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Title: GMD Coupling to Power Systems and Disturbance Mitigation

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GMD Coupling to Power Systems and Disturbance Mitigation

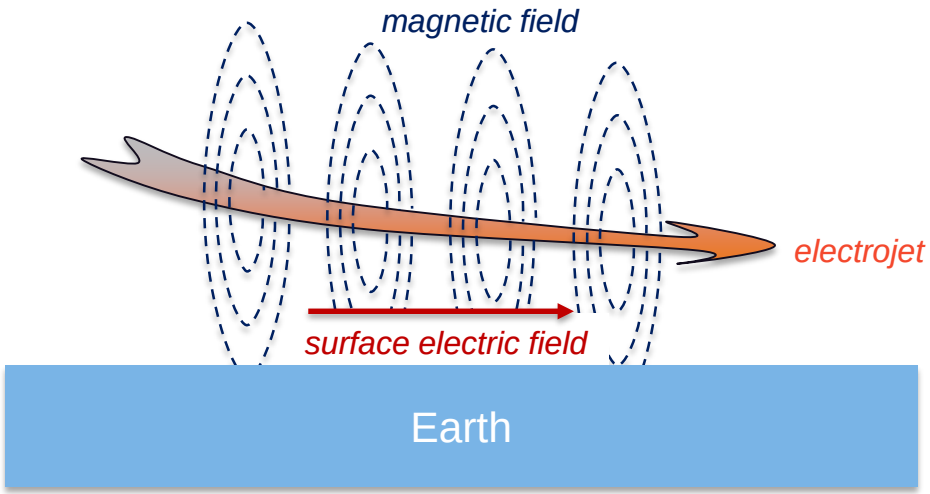
Michael K. Rivera

Russell Bent

Jan. 25, 2018

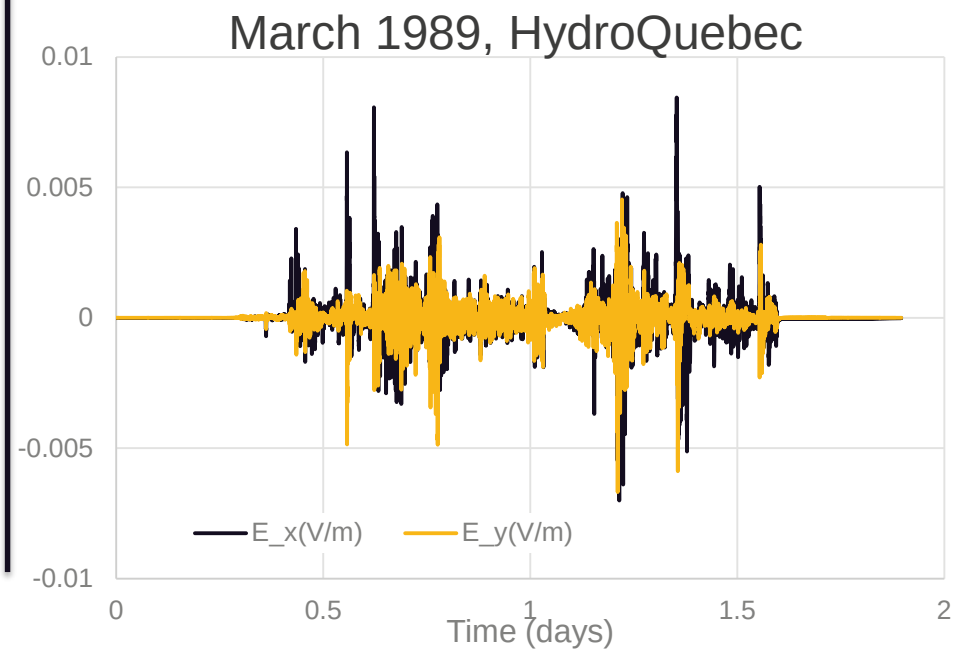
Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

Geomagnetic Disturbance: Ground Fields

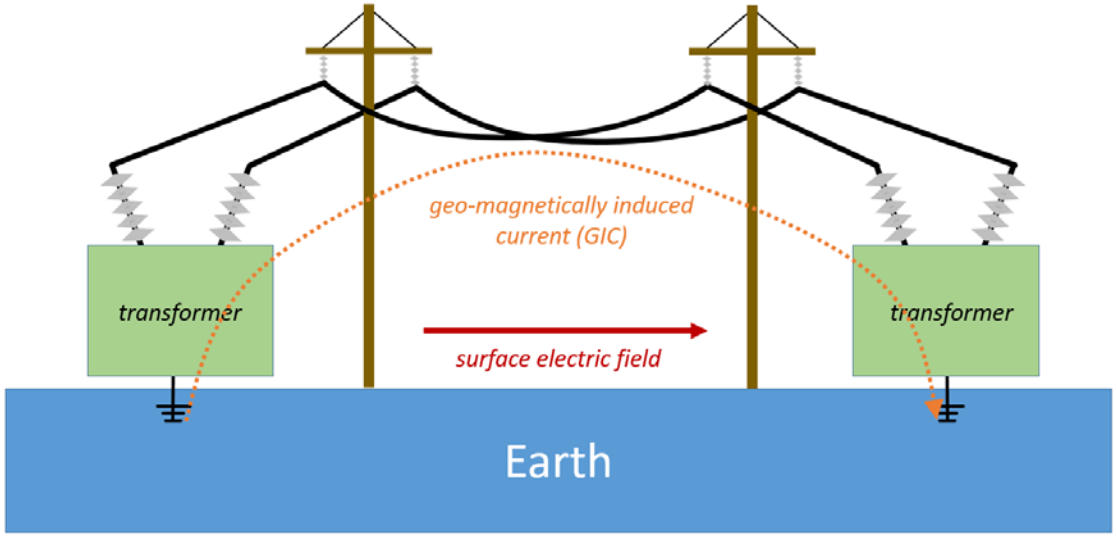


Fluctuations in the current within the electrojet cause changes in the magnetic field at the ground. This induces electric fields at the surface of the earth.

The electric fields tend to be weak, but can build up to significant voltage differences over long distances.



Geomagnetic Disturbance: Coupling to Bulk Electric System

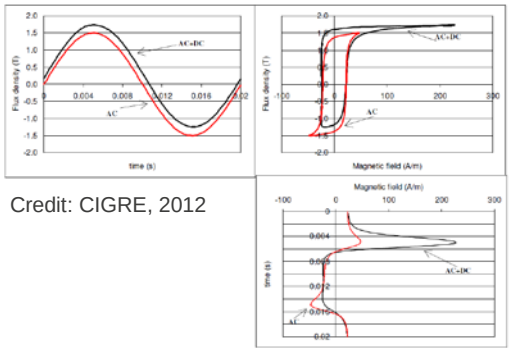


Systems that are grounded and connected by long conductive lines, such as transformers, will couple to the surface electric field generated by the GMD and experience a DC current flowing through the ground connection.

Geomagnetic Disturbance: Transformers

DC currents flowing through transformer neutrals have deleterious effects on transformers

Transformer Saturation



Credit: CIGRE, 2012

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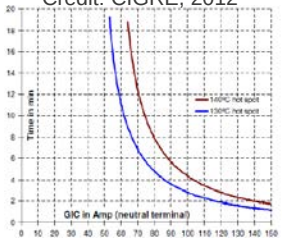
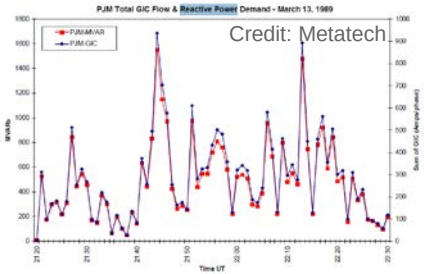
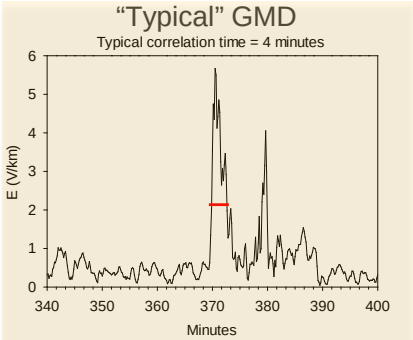


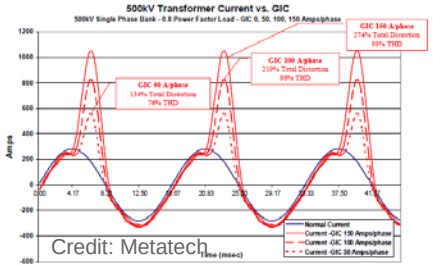
Transformer heating—degradation and potential failure–several minutes



Credit: Metatech

Increased transformer VAR consumption—potential voltage collapse—seconds→minutes



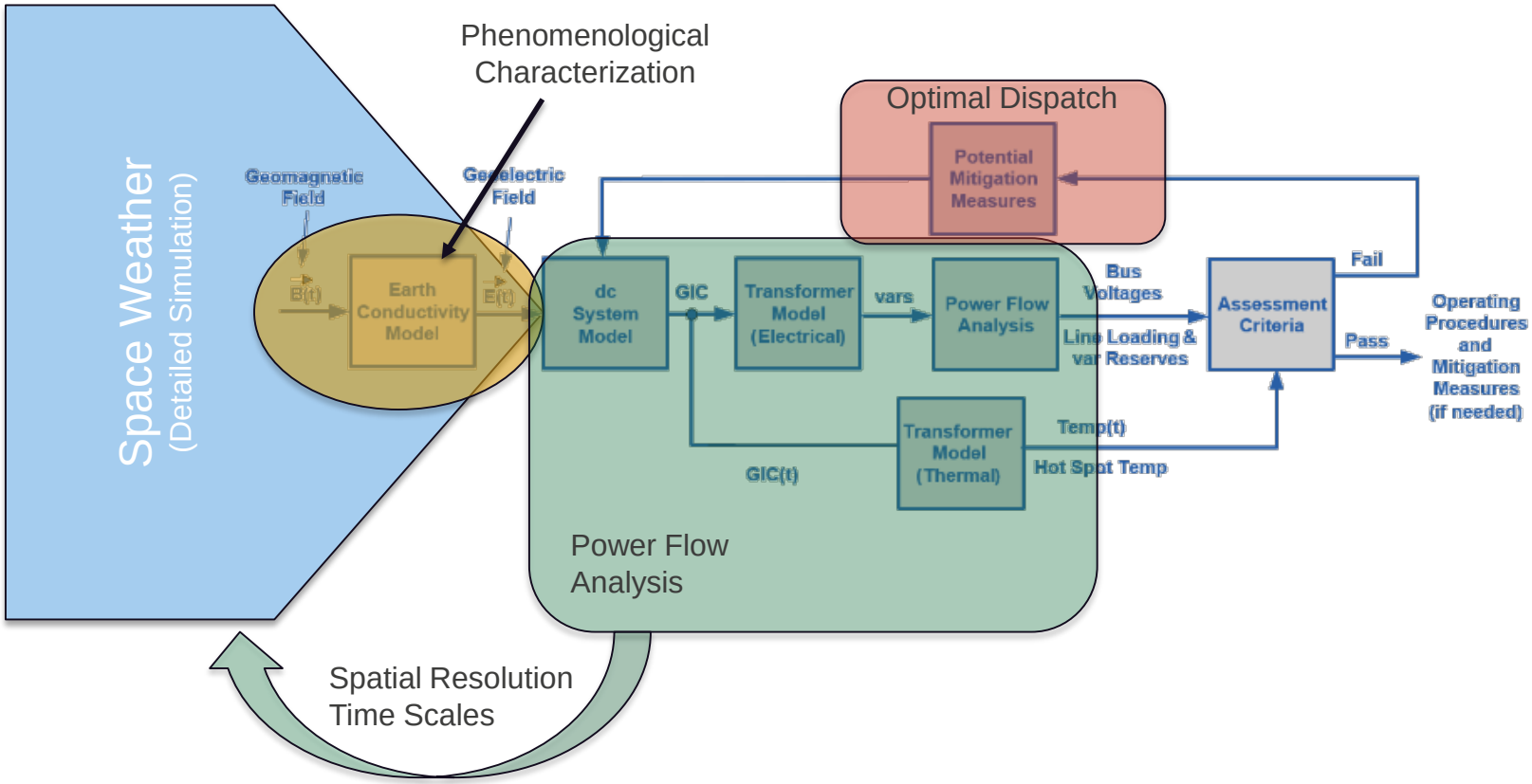


Credit: Metatech

Harmonic generation—potential relay misoperation—seconds

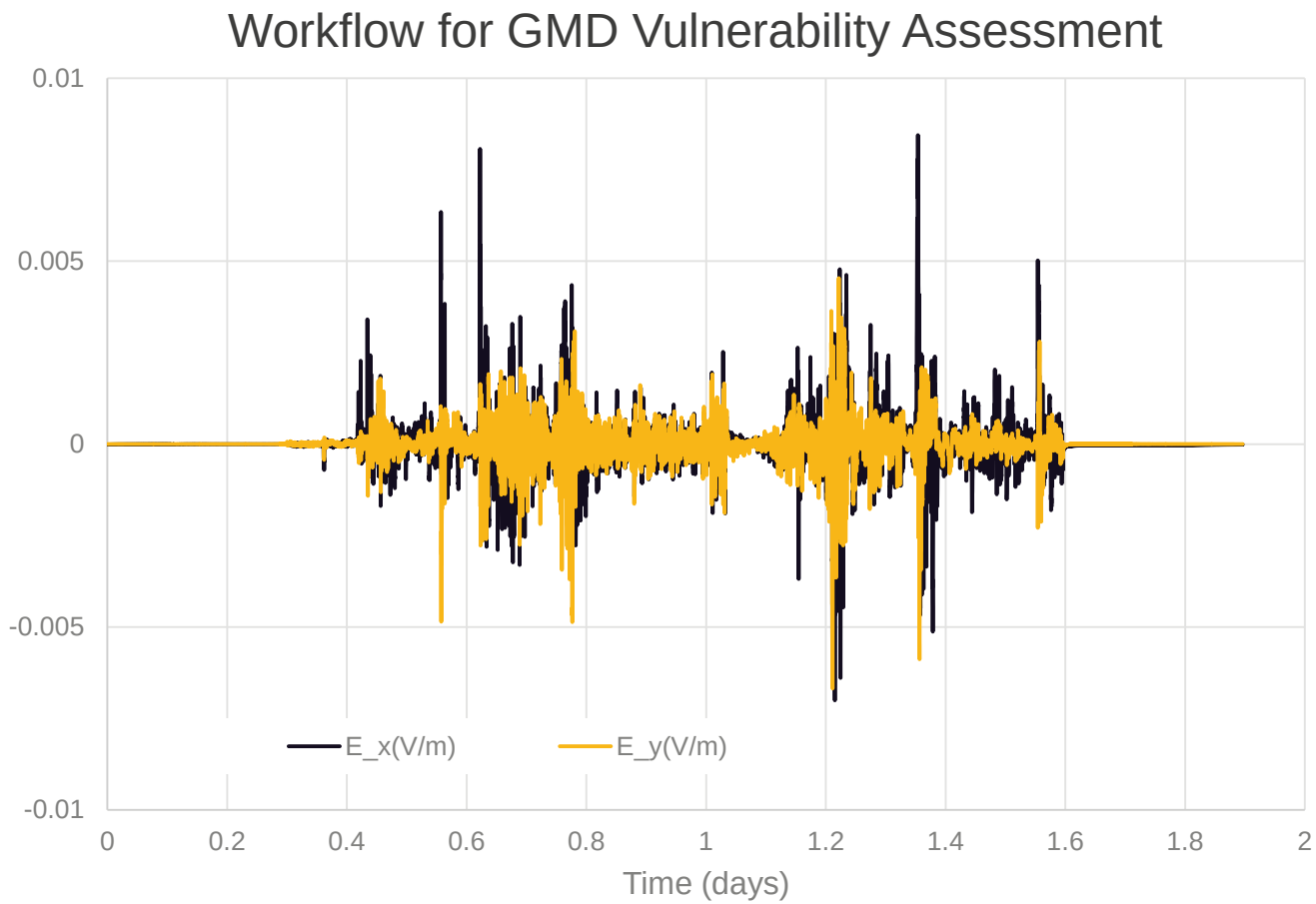
"Behaviour of transformers under DC/GIC excitation: Phenomenon, Impact on design/design evaluation process and Modelling aspects in support of Design" T. NGNEGUEU et al, CIGRE, 2012

GMD Assessment Workflow (TPL-007-1)



Phenomenological Characterization

Geomagnetic Disturbances: TPL-007-1



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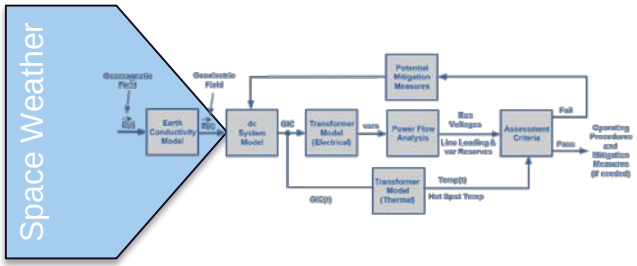
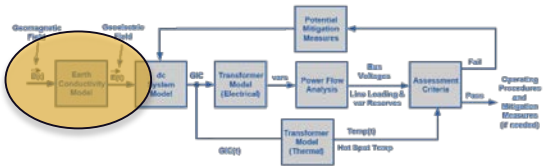
FERC order 830

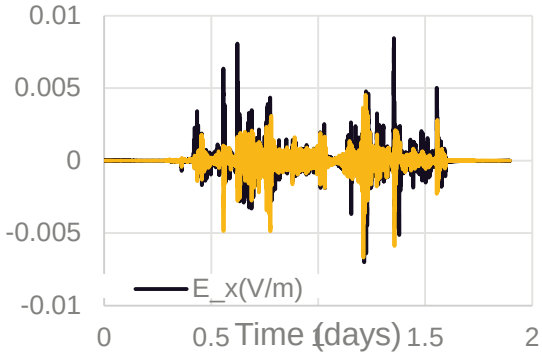
26. Furthermore, to improve the understanding of GMD events generally, the Commission directs NERC to submit within six months from the effective date of this Final Rule a GMD research work plan.**33** Specifically, we direct NERC to: (1) further analyze the area over which spatial averaging should be calculated for stability studies, including performing sensitivity analyses on squares less than 500 km per side (e.g., 100 km, 200 km); (2) further analyze earth conductivity models by, for example, using metered GIC and magnetometer readings to calculate earth conductivity and using 3-D readings; (3) determine whether new analyses and observations support modifying the use of single station readings around the earth to adjust the spatially averaged benchmark for latitude; (4) research, as discussed below, aspects of the required thermal impact assessments; and (5) in NERC's discretion, conduct any GMD-related research areas generally that may impact the development of new or modified GMD Reliability Standards. We expect that work completed through the GMD research work plan, as well as other analyses facilitated by the increased collection and availability of GIC monitoring and magnetometer data directed herein, will lead to further modifications to Reliability Standard TPL-007-1 as our collective understanding of the threats posed by GMD events improves.

Goals



Phenomenological Characterization

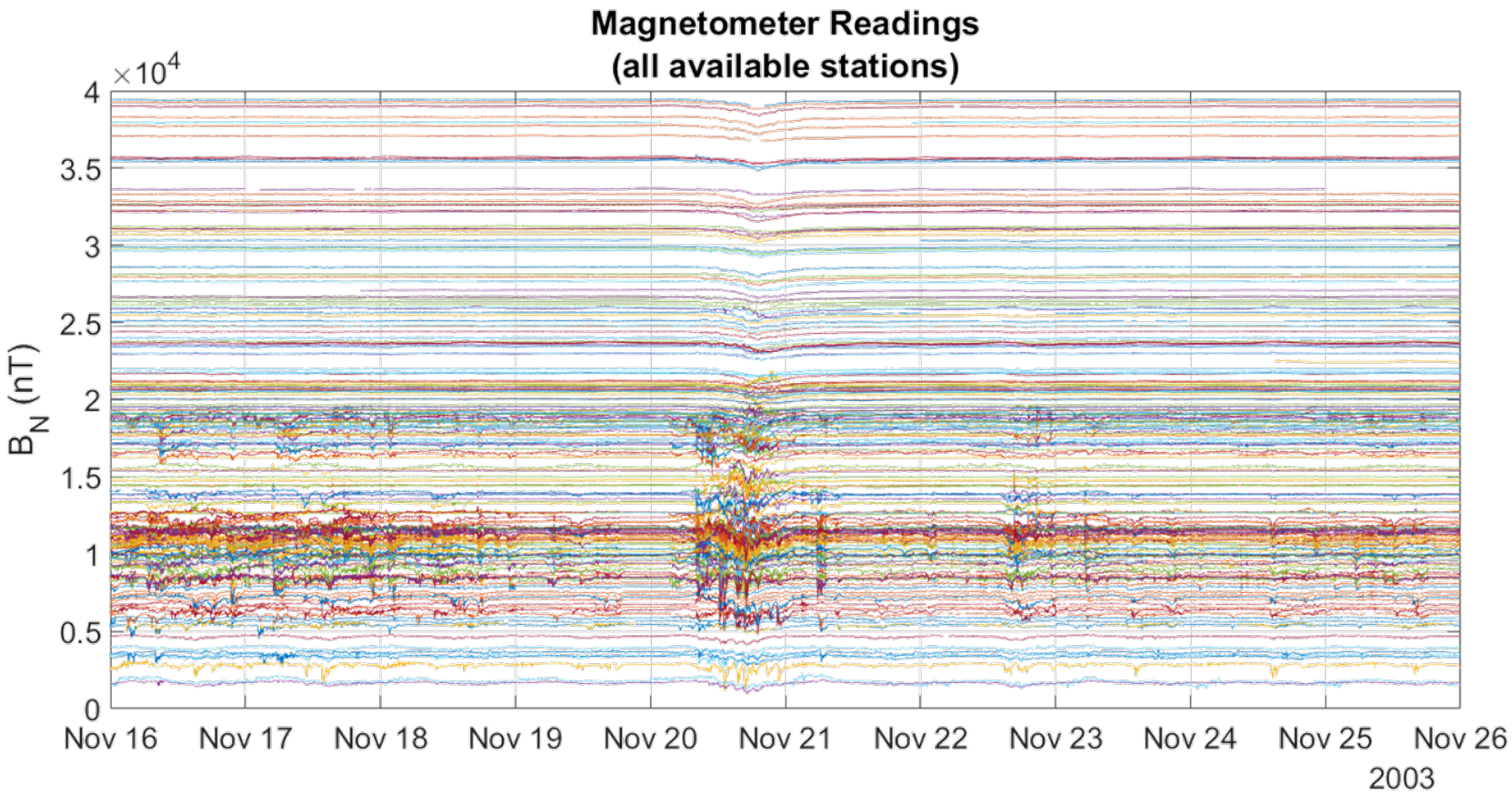




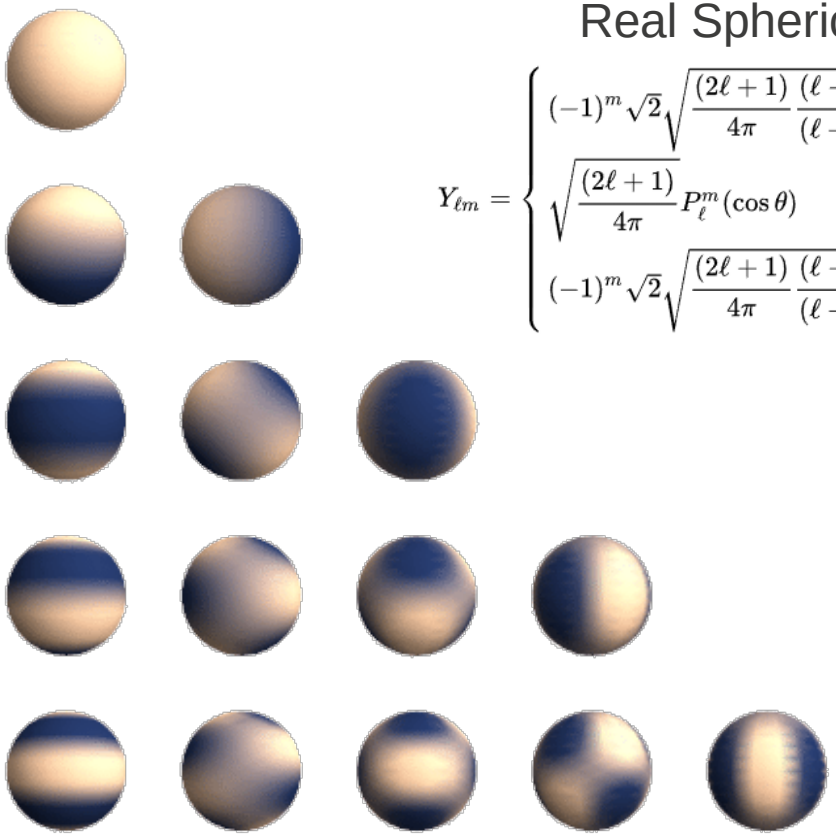
Accurate/Complex → Fast/Simple

- Determine if fast/simple approach contains adequate information
- Provide ground truth information for detailed simulation comparison
- Provide a statistical replacement for fast/simple signal

SuperMag (1 min data)
Nov. 20-21, 2003 Storm (DST = -422)



Spherical Harmonics



By Cyp, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=266718

Real Spherical Harmonics

$$Y_{\ell m} = \begin{cases} (-1)^m \sqrt{2} \sqrt{\frac{(2\ell+1)}{4\pi} \frac{(\ell-|m|)!}{(\ell+|m|)!}} P_\ell^{|m|}(\cos\theta) \sin|m|\varphi & \text{if } m < 0 \\ \sqrt{\frac{(2\ell+1)}{4\pi}} P_\ell^m(\cos\theta) & \text{if } m = 0 \\ (-1)^m \sqrt{2} \sqrt{\frac{(2\ell+1)}{4\pi} \frac{(\ell-m)!}{(\ell+m)!}} P_\ell^m(\cos\theta) \cos m\varphi & \text{if } m > 0 \end{cases}$$

Spherical Harmonic Transform

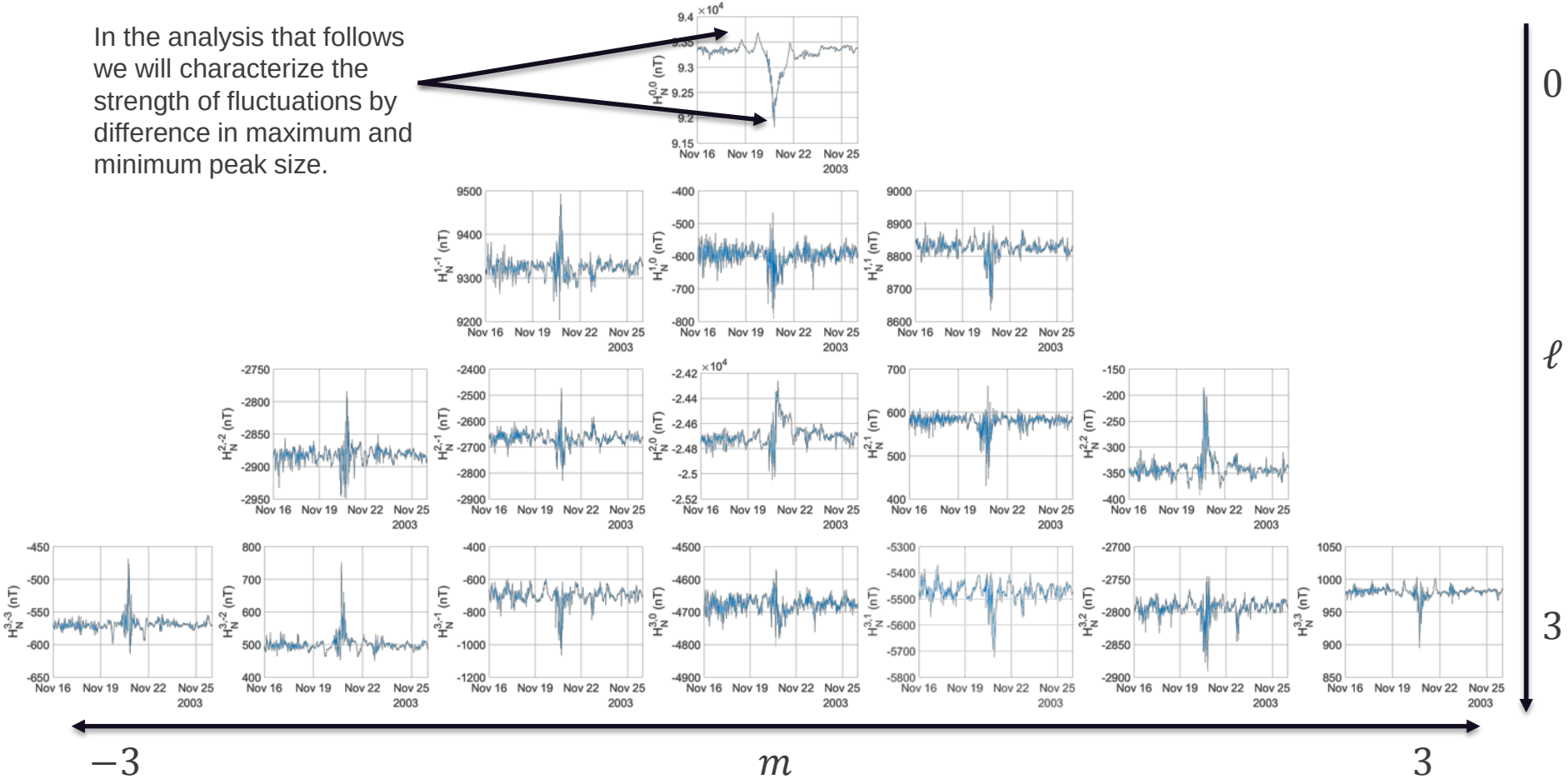
$$f_\ell^m = \int_\Omega f(\theta,\varphi)\, Y_\ell^{m*}(\theta,\varphi)\, d\Omega$$

$$B_N^{all\ stations} \rightarrow H_N^{\ell,m}$$

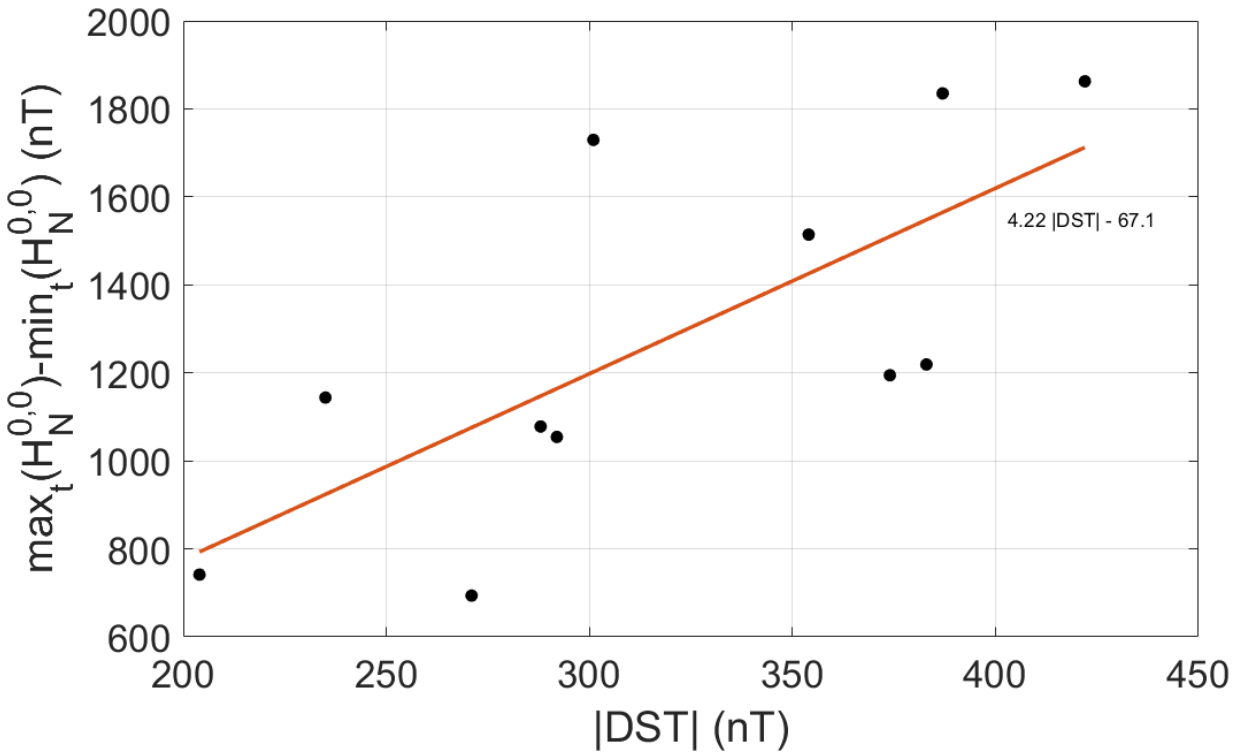
$$B_E^{all\ stations} \rightarrow H_E^{\ell,m}$$

Spherical Harmonics
Nov. 20-21, 2003 Storm (DST = -422)

In the analysis that follows we will characterize the strength of fluctuations by difference in maximum and minimum peak size.



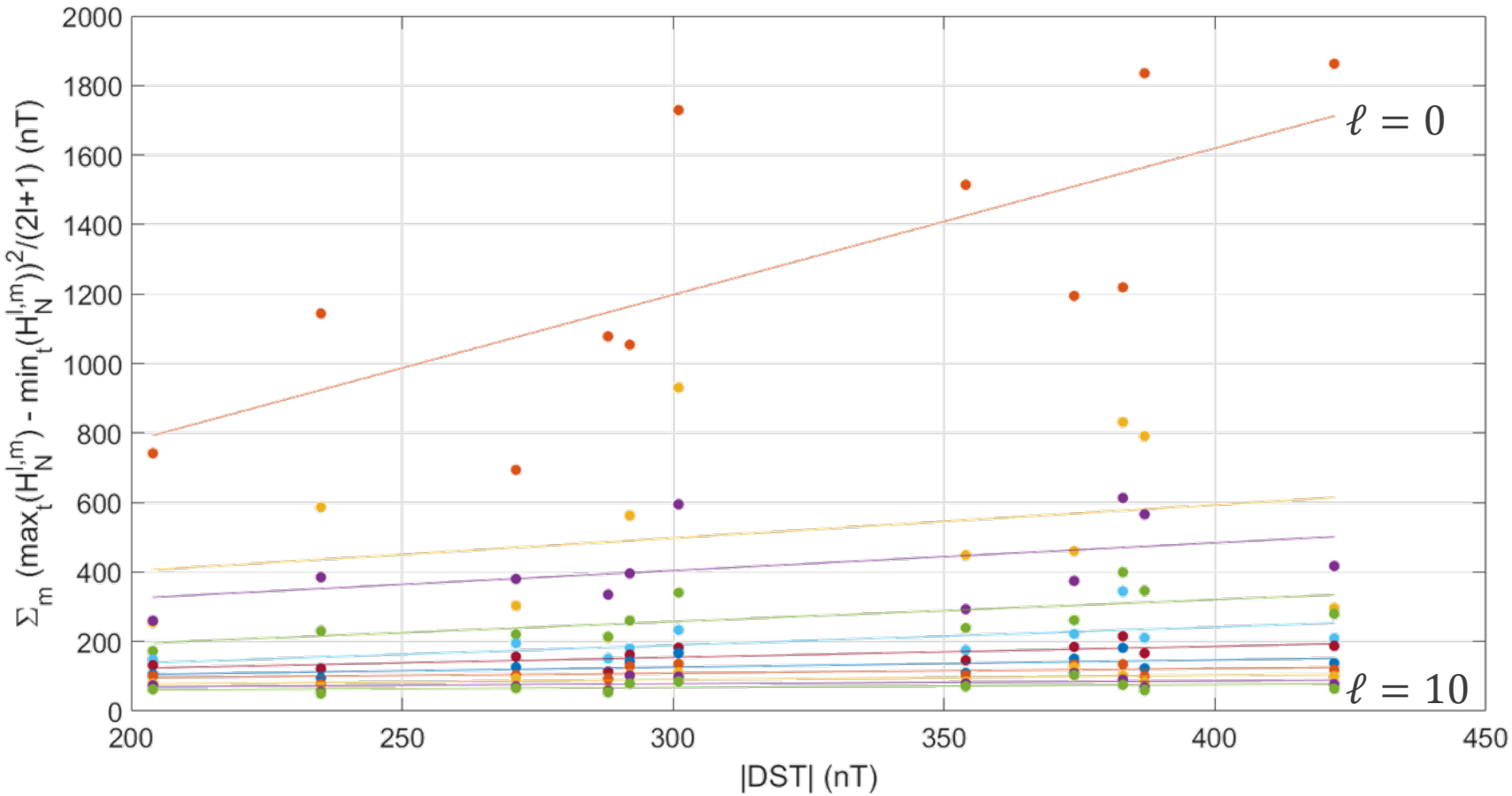
DST vs $H_N^{0,0}$



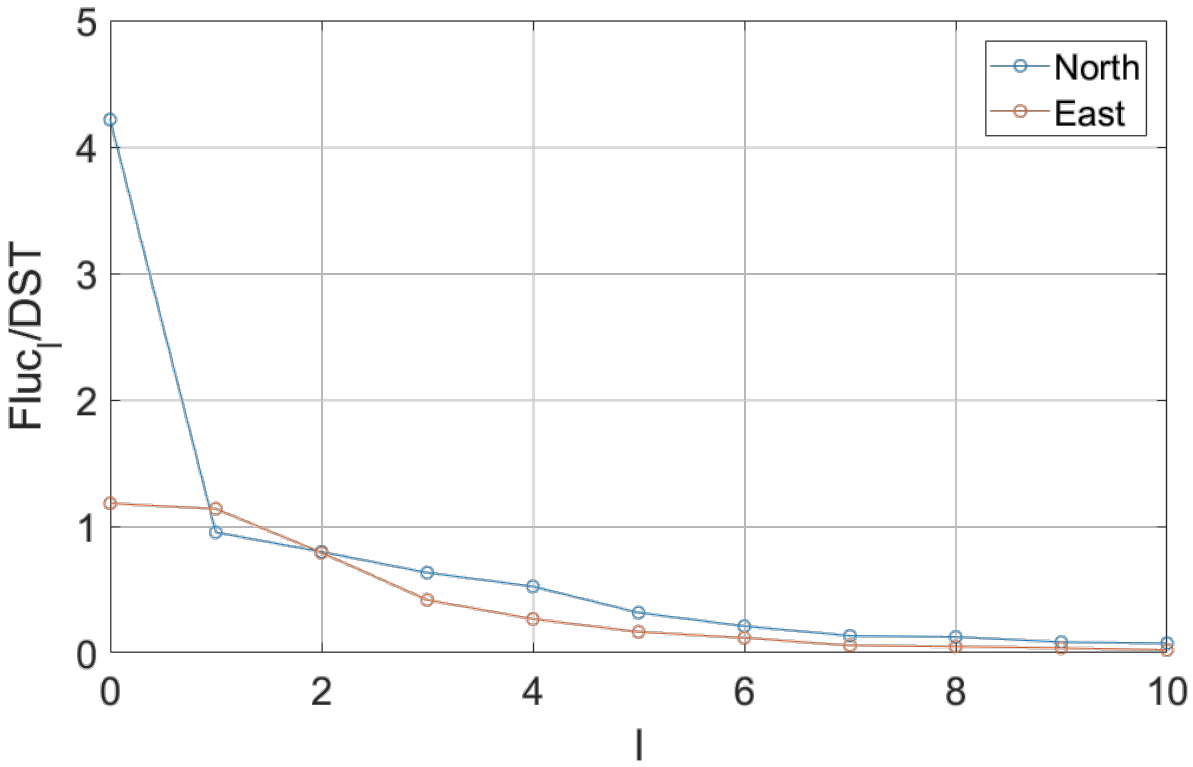
- Would expect magnitude of $\ell = 0$ component of B_N to scale with DST
- Approximate linear fit shown with slope 4.22
- $\frac{1}{4.22} \approx .24$; Expected value is

$$Y_0^0 = \frac{1}{2}\sqrt{\frac{1}{\pi}} \approx 0.28$$

Fluctuations vs. DST

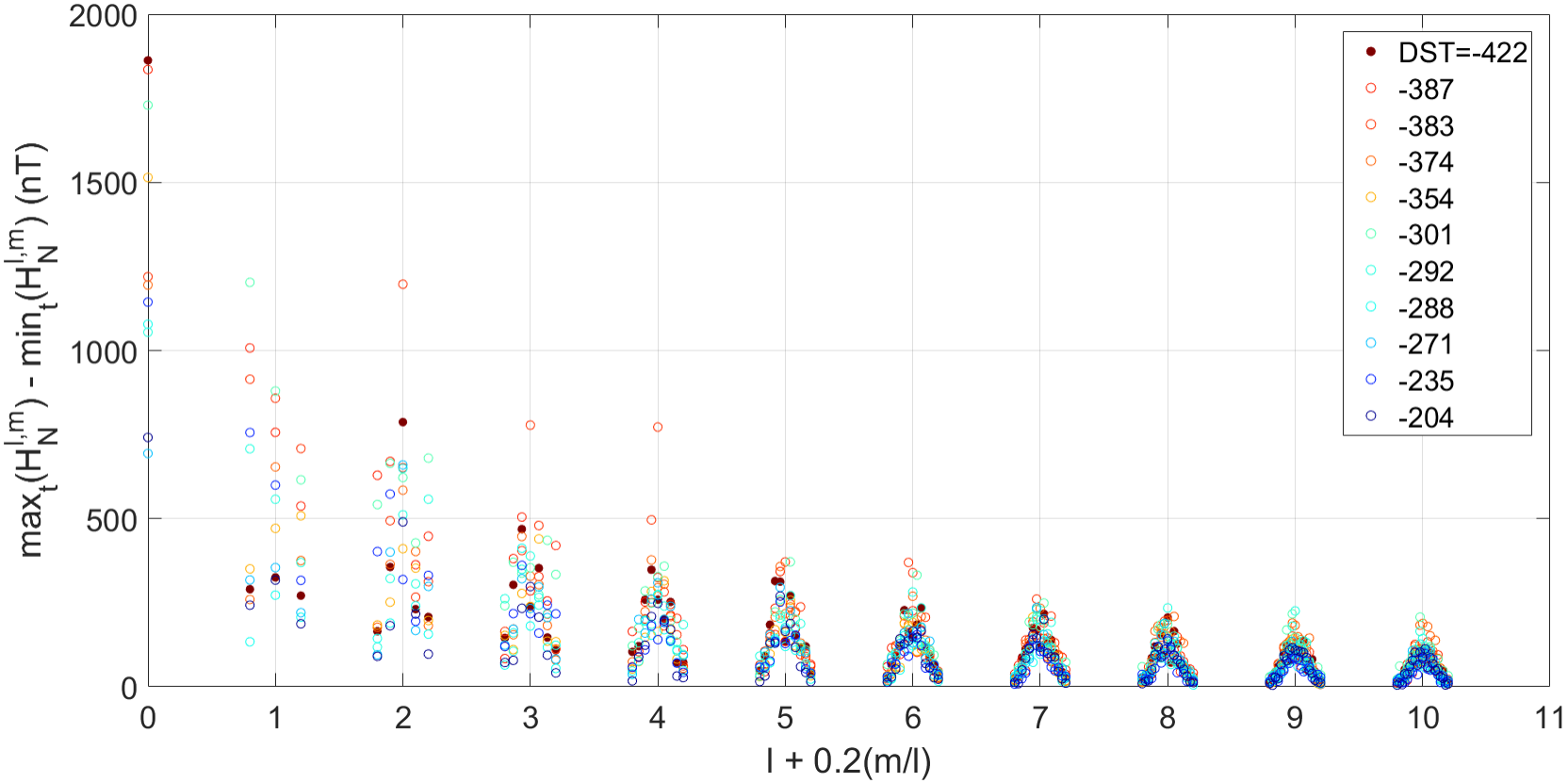


Fluctuations vs. DST



- The magnitude of fluctuations in the lowest order spherical harmonics (large scales) increase faster with storm strength than higher order harmonics (small scales)
- Magnitude of the fluctuations in the highest order harmonics are almost independent of storm strength.

Fluctuations



Conclusions and Next Steps

Conclusions

- The fluctuation in $H_N^{0,0}$ is roughly proportional to DST
- Increasing storm strength causes a proportionately larger response in larger spatial modes than smaller spatial modes.
    - Fluctuations in small spatial modes almost independent of storm strength
    - Smaller spatial modes are biased towards axial modes (smaller $|m|$ rather than azimuthal modes)
- The shape of peaks (magnitude vs. dominant width) is independent of storm strength

Next Steps:

- Look at frequency distribution of peaks as storm strength increases
- Cross-correlate peak occurrences between spherical harmonic modes.

Power Flow Analysis

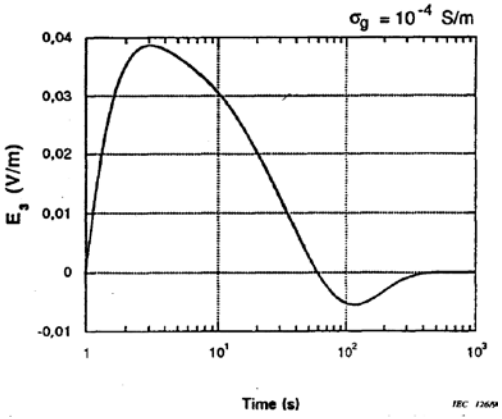
GMD Assessment Workflow (TPL-007-1)

26. Furthermore, to improve the understanding of GMD events generally, the Commission directs NERC to submit within six months from the effective date of this Final Rule a GMD research work plan.**33** Specifically, we direct NERC to: (1) further analyze the area over which spatial averaging should be calculated for stability studies, including performing sensitivity analyses on squares less than 500 km per side (e.g., 100 km, 200 km); (2) further analyze earth conductivity models by, for example, using metered GIC and magnetometer readings to calculate earth conductivity and using 3-D readings; (3) determine whether new analyses and observations support modifying the use of single station readings around the earth to adjust the spatially averaged benchmark for latitude; (4) research, as discussed below, aspects of the required thermal impact assessments; and (5) in NERC's discretion, conduct any GMD-related research areas generally that may impact the development of new or modified GMD Reliability Standards. We expect that work completed through the GMD research work plan, as well as other analyses facilitated by the increased collection and availability of GIC monitoring and magnetometer data directed herein, will lead to further modifications to Reliability Standard TPL-007-1 as our collective understanding of the threats posed by GMD events improves.

EMP E3 Coupling to Texas 2000 Bus Model

Goal: Compare impact of IEC + ORNL E3 waveform (current de facto "standard") with simulated E3 environment.

IEC de facto standard



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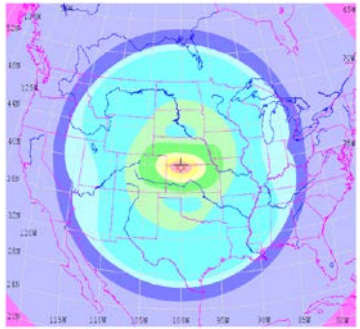
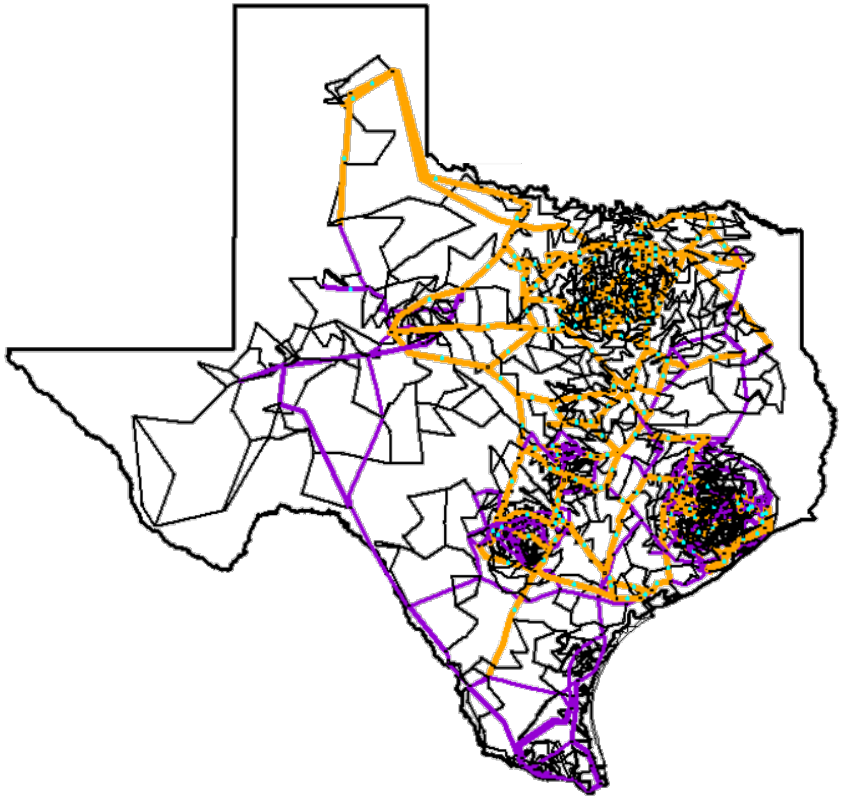
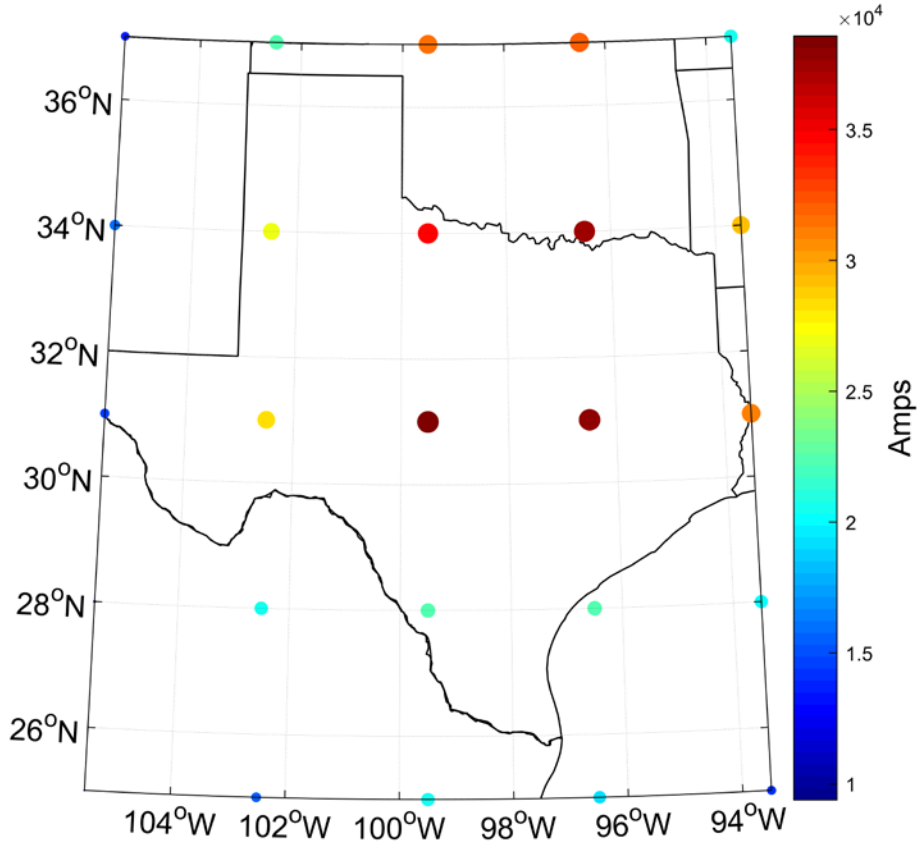


Texas 2000 Bus Model

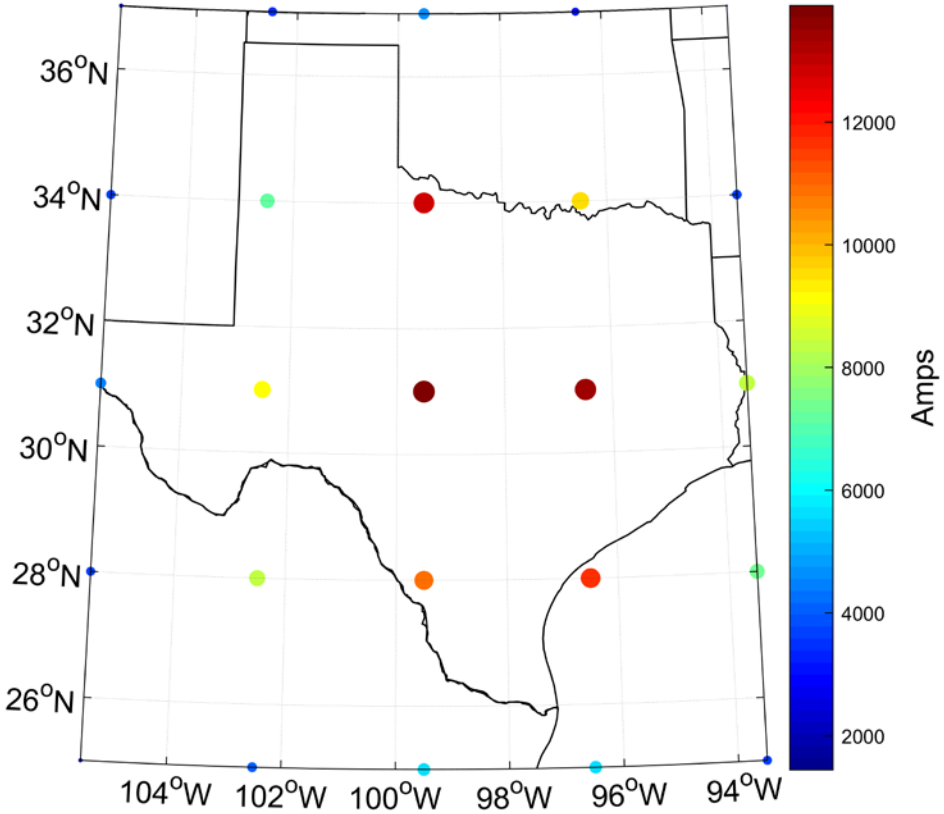


E3 Coupling Comparison (total GIC) Varying Ground Zero

IEC Model (scaled)

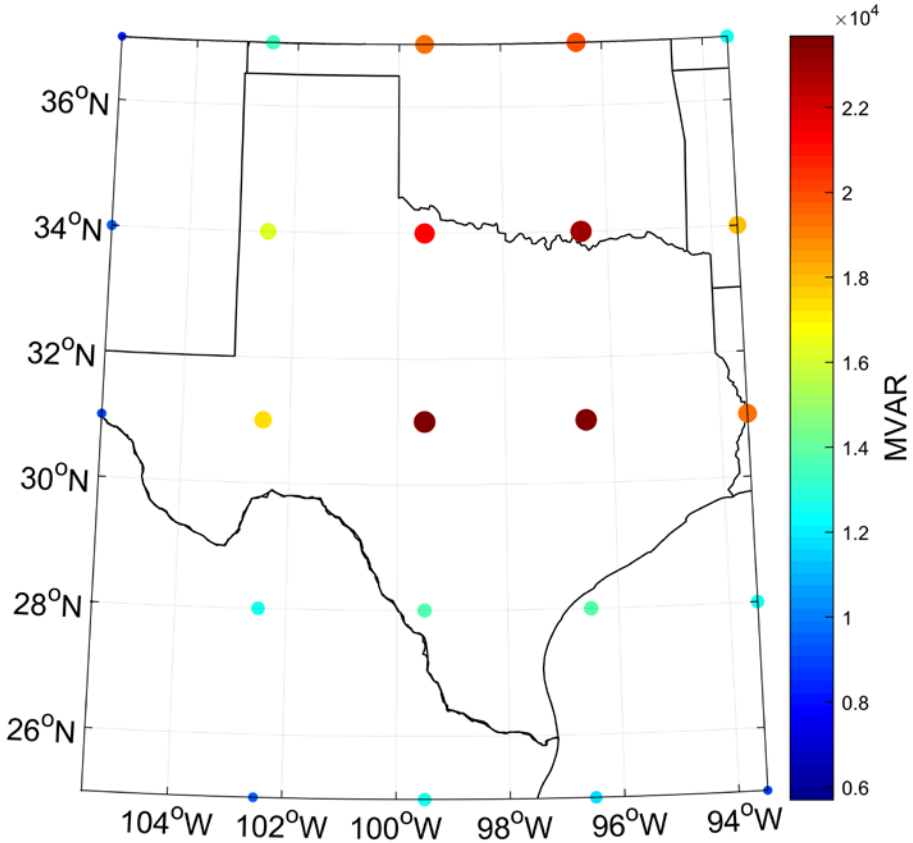


Simulated Environment

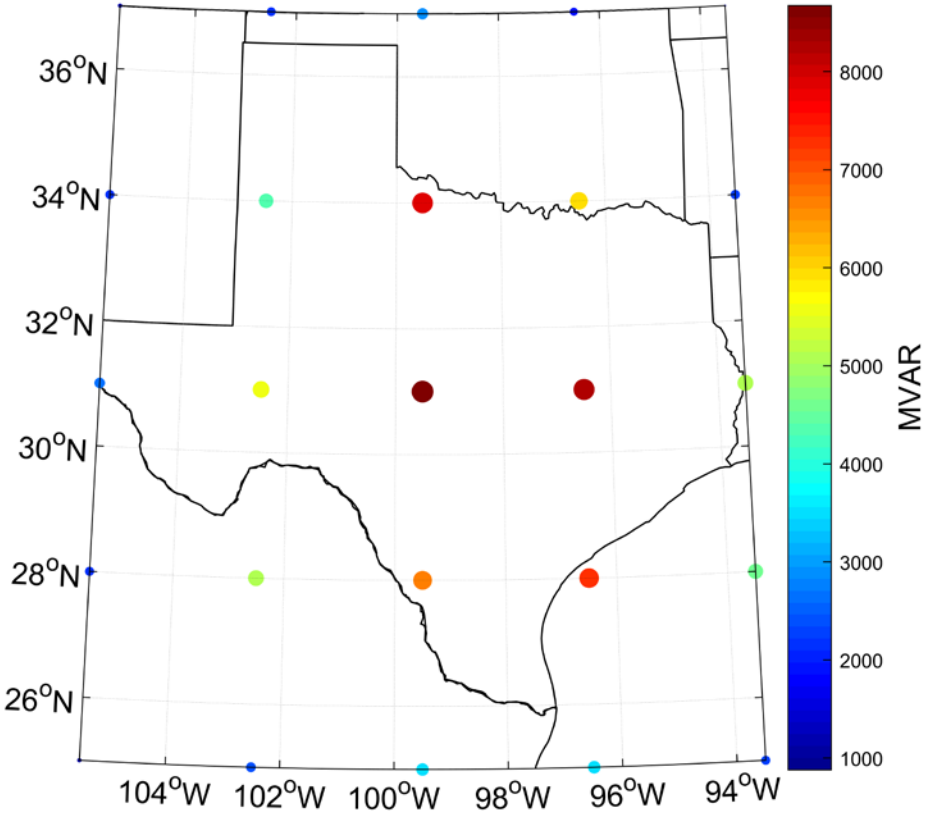


E3 Coupling Comparison (total MVAR) Varying Ground Zero

IEC Model (scaled)

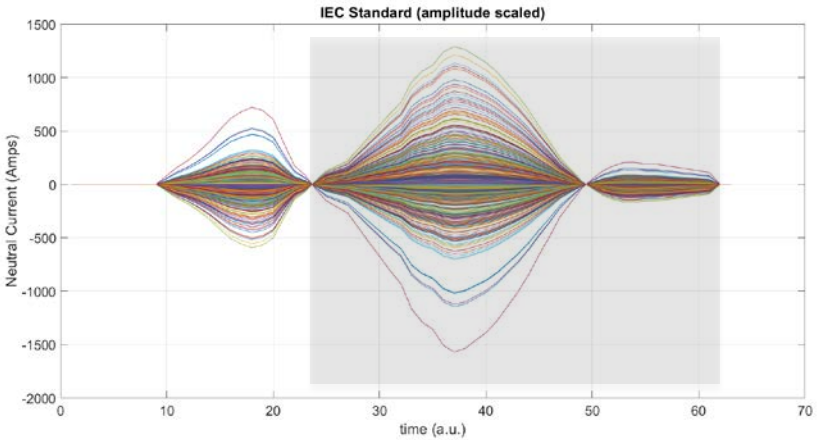


Simulated Environment

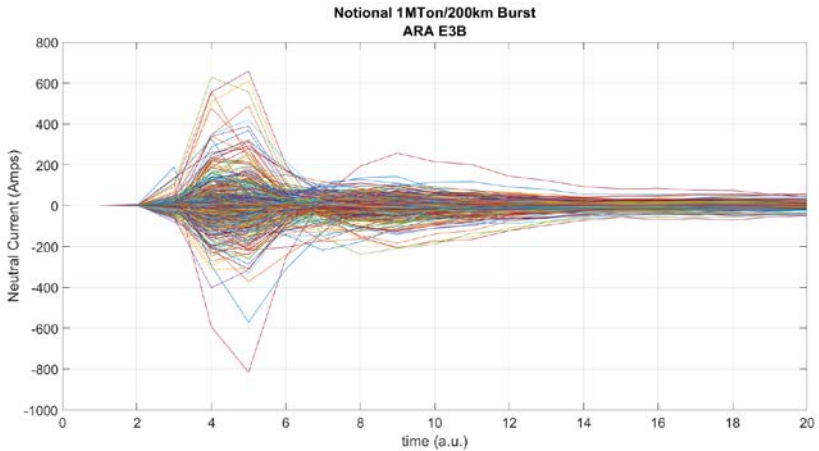


E3 Coupling Comparison (GIC) at Peak Ground Zero

IEC Model (scaled)



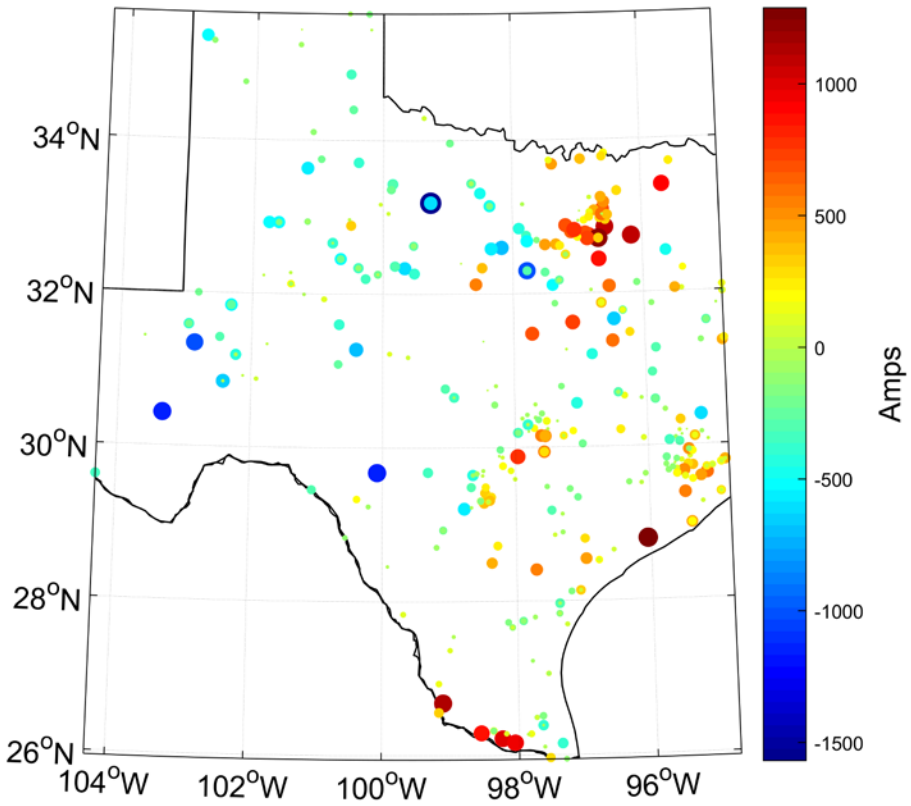
Simulated Environment



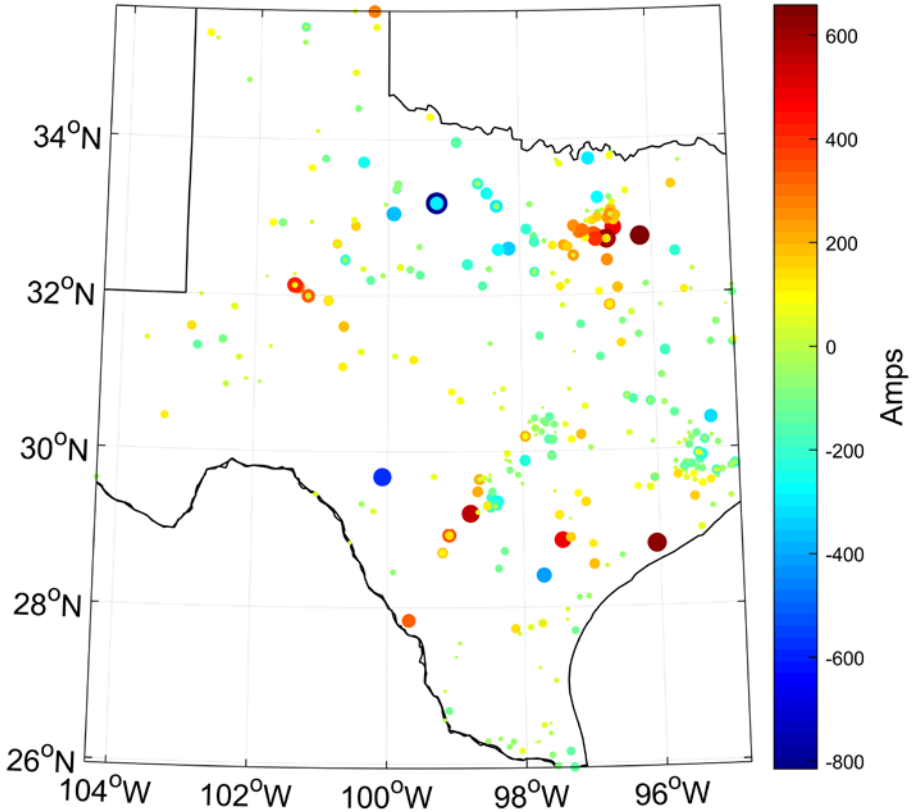
- Neutral current through transformers for worst case ground zero of the IEC Model and Simulated Environment.
- IEC Model:
  - significantly longer time coherence
  - Larger magnitude GIC's
  - Similar envelope shape to simulated environment

E3 Coupling Comparison (GIC) at Peak Ground Zero

IEC Model (scaled)



Simulated Environment



Conclusion

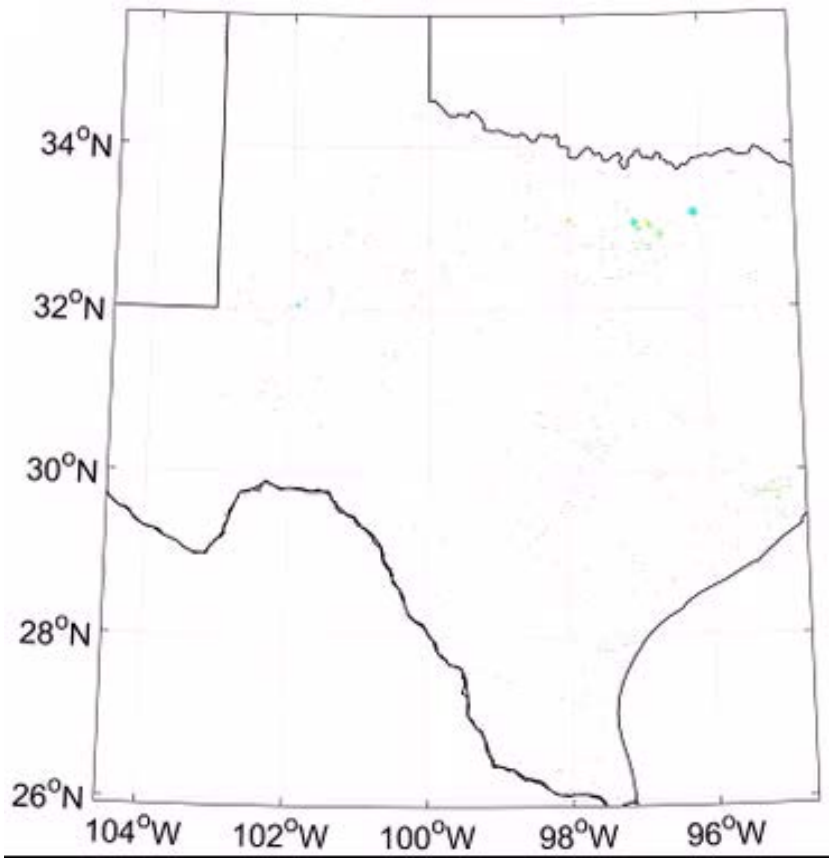
E3 Analysis:

- IEC + ORNL model has spatial behavior roughly in agreement with full simulated environment:
  - Determines the same worst case ground zero
  - Fair agreement of relative GIC values for individual transformers
- IEC + ORNL shows much longer temporal coherence than simulated environment
  - Overestimates integrated power, and therefore thermal heating, of transformer
- IEC + ORNL overestimates GIC's by factor ~ 3

DR Power Flow:

- Successfully implemented a power flow code that couples electric fields from (manmade) GMD's to model power system.

Next Steps



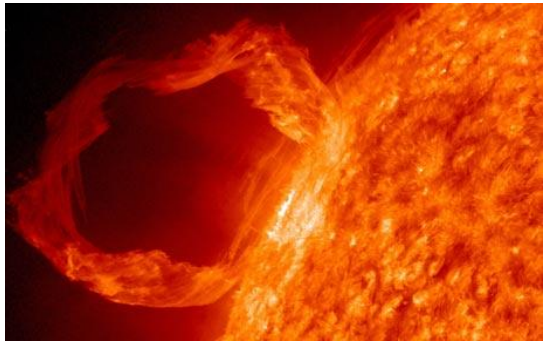
- Begin analysis of strong GMD events and explore impacts of temporal and spatial resolution
- Incorporate relay switching (voltage + frequency) as well as composite load models into dynamics simulation
- Improve transformer grounding model in Energy Visuals CONUS transmission system data

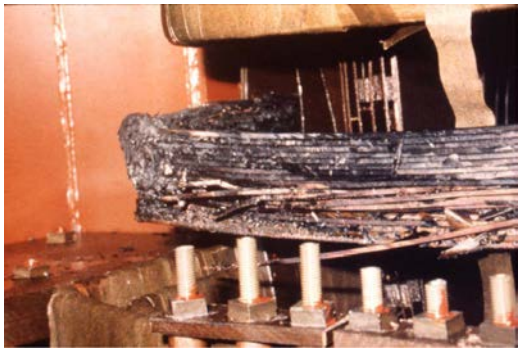
GMD Disturbance Mitigation

Joint work: Mowen Lu, Scott Backhaus, Harsha Nagarajan, and Emre Yamangil, and others

Introduction and Motivation (Review)

- **Global Magnetic Disturbances (GMD) have the potential to disrupt power delivery**
  - May 1806 – June, 1807: Alexander von Humboldt, Berlin
  - August 28 - September 2, 1859: United States and Europe
  - March 13, 1989: Hydro-Québec blackout
- **Motivates R&D of power system fragility**
  - Transformers
  - Generators
  - Control components
- **Motivates R&D on mitigation and prevention**
  - Blocking devices (Overbye 2013, 2015)
  - Defensive control and mitigation (Bent et al., 2017)
- **Presentation Focus**
  - Modeling GMD effects in a power system
  - Deriving constraints that ensure system protection
  - Optimize decisions to meet these constraints





Mitigation Model: Nomenclature

Sets

N	set of nodes (buses) in transmission grid
$G \subseteq N$	set of generators
$\mathcal{E}$	set of edges (lines and transformers) in transmission grid
$\mathcal{E}^{\tau} \subseteq \mathcal{E}$	set of transformer lines
$\mathcal{E}^{g} \subseteq \mathcal{E}$	set of edges (ij) such that either i or $j \in G$

Binary Variables

y_{ij}	1 if line (ij) is switched on; 0 otherwise

Continuous Variables

θ_i	phase angle at bus $i \in N$
θ_{ij}	phase angle difference of line $(ij) \in \mathcal{E}$
V_i	voltage magnitude at bus $i \in N$
V_i^d	DC voltage magnitude at bus $i \in N$
l_{ij}	current flow magnitude squared on line $(ij) \in \mathcal{E}$
I_{ij}^d	DC current flow on line $(ij) \in N$
I_i^d	DC current injection at bus $i \in N$
I_{ij}^a	AC current flow magnitude on transformer lines $(ij) \in \mathcal{E}^{\tau}$
$\widetilde{I}_i^d$	DC current injection magnitude at bus $i \in N$
Q_i^{loss}	Additional reactive power load due to transformer saturation at bus $i \in N$
p_{ij}, q_{ij}	real and reactive power flow on line $(ij) \in \mathcal{E}$
f_i^p, f_i^q	real and reactive power generated at bus $i \in N$
l_i^p, l_i^q	real and reactive power shed at bus $i \in N$

Parameters

c_i	cost of generation at bus $i \in N$
λ	cost of shedding load at bus $i \in N$
a_{ii}	admittance of grounding lines
a_{ij}	admittance of the edges $(ij) \in \mathcal{E}$
j_{ij}	induced current source by GMD on line $(ij) \in \mathcal{E}$
r_{ij}, x_{ij}	resistance and reactance of line $(ij) \in \mathcal{E}$
g_i, b_i	shunt conductance and susceptance at bus $i \in N$
g_{ij}, b_{ij}	conductance and susceptance of line $(ij) \in \mathcal{E}$
b_{ij}^c	branch charging susceptance of line $(ij) \in \mathcal{E}$
d_i^p, d_i^q	real and reactive power demand at bus $i \in N$
t_{ij}	apparent power thermal limit on line $(ij) \in \mathcal{E}$
$\overline{\theta}$	phase angle difference limit
$\underline{V}_i$, $\overline{V}_i$	lower and upper bound on AC voltage injection at bus $i \in N$
$\overline{V}^d$	DC voltage difference limit
$\overline{I}_{ij}^a$	AC current flow limit on line $(ij) \in \mathcal{E}$
I_{ij}	current magnitude causing magnetic saturation of transformers on line $(ij) \in \mathcal{E}^{\tau}$
T_{ij}	thermal limit on transformer line $(ij) \in \mathcal{E}^{\tau}$
K_i	transformer specific scalar at bus $i \in N$, 0 if there is no transformer at but $i \in N$
$V_{pu,i}$	per unit AC terminal voltage at bus $i \in N$
$\underline{gp}_i$, $\overline{gp}_i$	lower and upper bound on real power generation capacity at bus $i \in G$
$\underline{gq}_i$, $\overline{gq}_i$	lower and upper bound on reactive power generation capacity at bus $i \in G$

Normal Power System Operations

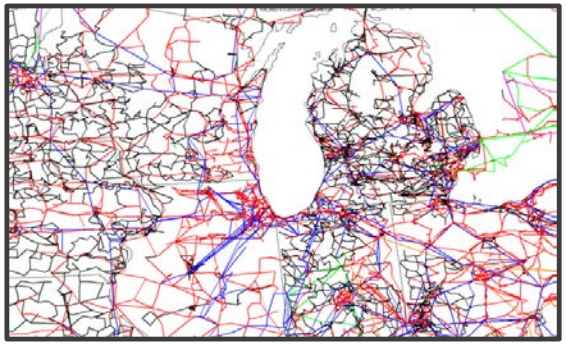
$$min \sum_{i \in N} c_2 (\boldsymbol{f}_i^p)^2 + c_1 \boldsymbol{f}_i^p + c_0$$

Minimize generation dispatch costs

$$\sum_{j:(ij) \in E} \boldsymbol{p}_{ij} = \boldsymbol{f}_i^p - d_i^p - \boldsymbol{V}_i^2 g_i$$

$$\sum_{j:(ij) \in E} \boldsymbol{q}_{ij} = \boldsymbol{f}_i^q - d_i^q + \boldsymbol{V}_i^2 b_i$$

Power flow balance constraints



$$\boldsymbol{p}_{ij} = g_{ij} \boldsymbol{V}_i^2 - \boldsymbol{V}_i \boldsymbol{V}_j g_{ij} \cos(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j) - \boldsymbol{V}_i \boldsymbol{V}_j b_{ij} \sin(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j)$$

$$\boldsymbol{q}_{ij} = -\left(b_{ij} + \frac{c_{ij}}{2}\right) \boldsymbol{V}_i^2 + \boldsymbol{V}_i \boldsymbol{V}_j b_{ij} \cos(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j) - \boldsymbol{V}_i \boldsymbol{V}_j g_{ij} \sin(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j)$$

$$\boldsymbol{p}_{ji} = g_{ij} \boldsymbol{V}_i^2 - \boldsymbol{V}_i \boldsymbol{V}_j g_{ij} \cos(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i) - \boldsymbol{V}_i \boldsymbol{V}_j b_{ij} \sin(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i)$$

$$\boldsymbol{q}_{ji} = -\left(b_{ij} + \frac{c_{ij}}{2}\right) \boldsymbol{V}_i^2 + \boldsymbol{V}_i \boldsymbol{V}_j b_{ij} \cos(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i) - \boldsymbol{V}_i \boldsymbol{V}_j g_{ij} \sin(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i)$$

Real and Reactive Power Flow Equations

$$\boldsymbol{p}_{ij} + \boldsymbol{p}_{ji} = r_{ij} \left(\boldsymbol{l}_{ij} + c_{ij} \boldsymbol{q}_{ij} + \left(\frac{c_{ij}}{2}\right)^2 \boldsymbol{V}_i^2\right)$$

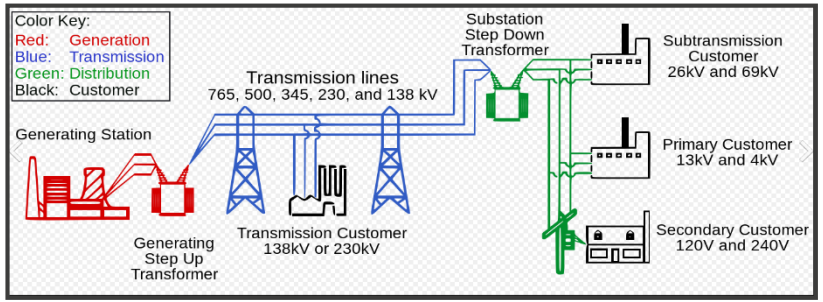
$$\boldsymbol{q}_{ij} + \boldsymbol{q}_{ji} = x_{ij} \left(\boldsymbol{l}_{ij} + c_{ij} \boldsymbol{q}_{ij} + \left(\frac{c_{ij}}{2}\right)^2 \boldsymbol{V}_i^2\right)$$

Power loss equations

$$\boldsymbol{p}_{ij}^2 + \boldsymbol{q}_{ij}^2 = \boldsymbol{l}_{ij} \boldsymbol{V}_i^2$$

$$\boldsymbol{l}_{ij} = \left(\boldsymbol{I}_{ij}^a\right)^2$$

Apparent and Current Power Flow Equations



Normal Power System Operations

$$\boldsymbol{p}_{ij}^2 + \boldsymbol{q}_{ij}^2 \leq t_{ij}$$

$$\boldsymbol{p}_{ji}^2 + \boldsymbol{q}_{ji}^2 \leq t_{ij}$$

Thermal line limits

$$0 \leq \boldsymbol{I}_{ij}^a \leq \overline{I}_{ij}^a$$

Current limits

$$\underline{V}_i \leq \boldsymbol{V}_i \leq \overline{V}_i$$

Voltage limits

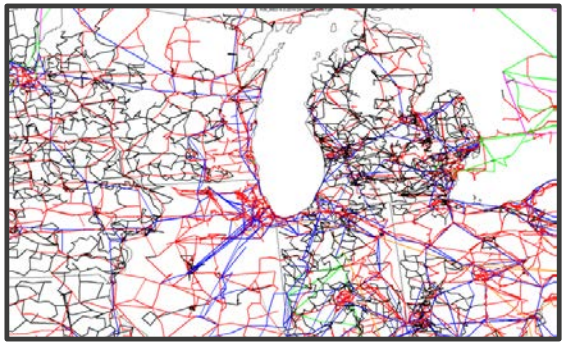
$$-\overline{\theta} \leq \boldsymbol{\theta}_i - \boldsymbol{\theta}_j \leq \overline{\theta}$$

Phase angle limits

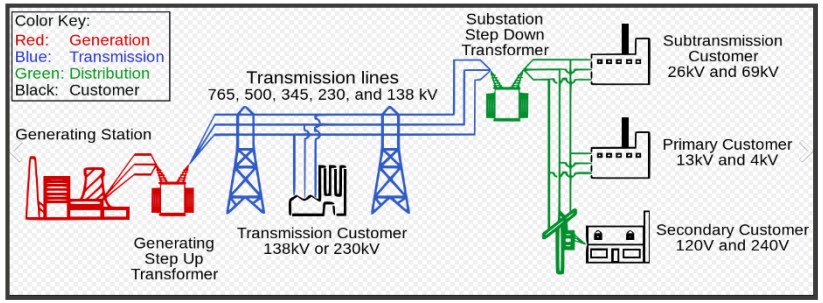
$$\underline{gp}_i \leq \boldsymbol{f}_i^p \leq \overline{gp}_i$$

$$\underline{gq}_i \leq \boldsymbol{f}_i^q \leq \overline{gq}_i$$

Generation limits



Optimization problems like this are solved every 15 - 60 minutes



GIC Power Flows

GIC power flow equations

$$\sum_{j:(ij)\in E} j_{ij} = \boldsymbol{I}_i^d - \sum_{j:(ij)\in E} a_{ij}(\boldsymbol{V}_i^d - \boldsymbol{V}_j^d)$$

$$\boldsymbol{I}_i^d = a_{ii}\boldsymbol{V}_i^d$$

$$\tilde{\boldsymbol{I}}_i^d \geq I_i^d, \qquad \tilde{\boldsymbol{I}}_i^d \geq -I_i^d$$

Computing Geomagnetically-Induced Current in the Bulk Power System, NERC, 2013

GIC injections and magnitudes

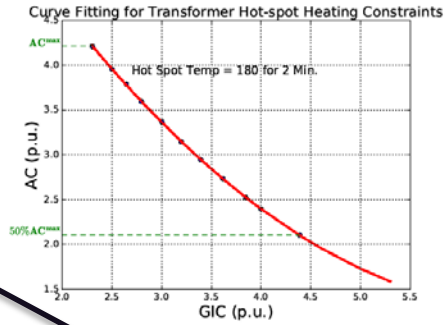
GIC effects on Transformers

$$\eta_{ij}^0 + \eta_{ij}^1\,\tilde{\boldsymbol{I}}_i^d + \eta_{ij}^2\left(\tilde{\boldsymbol{I}}_i^d\right)^2$$

$$\boldsymbol{Q}_i^{loss} = K_i V_{pu,i}\boldsymbol{I}_i^d$$

Transformer heating

Induced reactive losses



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Coupled Model: GIC Induces Voltage Drops

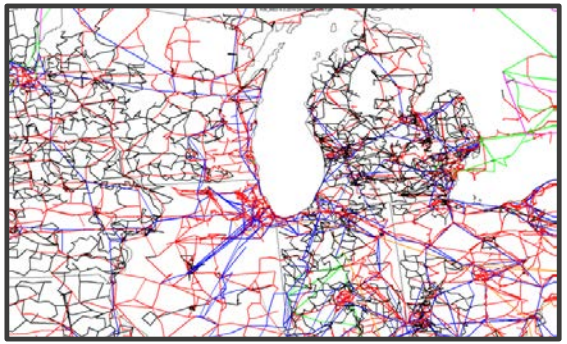
$$min \sum_{i \in N} c_2 (f_i^p)^2 + c_1 f_i^p + c_0$$

Minimize generation dispatch costs

$$\sum_{j:(ij) \in E} p_{ij} = f_i^p - d_i^p - V_i^2 g_i$$

$$\sum_{j:(ij) \in E} q_{ij} = f_i^q - d_i^q + V_i^2 b_i - Q_i^{loss}$$

Power flow balance constraints



$$p_{ij} = g_{ij} V_i^2 - V_i V_j g_{ij} \cos(\theta_i - \theta_j) - V_i V_j b_{ij} \sin(\theta_i - \theta_j)$$

$$q_{ij} = -\left(b_{ij} + \frac{c_{ij}}{2}\right) V_i^2 + V_i V_j b_{ij} \cos(\theta_i - \theta_j) - V_i V_j g_{ij} \sin(\theta_i - \theta_j)$$

$$p_{ji} = g_{ij} V_i^2 - V_i V_j g_{ij} \cos(\theta_j - \theta_i) - V_i V_j b_{ij} \sin(\theta_j - \theta_i)$$

$$q_{ji} = -\left(b_{ij} + \frac{c_{ij}}{2}\right) V_i^2 + V_i V_j b_{ij} \cos(\theta_j - \theta_i) - V_i V_j g_{ij} \sin(\theta_j - \theta_i)$$

Real and Reactive Power Flow Equations

$$p_{ij} + p_{ji} = r_{ij}\left(l_{ij} + c_{ij} q_{ij} + \left(\frac{c_{ij}}{2}\right)^2 V_i^2\right)$$

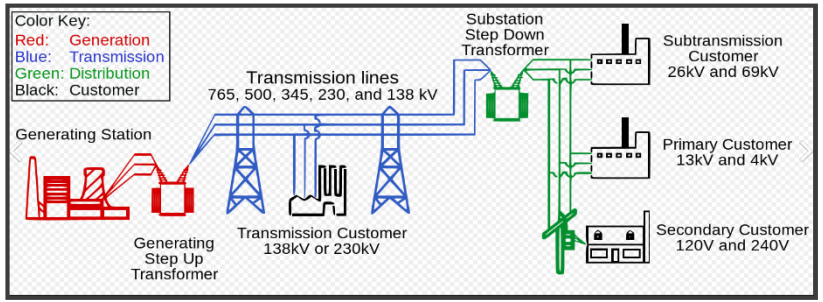
$$q_{ij} + q_{ji} = x_{ij}\left(l_{ij} + c_{ij} q_{ij} + \left(\frac{c_{ij}}{2}\right)^2 V_i^2\right)$$

Power loss equations

$$p_{ij}^2 + q_{ij}^2 = l_{ij} V_i^2$$

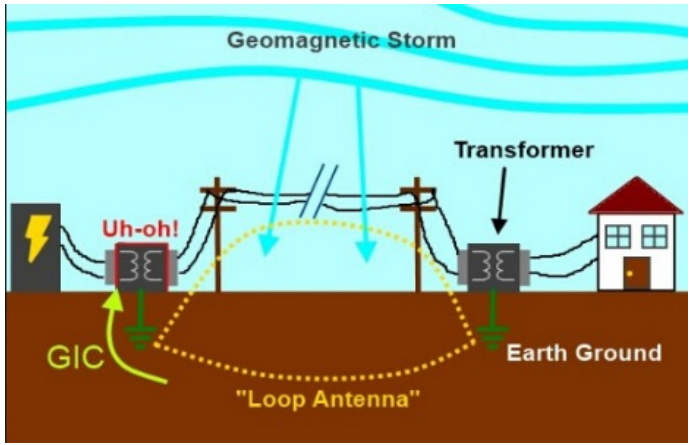
$$l_{ij} = \left(I_{ij}^a\right)^2$$

Apparent and Current Power Flow Equations



Mitigation Models

- **Challenging mixed-integer, non-convex optimization problem**
- **Prior work (Overbye 2013, 2015)**
  - Siting of protective devices
    - Blocks DC current
      - Essentially “unground” the network, makes the network more susceptible to other events
      - Lightning strikes
    - Expensive
  - Develop a proxy for safe operations
    - Minimize induced reactive losses
    - Ignores AC (normal) physics
    - Advantages
      - Mixed-Integer Linear Program
    - Disadvantages
      - Conservative
      - Neglects thermal heating
  - Our solution
    - Incorporate AC (normal physics)
    - Focus on utilizing existing control points
      - Line switching, generator set points, load shedding
      - Less expensive



Coupled Model: Safe Operating Temperatures

GIC power flow equations

$$\sum_{j:(ij)\in E} j_{ij} = \boldsymbol{I}_i^d - \sum_{j:(ij)\in E} a_{ij}(\boldsymbol{V}_i^d - \boldsymbol{V}_j^d)$$

$$\boldsymbol{I}_i^d = a_{ii}\boldsymbol{V}_i^d$$

$$\tilde{\boldsymbol{I}}_i^d \geq I_i^d, \qquad \tilde{\boldsymbol{I}}_i^d \geq -I_i^d$$

GIC injections and magnitudes

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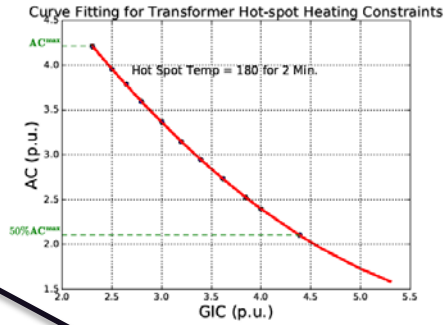
GIC effects on Transformers

$$\boldsymbol{I}_{ij}^a \leq \eta_{ij}^0 + \eta_{ij}^1 \tilde{\boldsymbol{I}}_i^d + \eta_{ij}^2 (\tilde{\boldsymbol{I}}_i^d)^2$$

Transformer heating

$$\boldsymbol{Q}_i^{loss} = K_i V_{pu,i} \boldsymbol{I}_i^d$$

Induced reactive losses



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Coupled Model: Safe Operating Temperatures

$$min \sum_{i \in N} c_2 (\boldsymbol{f}_i^p)^2 + c_1 \boldsymbol{f}_i^p + c_0$$

Minimize generation dispatch costs

$$\sum_{j:(ij) \in E} \boldsymbol{p}_{ij} = \boldsymbol{f}_i^p - d_i^p - \boldsymbol{V}_i^2 g_i$$

$$\sum_{j:(ij) \in E} \boldsymbol{q}_{ij} = \boldsymbol{f}_i^q - d_i^q + \boldsymbol{V}_i^2 b_i - \boldsymbol{Q}_i^{loss}$$

Power flow balance constraints

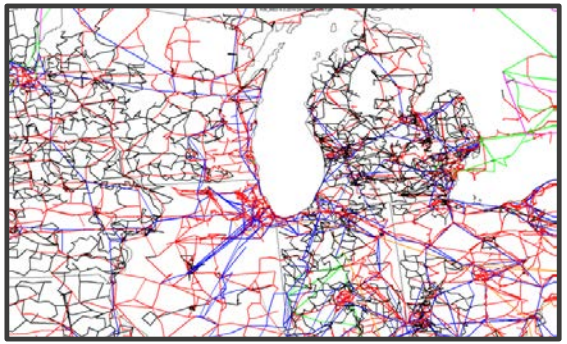
$$\boldsymbol{p}_{ij} = g_{ij} \boldsymbol{V}_i^2 - \boldsymbol{V}_i \boldsymbol{V}_j g_{ij} \cos(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j) - \boldsymbol{V}_i \boldsymbol{V}_j b_{ij} \sin(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j)$$

$$\boldsymbol{q}_{ij} = -\left(b_{ij} + \frac{c_{ij}}{2}\right) \boldsymbol{V}_i^2 + \boldsymbol{V}_i \boldsymbol{V}_j b_{ij} \cos(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j) - \boldsymbol{V}_i \boldsymbol{V}_j g_{ij} \sin(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j)$$

$$\boldsymbol{p}_{ji} = g_{ij} \boldsymbol{V}_i^2 - \boldsymbol{V}_i \boldsymbol{V}_j g_{ij} \cos(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i) - \boldsymbol{V}_i \boldsymbol{V}_j b_{ij} \sin(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i)$$

$$\boldsymbol{q}_{ji} = -\left(b_{ij} + \frac{c_{ij}}{2}\right) \boldsymbol{V}_i^2 + \boldsymbol{V}_i \boldsymbol{V}_j b_{ij} \cos(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i) - \boldsymbol{V}_i \boldsymbol{V}_j g_{ij} \sin(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i)$$

Real and Reactive Power Flow Equations



$$\boldsymbol{p}_{ij} + \boldsymbol{p}_{ji} = r_{ij}\left(\boldsymbol{l}_{ij} + c_{ij} \boldsymbol{q}_{ij} + \left(\frac{c_{ij}}{2}\right)^2 \boldsymbol{V}_i^2\right)$$

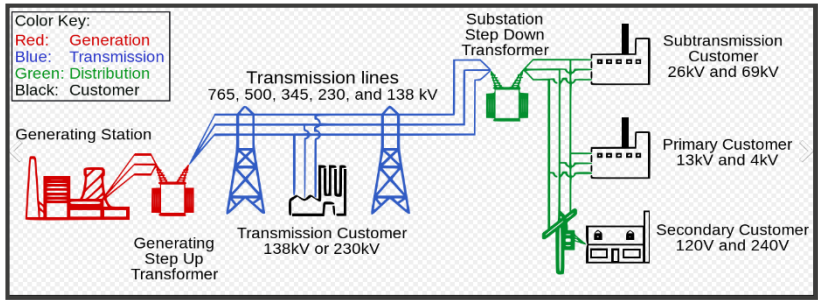
$$\boldsymbol{q}_{ij} + \boldsymbol{q}_{ji} = x_{ij}\left(\boldsymbol{l}_{ij} + c_{ij} \boldsymbol{q}_{ij} + \left(\frac{c_{ij}}{2}\right)^2 \boldsymbol{V}_i^2\right)$$

Power loss equations

$$\boldsymbol{p}_{ij}^2 + \boldsymbol{q}_{ij}^2 = \boldsymbol{l}_{ij} \boldsymbol{V}_i^2$$

$$\boldsymbol{l}_{ij} = \left(\boldsymbol{I}_{ij}^a\right)^2$$

Apparent and Current Power Flow Equations



Mitigation: Load Shedding and Line Switching

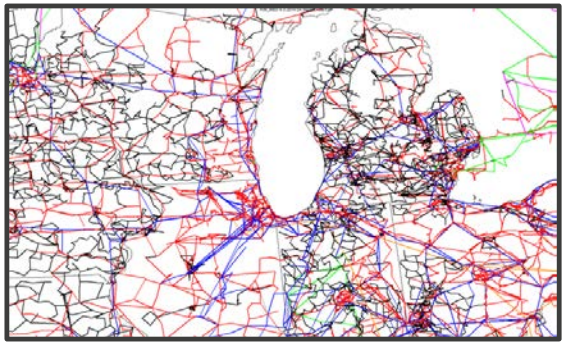
$$min \sum_{i \in N} c_2(\boldsymbol{f}_i^p)^2 + c_1 \boldsymbol{f}_i^p + c_0 + \lambda_i \boldsymbol{l}_i^p + \lambda_i \boldsymbol{l}_i^q$$

Minimize generation dispatch costs and load shedding costs

$$\sum_{j:(ij) \in E} \boldsymbol{p}_{ij} = \boldsymbol{f}_i^p - d_i^p + l_i^p - \boldsymbol{V}_i^2 g_i$$

$$\sum_{j:(ij) \in E} \boldsymbol{q}_{ij} = \boldsymbol{f}_i^q - d_i^q + l_i^q + \boldsymbol{V}_i^2 b_i - \boldsymbol{Q}_i^{loss}$$

Power flow balance constraints



$$\boldsymbol{p}_{ij} = y_{ij}(g_{ij}\boldsymbol{V}_i^2 - \boldsymbol{V}_i\boldsymbol{V}_j g_{ij} \cos(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j) - \boldsymbol{V}_i\boldsymbol{V}_j b_{ij} \sin(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j))$$

$$\boldsymbol{q}_{ij} = -y_{ij}(\left(b_{ij} + \frac{c_{ij}}{2}\right)\boldsymbol{V}_i^2 + \boldsymbol{V}_i\boldsymbol{V}_j b_{ij} \cos(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j) - \boldsymbol{V}_i\boldsymbol{V}_j g_{ij} \sin(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j))$$

$$\boldsymbol{p}_{ji} = y_{ij}(g_{ij}\boldsymbol{V}_i^2 - \boldsymbol{V}_i\boldsymbol{V}_j g_{ij} \cos(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i) - \boldsymbol{V}_i\boldsymbol{V}_j b_{ij} \sin(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i))$$

$$\boldsymbol{q}_{ji} = -y_{ij}(\left(b_{ij} + \frac{c_{ij}}{2}\right)\boldsymbol{V}_i^2 + \boldsymbol{V}_i\boldsymbol{V}_j b_{ij} \cos(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i) - \boldsymbol{V}_i\boldsymbol{V}_j g_{ij} \sin(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i))$$

Real and Reactive Power Flow Equations

$$\boldsymbol{p}_{ij} + \boldsymbol{p}_{ji} = y_{ij} r_{ij}(\boldsymbol{l}_{ij} + c_{ij}\boldsymbol{q}_{ij} + \left(\frac{c_{ij}}{2}\right)^2 \boldsymbol{V}_i^2)$$

$$\boldsymbol{q}_{ij} + \boldsymbol{q}_{ji} = y_{ij} x_{ij}(\boldsymbol{l}_{ij} + c_{ij}\boldsymbol{q}_{ij} + \left(\frac{c_{ij}}{2}\right)^2 \boldsymbol{V}_i^2)$$

Power loss equations

$$\boldsymbol{p}_{ij}^2 + \boldsymbol{q}_{ij}^2 = \boldsymbol{l}_{ij}\boldsymbol{V}_i^2$$

$$\boldsymbol{l}_{ij} = \left(\boldsymbol{I}_{ij}^a\right)^2$$

Apparent and Current Power Flow Equations

Load Shedding: Reduce AC Loading on Transformers and Increase Voltages

Line Switching: Reduce AC Loading on Transformers and Shift Voltages

Mitigation: Load Shedding and Line Switching

GIC power flow equations

$$\sum_{j:(ij)\in E} y_{ij} j_{ij} = \boldsymbol{I}_i^d - \sum_{j:(ij)\in E} y_{ij} a_{ij} (\boldsymbol{V}_i^d - \boldsymbol{V}_j^d)$$

$$\boldsymbol{I}_i^d = a_{ii} \boldsymbol{V}_i^d$$

$$\tilde{\boldsymbol{I}}_i^d \geq I_i^d, \qquad \tilde{\boldsymbol{I}}_i^d \geq -I_i^d$$

GIC injections and magnitudes

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Line Switching: Reduce DC Loading on Transformers

GIC effects on Transformers

$$\boldsymbol{I}_{ij}^a \leq \eta_{ij}^0 + \eta_{ij}^1 \tilde{\boldsymbol{I}}_i^d + \eta_{ij}^2 \left(\tilde{\boldsymbol{I}}_i^d\right)^2$$

Transformer heating

$$\boldsymbol{Q}_i^{loss} = K_i V_{pu,i} \boldsymbol{I}_i^d$$

Induced reactive losses

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Zhu, Hao, and Thomas J. Overbye. *Blocking device placement for mitigating the effects of geomagnetically induced currents*. *IEEE Transactions on Power Systems* 30.4 (2015): 2081-2089

Computational Challenge: Non-Convex Optimization

$$min \sum_{i \in N} c_2(\boldsymbol{f}_i^p)^2 + c_1 \boldsymbol{f}_i^p + c_0 + \lambda_i \boldsymbol{l}_i^p + \lambda_i \boldsymbol{l}_i^q$$

$$\sum_{j:(ij)\in E} \boldsymbol{p}_{ij} = \boldsymbol{f}_i^p - d_i^p + l_i^p - \boldsymbol{V}_i^2 g_i$$

$$\sum_{j:(ij)\in E} \boldsymbol{q}_{ij} = \boldsymbol{f}_i^q - d_i^q + l_i^q + \boldsymbol{V}_i^2 b_i - \boldsymbol{Q}_i^{loss}$$

Discrete Variables

$$\boldsymbol{p}_{ij} = y_{ij}(g_{ij}\boldsymbol{V}_i^2 - \boldsymbol{V}_i\boldsymbol{V}_j g_{ij} \cos(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j) - \boldsymbol{V}_i\boldsymbol{V}_j b_{ij} \sin(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j))$$

$$\boldsymbol{q}_{ij} = -y_{ij}(\left(b_{ij} + \frac{c_{ij}}{2}\right)\boldsymbol{V}_i^2 + \boldsymbol{V}_i\boldsymbol{V}_j b_{ij} \cos(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j) - \boldsymbol{V}_i\boldsymbol{V}_j g_{ij} \sin(\boldsymbol{\theta}_i - \boldsymbol{\theta}_j))$$

$$\boldsymbol{p}_{ji} = y_{ij}(g_{ij}\boldsymbol{V}_i^2 - \boldsymbol{V}_i\boldsymbol{V}_j g_{ij} \cos(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i) - \boldsymbol{V}_i\boldsymbol{V}_j b_{ij} \sin(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i))$$

$$\boldsymbol{q}_{ji} = -y_{ij}(\left(b_{ij} + \frac{c_{ij}}{2}\right)\boldsymbol{V}_i^2 + \boldsymbol{V}_i\boldsymbol{V}_j b_{ij} \cos(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i) - \boldsymbol{V}_i\boldsymbol{V}_j g_{ij} \sin(\boldsymbol{\theta}_j - \boldsymbol{\theta}_i))$$

Trigometric functions

$$\boldsymbol{p}_{ij} + \boldsymbol{p}_{ji} = y_{ij} r_{ij}(\boldsymbol{l}_{ij} + c_{ij}\boldsymbol{q}_{ij} + \left(\frac{c_{ij}}{2}\right)^2 \boldsymbol{V}_i^2)$$

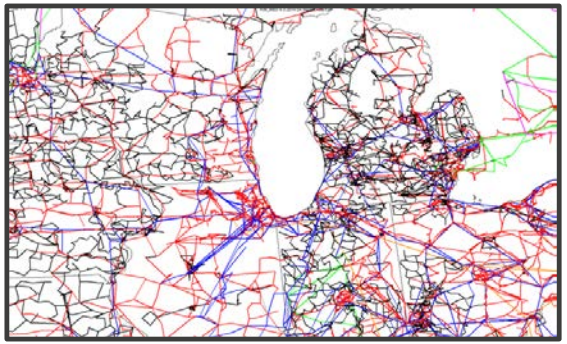
$$\boldsymbol{q}_{ij} + \boldsymbol{q}_{ji} = y_{ij} x_{ij}(\boldsymbol{l}_{ij} + c_{ij}\boldsymbol{q}_{ij} + \left(\frac{c_{ij}}{2}\right)^2 \boldsymbol{V}_i^2)$$

Bilinear functions

$$\boldsymbol{p}_{ij}^2 + \boldsymbol{q}_{ij}^2 = \boldsymbol{l}_{ij}\boldsymbol{V}_i^2$$

$$\boldsymbol{l}_{ij} = \left(\boldsymbol{I}_{ij}^a\right)^2$$

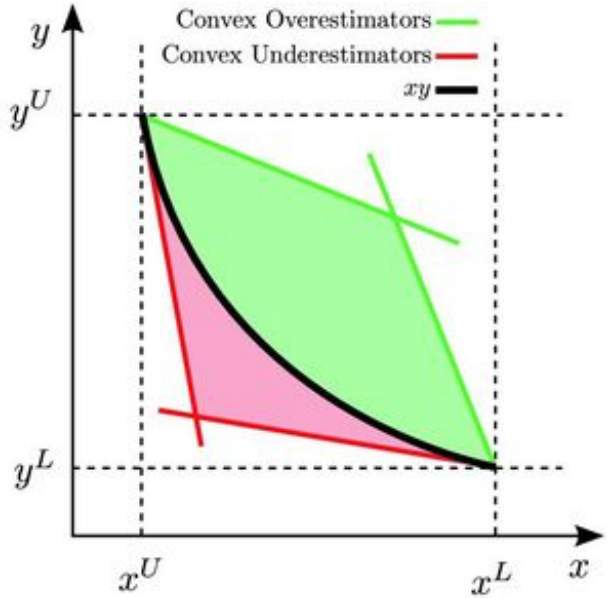
Quadratic terms with equality



NP-Hardness

Solution: Convex Relaxations

- **Replace non-convex terms with convex envelopes (Ex: McCormick)**
  - See Coffrin, van Hentenryck, and Hijazi 2014, 2016
- Solution with convex envelope is a *lower bound* on the solution to the original problem



Bilinear terms (McCormick, 1976)

$$\boxed{\widehat{x_{ij}} \in \langle x_i, x_j \rangle^{MC}}$$

$$\widehat{x_{ij}} \geq x_i^l x_j + x_j^l x_i - x_i^l x_j^l$$

$$\widehat{x_{ij}} \geq x_i^u x_j + x_j^u x_i - x_i^u x_j^u$$

$$\widehat{x_{ij}} \leq x_i^l x_j + x_j^u x_i - x_i^l x_j^u$$

$$\widehat{x_{ij}} \leq x_i^u x_j + x_j^l x_i - x_i^u x_j^l$$

Mitigation Algorithm

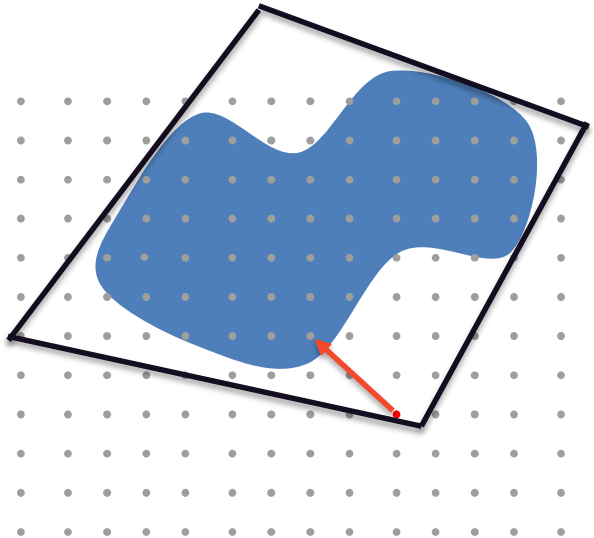
Relaxed solution is a lower bound, but may not be feasible (actionable)

Algorithm $\mathbf{GMDMitigation}(M)$

$\quad \underline{\sigma} \leftarrow \mathbf{SolveRelaxation}(M)$

$\quad \overline{\sigma} \leftarrow \mathbf{SolveNLP}(M, \underline{\sigma})$

$\mathbf{return}\ \langle \underline{\sigma}, \overline{\sigma} \rangle$



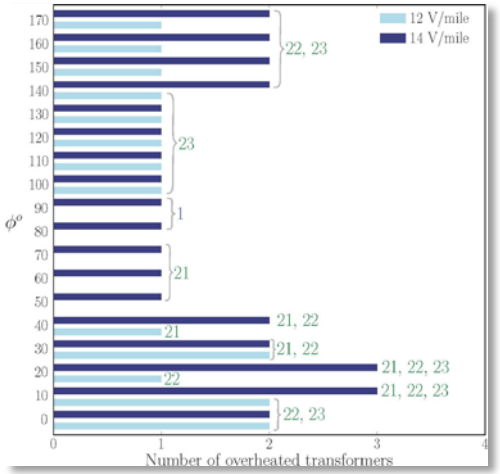
Overview

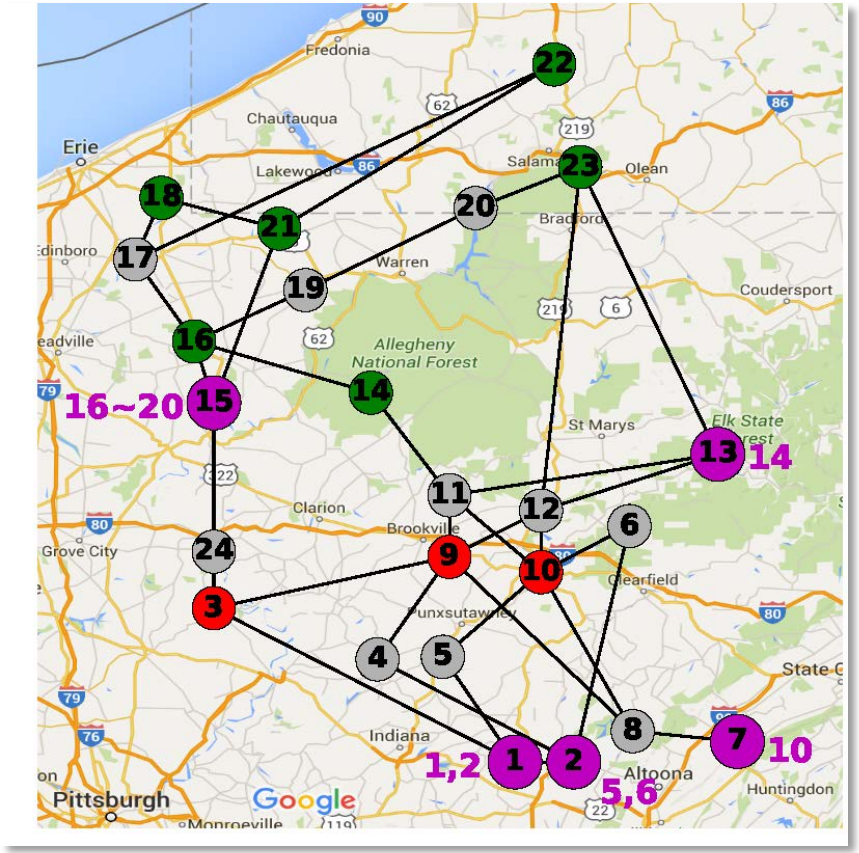
1. **Find the solution to the relaxation (lower bound).**
2. **Use gradient descent to recover a feasible solution (upper bound)**
3. **Return both solutions**

Case Study

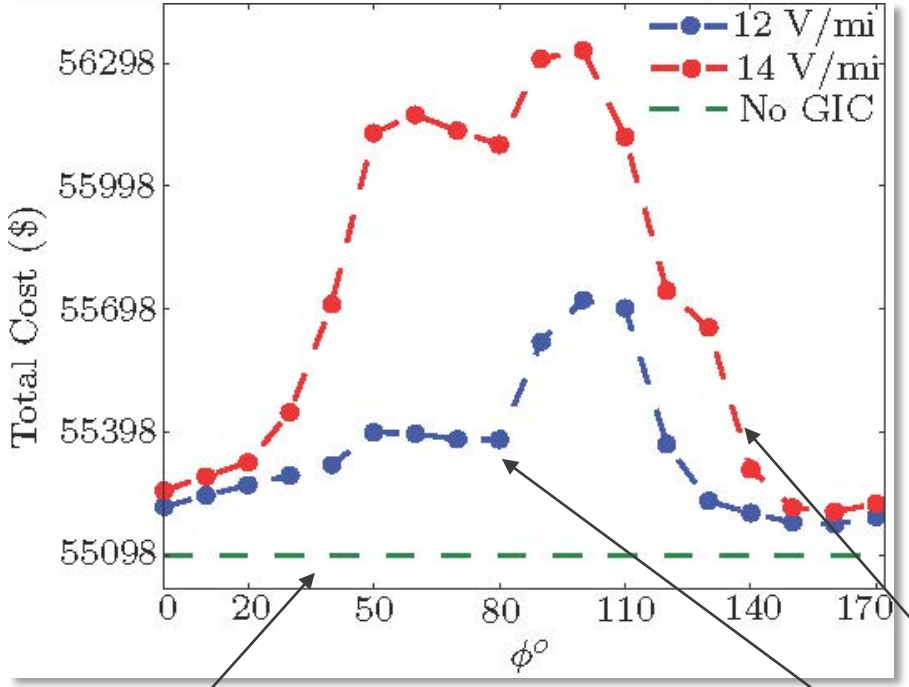
- Notional power system model
- IEEE RTS System
  - 3 transformers (red)
  - 5 nodes with generators (purple) - transformers
  - 6 nodes with load (green)
- Uniform field strength applied at angle ϕ

<u>Overloads without mitigation</u>





Cost of Mitigation

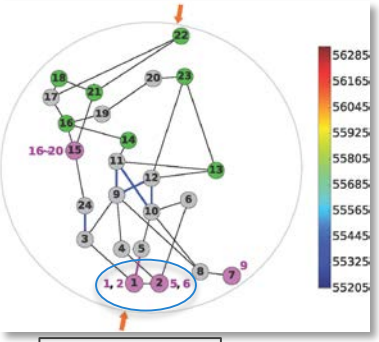


Under modest GMD, operational adjustments can preserve equipment

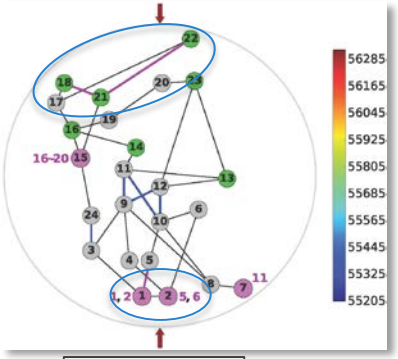
No GMD Cost

With GMD Cost

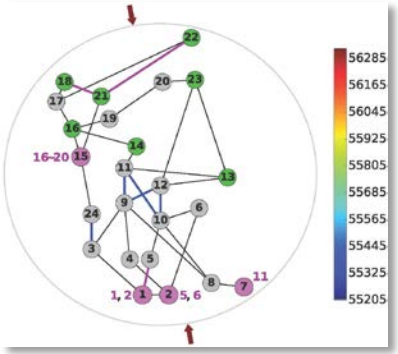
Solution Features



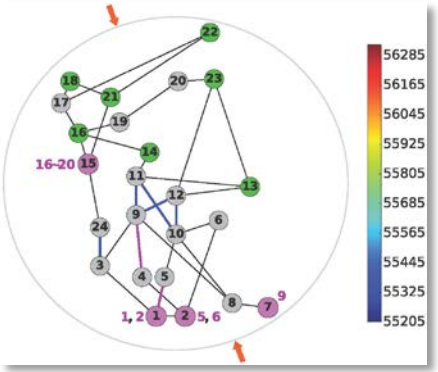
14 V/miles 80º



14 V/miles 90º



14 V/miles 100º



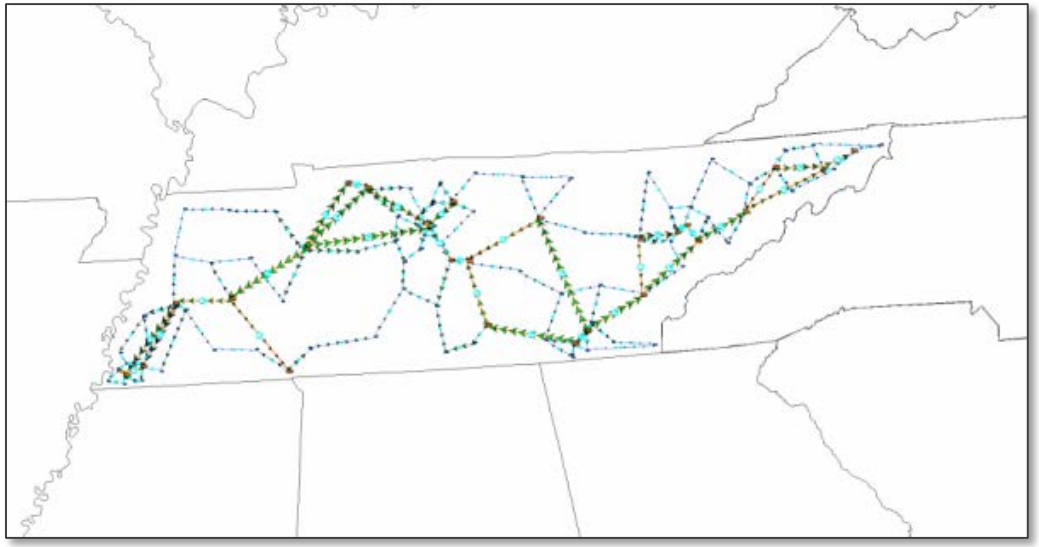
14 V/miles 110º

<u>14 V/miles applied to different directions</u>

- 80º - One line switched off
- 90º – Three lines switched off, and cost of mitigation increases
- 100º – Similar to 90º
- 110º – One line switched of, and cost of mitigation decreases

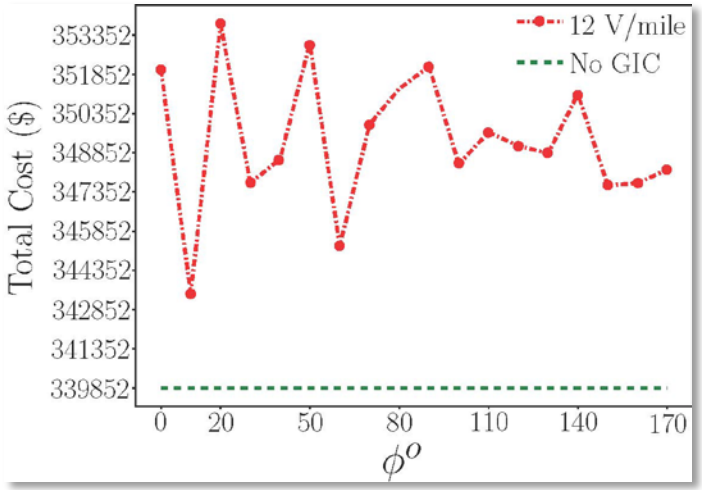
Computational Scalability

UIUC 150 Synthetic System

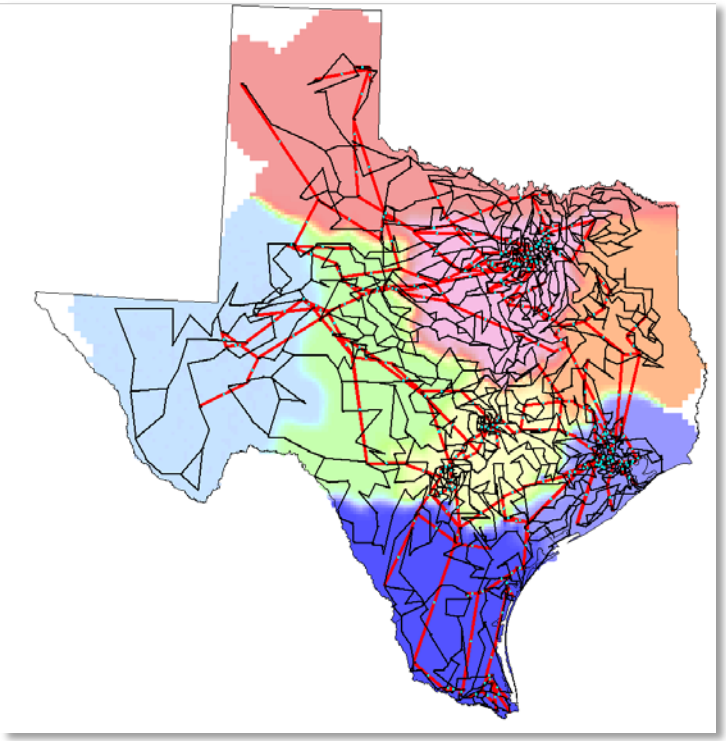


Wall Time (sec)

Strength (V/miles)	Avg.	Min.	Max	Std. Dev.
12	996	649	1587	290
14	1162	508	2896	750



Texas 2000 System



- Synthetic power system overlaid on the state of Texas
- Network is generated to show properties of physical networks
- DC network parameters inferred automatically
- Case Summary
  - 2007 buses
  - 282 generators
  - 1417 loads
  - 2481 lines
  - 562 transformers
  - 49.78 GW / 14.2 GVAR

Contributions

- **The first optimization model of transformer heating as a response to AC and GIC-induced DC**
- **A realistic, coupled model of convex, relaxed AC power flows with GIC effects**
- **An algorithm to recover good, feasible solutions quickly**
- **An optimization problem that protects the system from reactive losses and thermal heating induced by GIC**
- **Software posted here https://github.com/lanl-ansi/PowerModelsGMD.jl**
- **PhD thesis for Mowen Lu, Clemson University**

Mowen Lu, Harsha Nagarajan, Emre Yamangil, Russell Bent, Scott Backhaus, and Arthur Barnes. *Optimal Transmission Line Switching under Geomagnetic Disturbances*. IEEE Transactions on Power Systems, in press.

Future Efforts

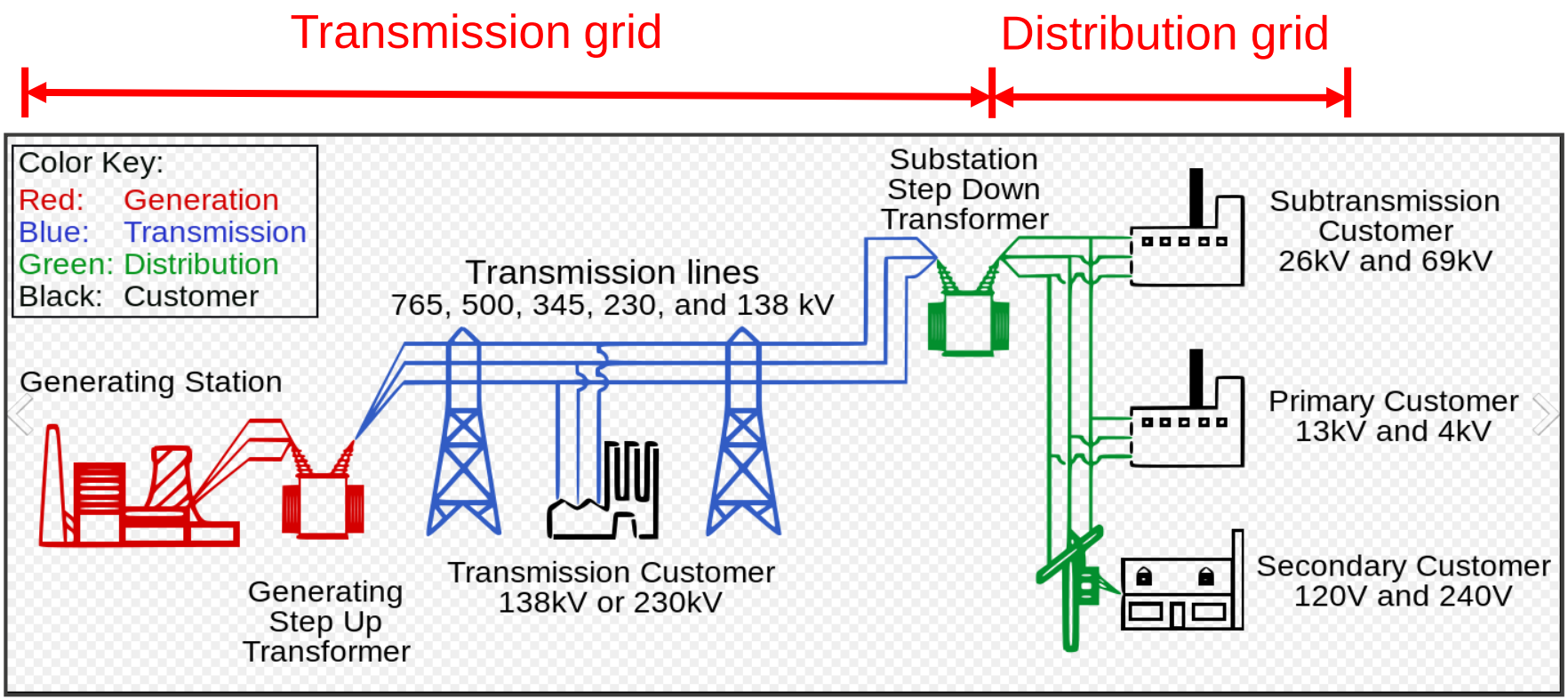
- **Modeling**
  - Current focus – mitigate for peak conditions
  - Effects can build over time
    - Transformer temperature
    - Voltage dynamics – Horton, 2017
- **Uncertainty**
  - GMD Forecasts are not perfect
  - Mitigation that is robust to forecast error
- **Real System Studies**
  - Building a power system data set for the western United States
  - Applying fields generated by other parts of this LDRD to this system
  - Demonstrate integration

Conclusions

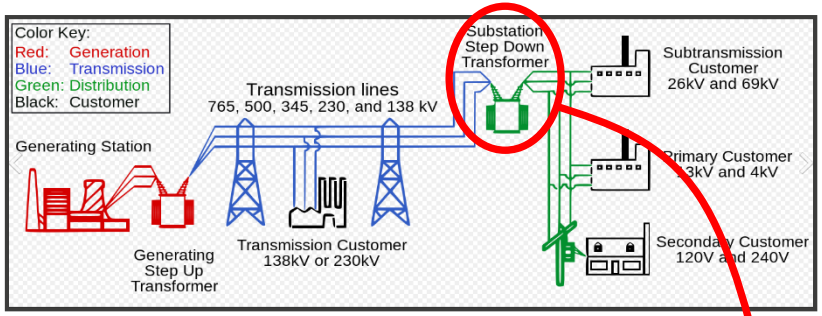
- **Contributions**
  - A model of GIC physics combined with AC power flow physics
    - A model of power system component safety margins
    - Optimization of operations that respect safety margins.
  - Builds on previous work
    - Focused on placing (expensive) blocking devices
    - Minimized a safety metric (reactive power loading at transformers)
      - Overbye et al., 2013, 2015
    - To the best of our knowledge, we have the first model that builds in the safety margins directly
  - A dynamic spatial branching algorithm
- **Publications**
  - H. Nagarajan, M. Lu, E. Yamangil, and R. Bent. *Tightening McCormick Relaxations for Nonlinear Programs via Dynamic Multivariable Partitioning*, 22nd International Conference on Principles and Practice of Constraint Programing, 2016.
  - M. Lu, H. Hagarajan, E. Yamangil, R. Bent, and S. Backhaus. *Optimal Transmission Line Switching under Geomagnetic Disturbances*, in progress.

Backup

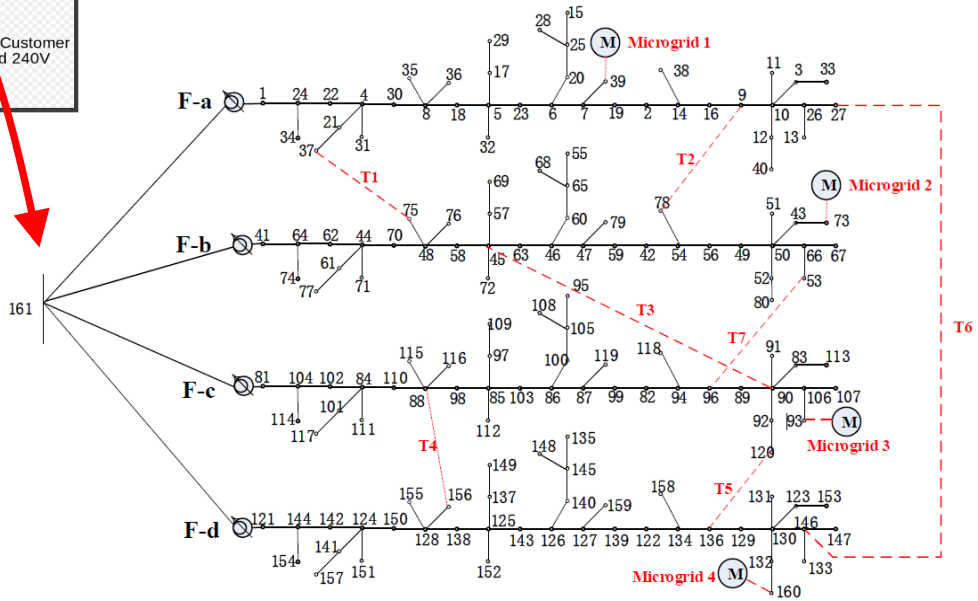
Power Systems Basics: Components and Subsystems



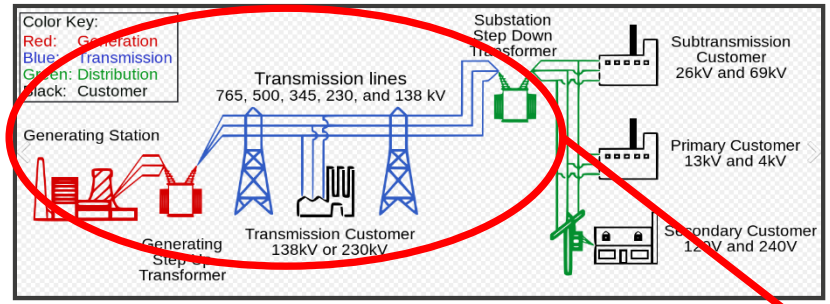
Power Systems Basics: Distribution Grids

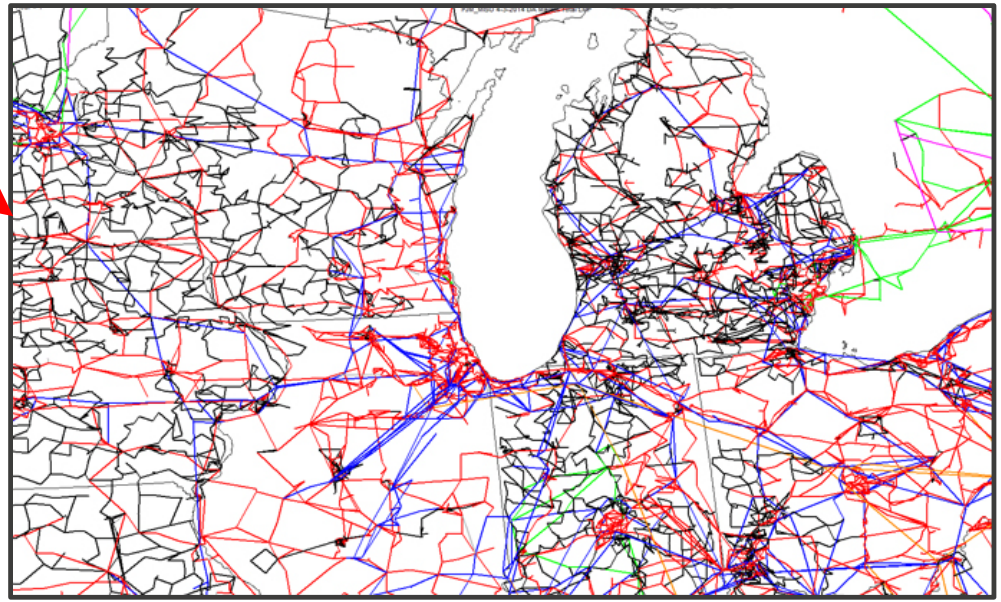


- **Tree-like topology**
- **Load served ~ 10's of MW per network**
  - Impact is relatively small if entire network is lost
  - Minor interaction between networks
- **Less interaction with GMD and geo-electric fields**
  - Spatial extent ~ 10 miles
  - Relatively high network resistance
- **…. Less attention paid to GMD effects on distribution**



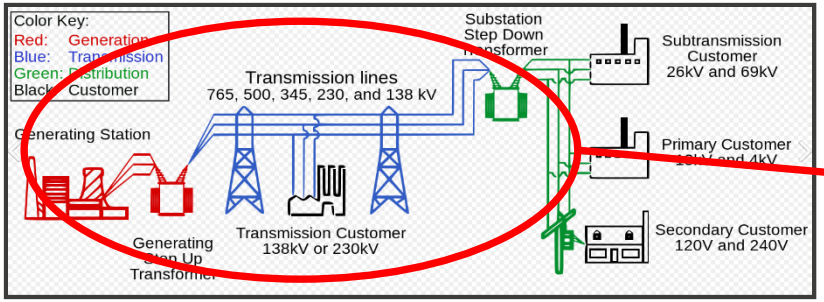
Power System Basics: Transmission Grids

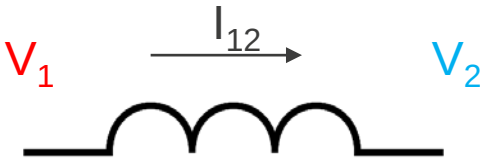




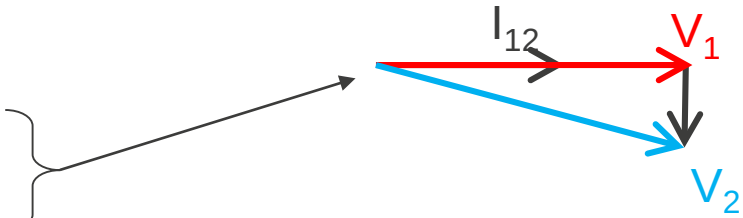
- **Meshed topology**
- **Load served ~ 100,000 MW**
  - Large impact if entire network is lost
- **Significant interaction with GMD and geo-electric fields**
  - Spatial extent ~ 100's of miles
  - Relatively low network resistance
- **…. GMD effects on transmission have been a ongoing focus of regulators, utilities, national labs, academia**

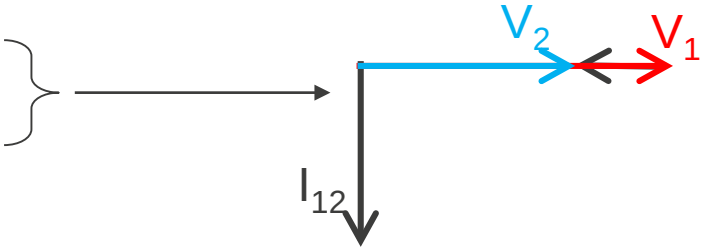
Normal AC Physics @ 60 Hz: Real and Reactive Power



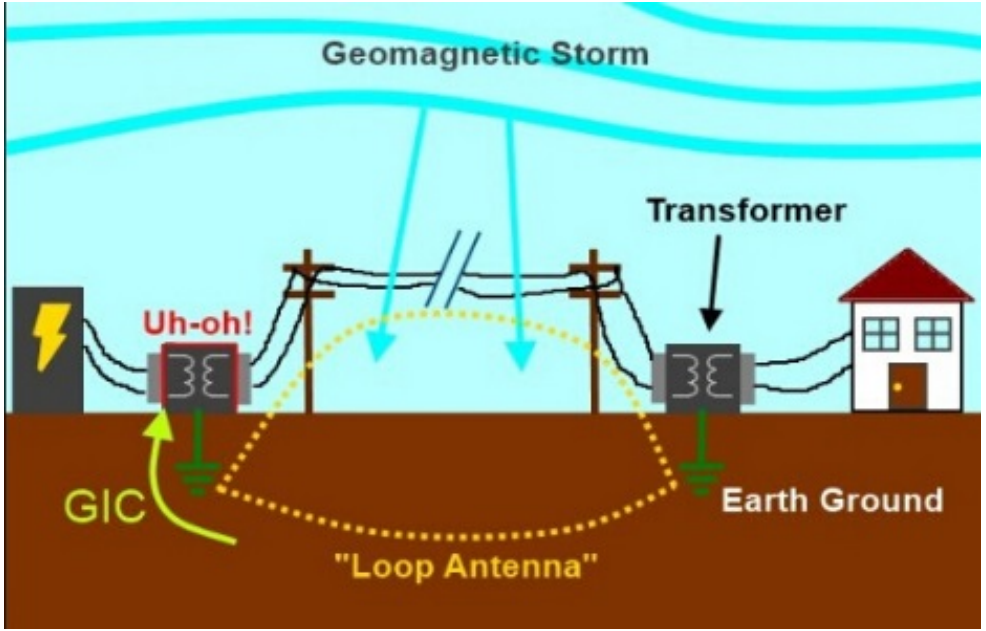


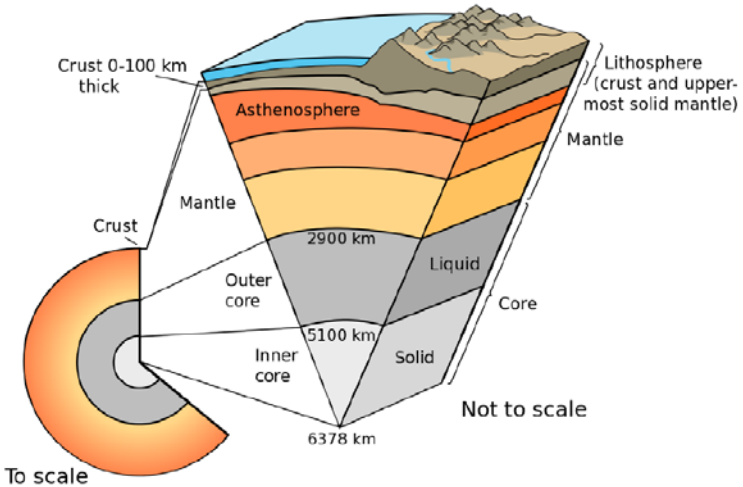
- **Transmission lines impedance typically dominated by reactance**
- **"Real" Power (P)—Current in-phase with voltage**
  - Transmission impedance mostly creates a phase shift of voltage
  - Voltage magnitude nearly fixed
- **"Reactive" Power (Q)—Current out-of-phase with voltage**
  - Transmission impedance mostly creates a change in voltage magnitude
- **"Reactive" Power (Q) is used to control voltage**





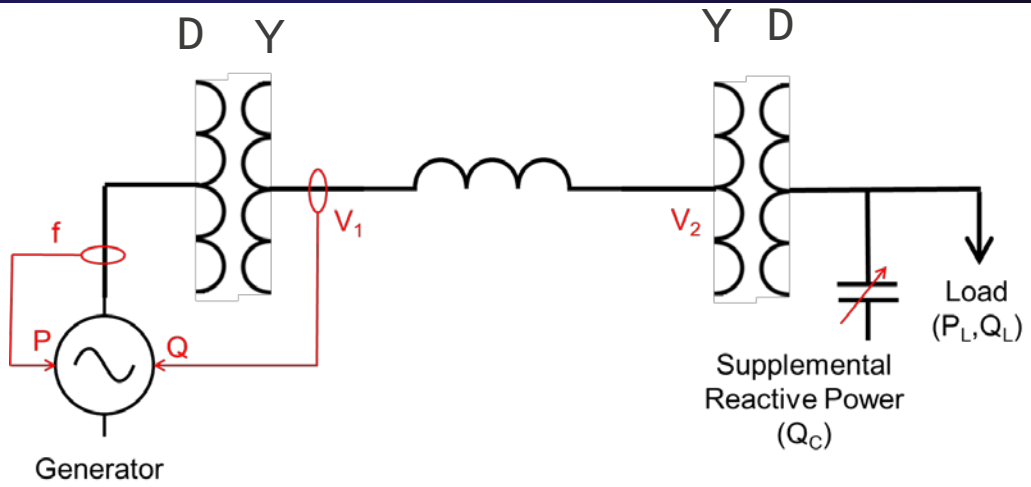
GMD and Physics: DC-Source Terms





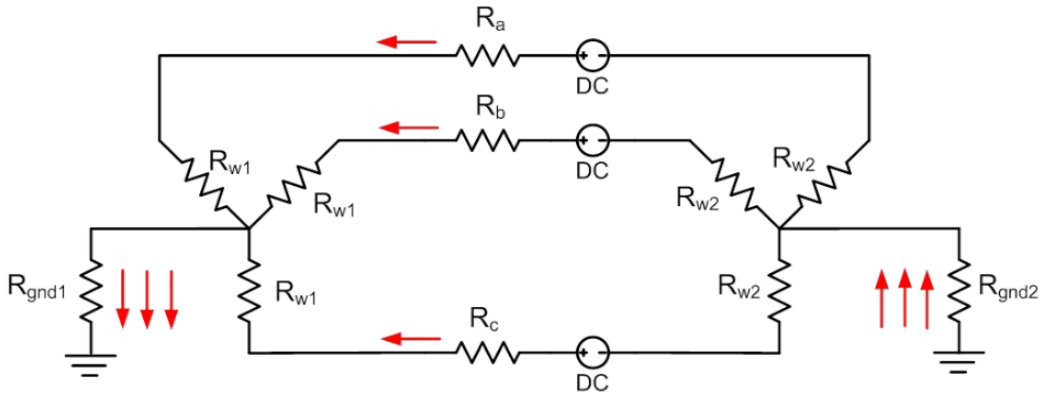
GMD Physics: DC vs AC Network

Simple AC Network—AC power flow is from left to right

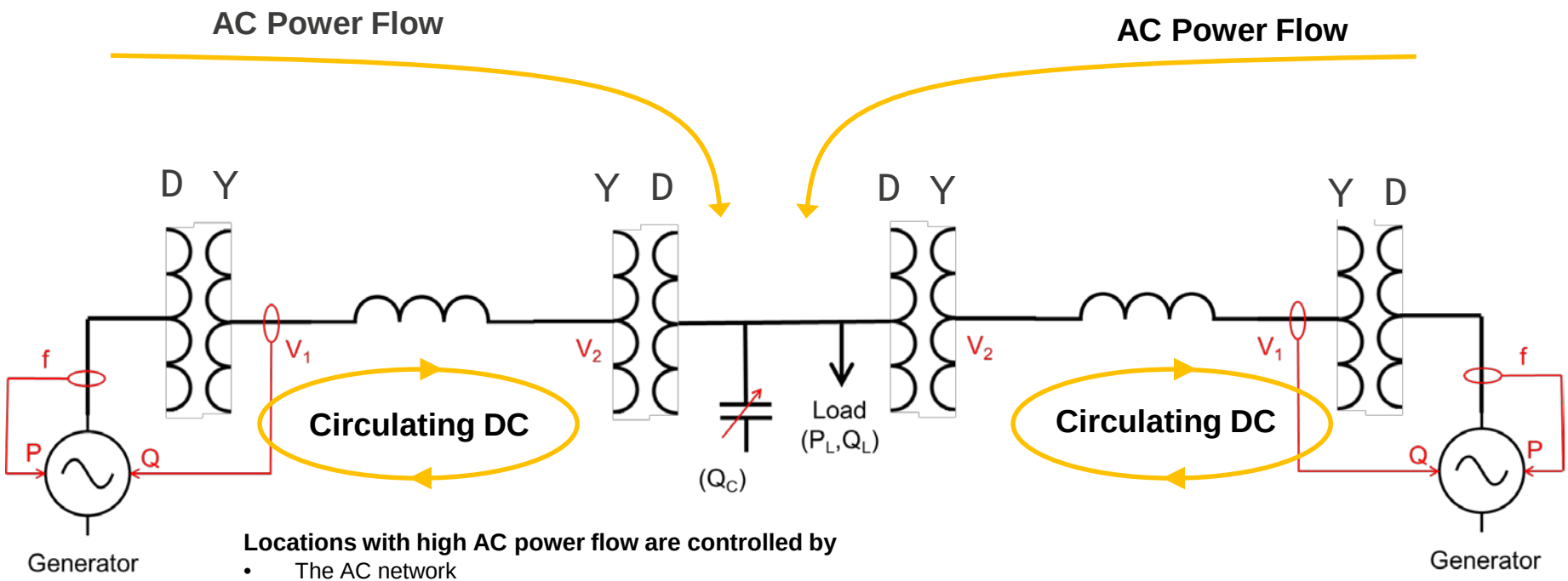


Associated DC Network

- GMD induced DC currents circulate between the two grounded-wye transformers
- No DC current on the ungrounded delta side of the transformers



GMD Physics: AC and DC Networks are Independent



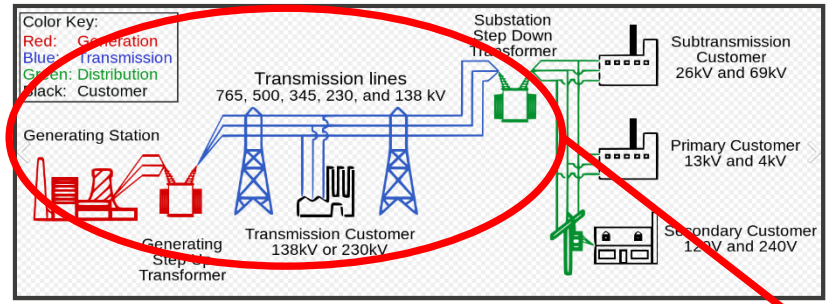
Locations with high AC power flow are controlled by

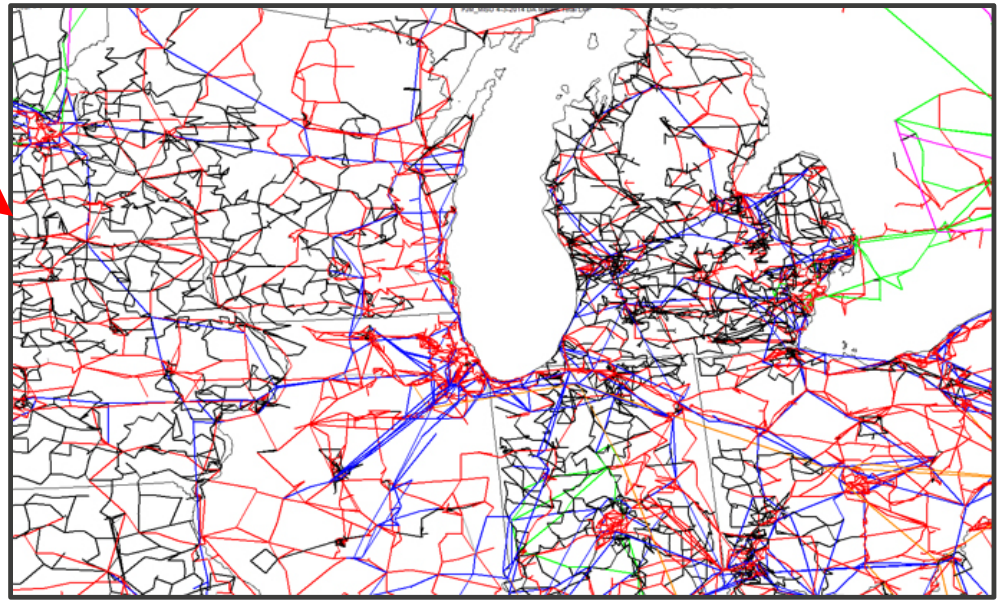
- The AC network
- Generator outputs

Locations with high DC currents

- The DC network
- Strength and orientation of the GMD

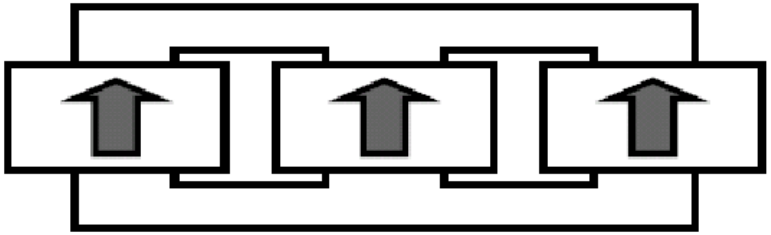
GMD Physics: Real World Interpenetrating AC and DC Networks



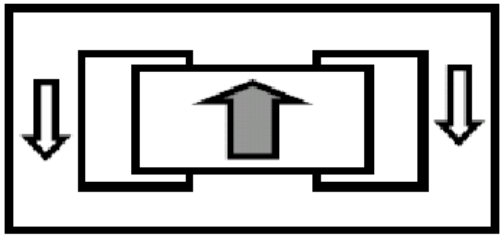


- **AC and DC networks are not completely independent**
- **Interactions occur at the transformers via nonlinearities**
- **Size and interconnectivity of real-world networks make calculation and control of simultaneous of AC and DC flows complex**
  - Simulation tools are becoming mature, but require validation
  - Simultaneous control of AC and DC is emerging R&D

AC and DC Interaction via Transformers

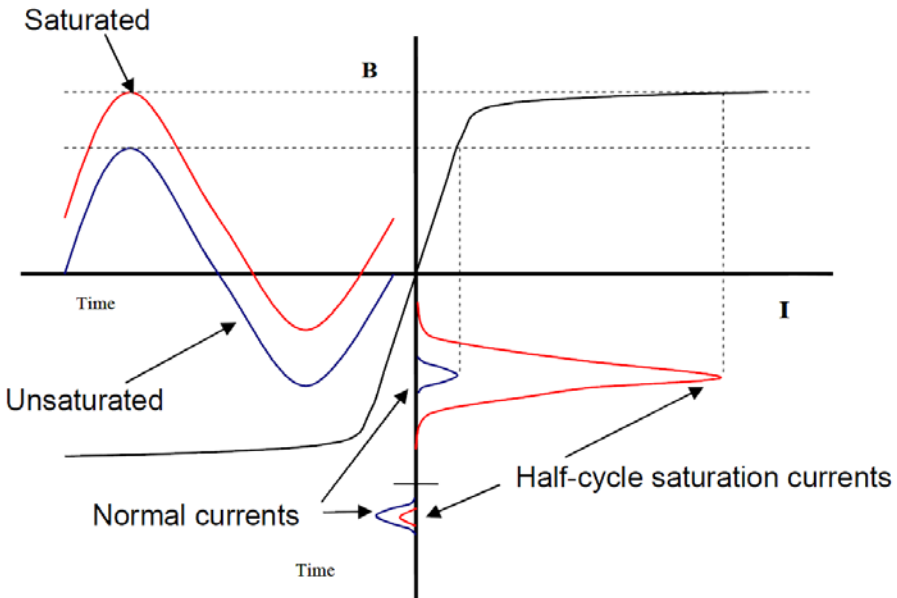


Core Form, 3 phase, 3 limb



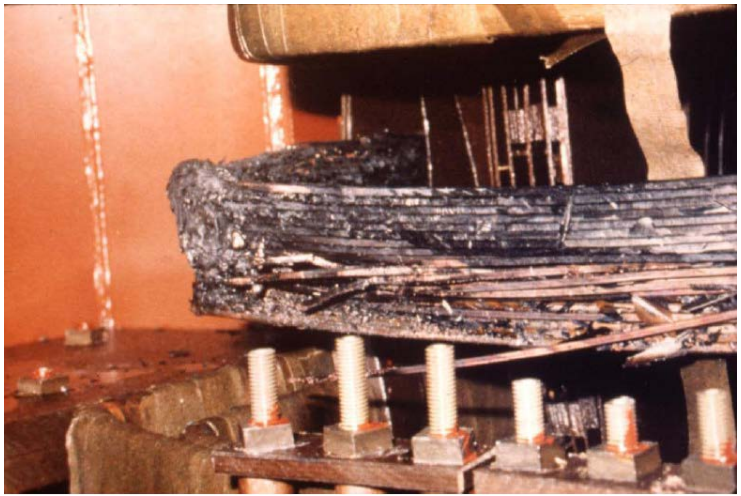
Core / Shell Form, 1 phase

- **DC (GMD) current creates a DC bias to the flux, leading to periodic transformer core saturation**
  - Degree of saturation depends on core configuration
  - Single phase construction is favored for weight and sparing considerations
- **Core saturation leads to:**
  - Stray flux that induces eddy currents in other parts of the transformer structure and housing
  - "Spiky" saturation currents have 60 Hz component—increased reactive (Q) power consumption
  - Significant increase in harmonic generation



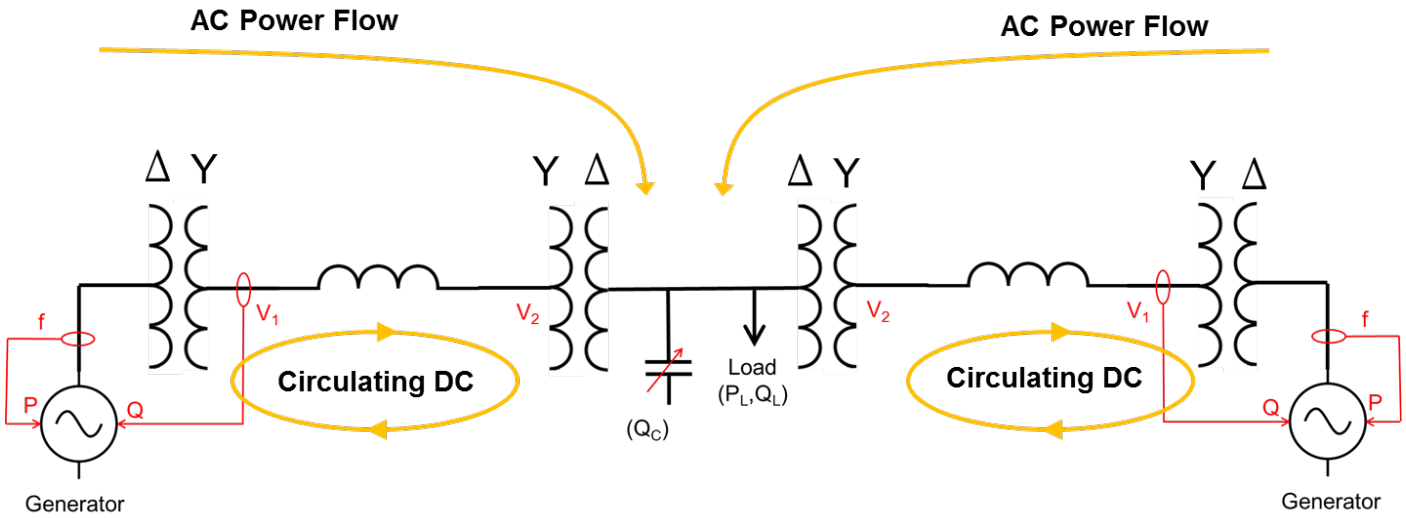
Impacts of Stray Flux

- **Stray flux—If severe enough and left unchecked, eddy current heating can cause permanent damage and subsequent transformer failure**
  - Damage accumulates over time
  - Thermal time constants ~ 5-15 minutes



Impacts of Harmonics and Reactive Power Consumption

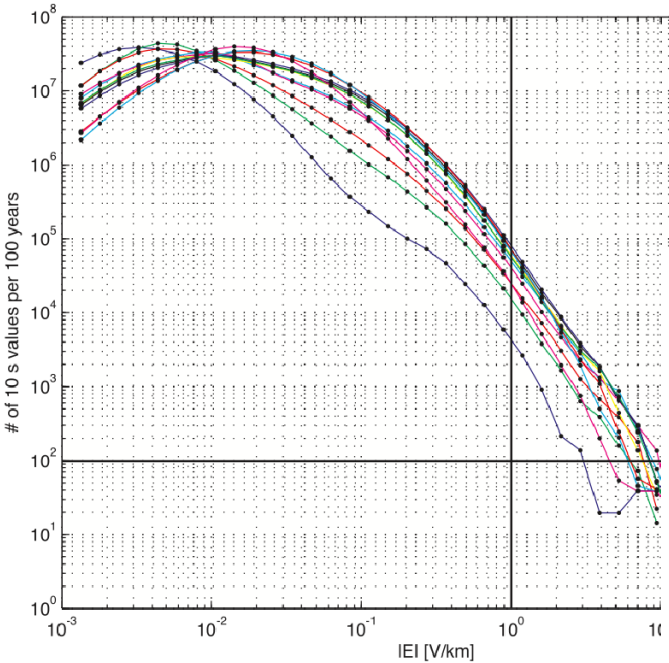
- **Increased reactive power consumption and harmonic generation can generate compounding effects**
  - Harmonics may be misinterpreted by protective relays as a fault or other dangerous condition
  - Subsequent relay misoperation can lead to disconnection of supplemental reactive power support and voltage suppression
  - Continued transformer saturation keeps reactive power loading high
  - System is very susceptible to voltage collapse and cascading failure

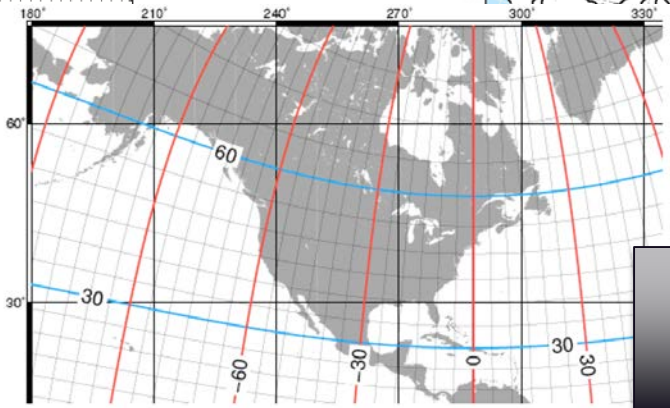


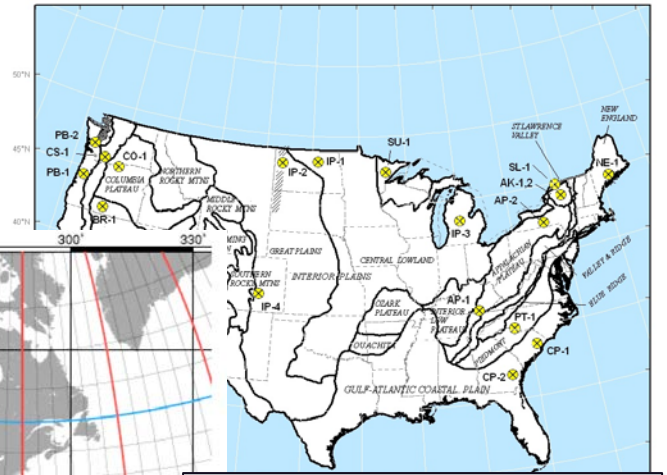
Current State of Practice

FERC (soon to be?) Standard TPL-007-1—A "Phase 1" approach

- **Phase 1—Assess the risk by including GMD simulation studies in required transmission planning studies that evaluate system reliability**
  - Defines a risk screening process for a locally-adapted 1/100 year GMD event



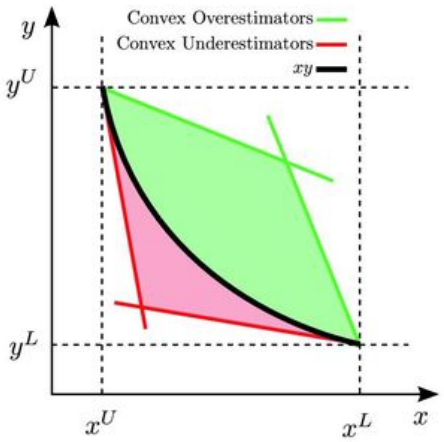




Next Step: Mitigation

Convex Relaxation Weaknesses

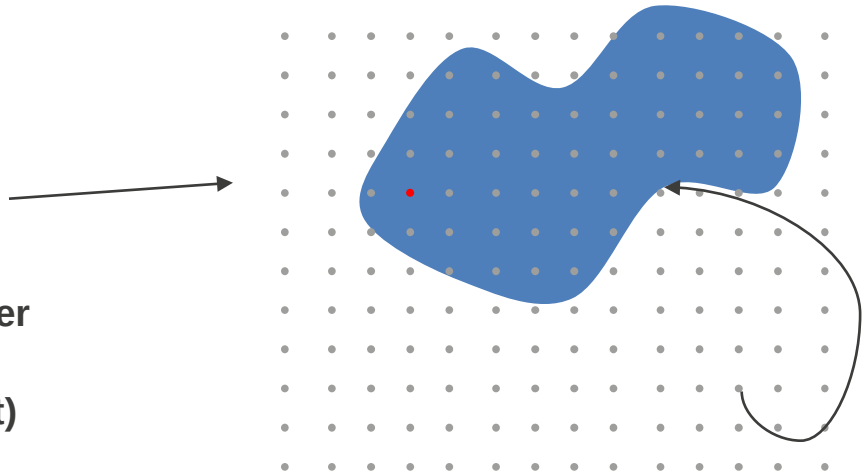
- **The convex envelopes yield good results when the upper and lower bounds on variables are tight**
- **GIC voltages and currents do not have tight bounds**
  - We still have a (weak) lower bound
  - Sometimes “0”
- **Global spatial branching solvers are also challenged**



Bound Tightening

Infer new bounds

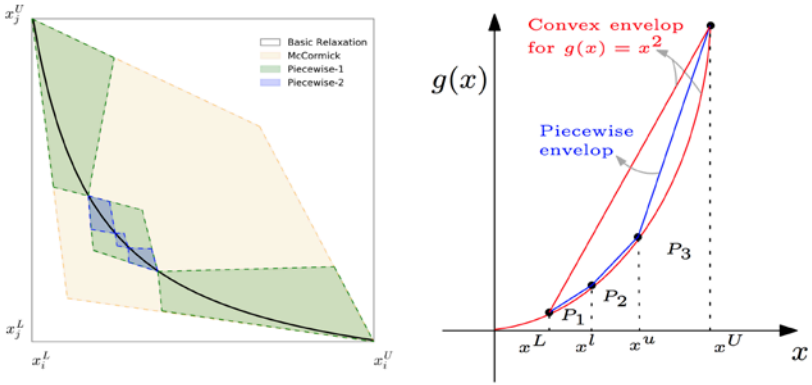
1. **Find a "local" solution to the original non-convex formulation**
   1. Gradient descent
   2. This solution is an upper bound
2. **Introduce a constraint that restricts solutions to have a value <= this upper bound**
3. **For each variable (i.e. GIC DC current) solve 2 problems with the convex formulation**
   1. Maximize the upper bound
   2. Minimize the lower bound
   3. Possible to iterate
4. **This procedure deduces tighter variable bounds that tighten the convex envelopes and improve solution quality**
   – There exist other (better) ways to do this, but this simple approach worked rather well



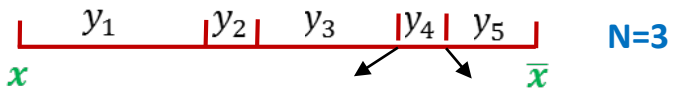
Spatial Branching

Discretize the bounds

1. **Solve the convex relaxation**
2. **Split the bounds of the variables into valid ranges around the relaxed solution**
   1. Applies different convex envelopes depending on the variable choice
   2. Further tightens the relaxation
      1. Drawback: introduces binary variables
3. **Solve again**
4. **Further split the bounds for any variable whose value changes (xlocal)**
5. **Repeat until upper and lower bound are tight**



(a) Bilinear term (b) Quadratic term

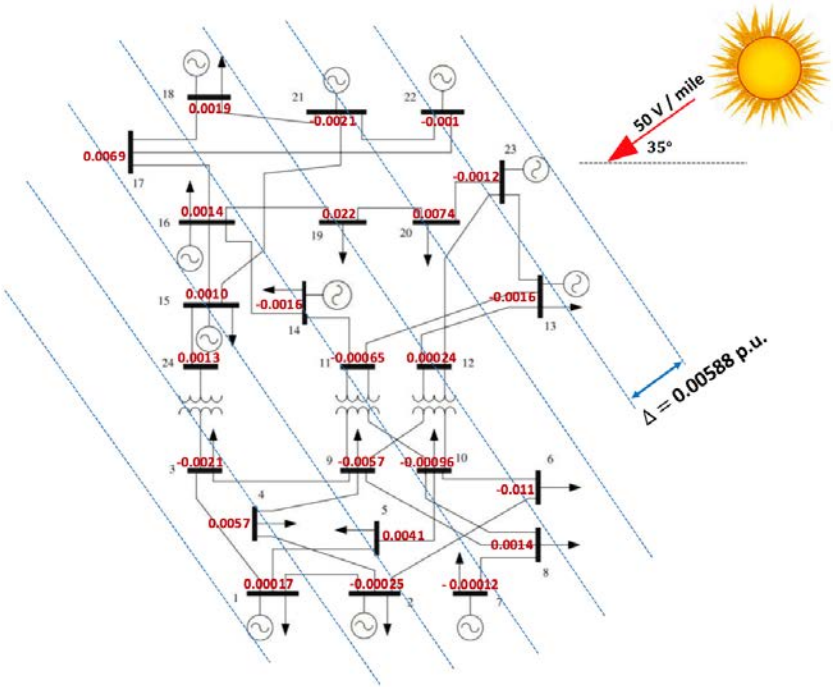


Note: This can be done with log discrete variables (Vielma et al 2010, and others) or SOS constraints

Mitigation Model: Components

PhD Student Intern Project: Mowen Lu

- **Modeled as a network**
  - Nodes
    - Generators (producers of power)
    - Loads (consumers of power)
- **Edges**
  - Power lines
  - Transformers
  - Transport power from one location to another
- **GMD Events (E3)**
  - Introduce a DC current on the system
  - Combination of existing AC current and extra DC current can cause problems



Mitigation Model: High Level

Minimize generation cost and load shedding cost

Subject to:

a) Power flow balance constraints
b) Power flow equations
c) Power loss equations
d) Magnitude of AC current flow equations
e) Operational limits constrains

AC-OTS with reactive power losses induced by GIC

f) GICs calculation equations
g) Magnitude of GICs injection equations
h) Transformer thermal limits constraints
i) Reactive power losses equations
j) Topology decisions

DC-induced network by GMD