input

```
GICFILEVRSN=3
1,'Sub A',0, 40.0000,-89.0000,   0.200,''
2,'Sub B',0, 40.0000,-87.0000,   0.200,''
0 / End of Substation data, Begin Bus Substation Data
1,1
2,2
3,1
4,2
0 / End of Bus Substation Data, Begin Transformer Data
1,3,0,' 1',  0.3000,  0.1000,  0.0000,0,0,0,'YNd0        ', 1,  1.1023,0,0,0,0
2,4,0,' 1',  0.3000,  0.1000,  0.0000,0,0,0,'YNd0        ', 1,  1.1023,0,0,0,0
0 / End of Transformer Data, Begin Bus Fixed Shunt Data
0 / End of Bus Fixed Shunt Data, Begin Branch Data
1,2,' 1',0, ,
0 / End of Branch Data, Begin User Earth Model Data
0 / End of User Earth Model Data
Q
```

Finally...An Analysis!

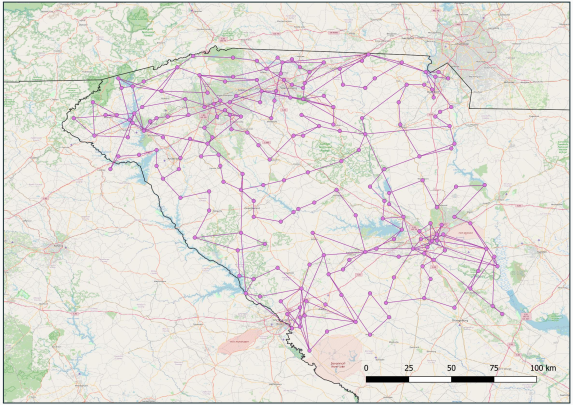


Figure 12: ACTIVSg500

- Consider the ACTIVSg500 case[a]
- 10V/km East-West uniform field
- Screening criterion: how many transformers have neutral currents over 100 A?
- Analysis: run matrix-based solve assuming ac voltages near 1.0 pu

[a] https://smartgridcenter.tamu.edu/research/electric-grid-test-case-repository/

Results

```
julia> df[1:20,:]
20×5 DataFrame
 Row │ index  f_bus  t_bus  ieff      qloss
     │ Int64  Int64  Int64  Float64   Float64
─────┼─────────────────────────────────────────
   1 │   550    372    371  237.502   155.822
   2 │   507    176    175  223.789   147.311
   3 │   598    497    496  215.111    56.7195
   4 │   541    319    318  190.938    50.3456
   5 │   470      9      7  182.687   120.425
   6 │   471      9      7  182.687   120.425
   7 │   525    250    246  178.906   118.08
   8 │   524    250    246  171.24    113.02
   9 │   588    458    457  168.449    44.0469
  10 │   477     24     23  109.073    71.9092
  11 │   590    465    464  105.235    69.4771
  12 │   535    275    274  104.135    27.3585
  13 │   597    494    493  101.712    26.7216
  14 │   489     82     80   97.925    64.8499
  15 │   561    396    386   84.5904   55.7847
  16 │   492    126    123   84.1744   55.5832
  17 │   478     40     39   79.6352   52.5184
  18 │   499    147    146   79.2606   52.0107
  19 │   599    498    496   78.9331   20.7225
  20 │   494    128    123   78.9135   52.1092
```

Figure 13: ACTIVSg500

- 131 total transformers
- Look at the top 20 transformers
- 13 transformers over 100 A
- This is a typical - less than 10% of transformers affected

References

Sebastien Guillon, Patrick Toner, Louis Gibson, and David Boteler.
A colorful blackout: The havoc caused by auroral electrojet generated magnetic field variations in 1989.
IEEE Power and Energy Magazine, 14(6):59–71, 2016.

David H Boteler, Risto J Pirjola, and Luis Marti.
Analytic calculation of geoelectric fields due to geomagnetic disturbances: A test case.
IEEE Access, 7:147029–147037, 2019.

Hongwei Jin, Prasanna Balaprakash, Allen Zou, Pieter Ghysels, Aditi S Krishnapriyan, Adam Mate, Arthur Barnes, and Russell Bent.
Physics-informed heterogeneous graph neural networks for dc blocker placement.
arXiv preprint arXiv:2405.10389, 2024.

Questions?

Github Repo: `http://github.com/lanl-ansi/PowerModelsGMD.jl`