Geomagnetic Disturbance Analysis: State Estimation, Integrated GIC and Harmonics Analysis, and the Latest G5 Storm

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Audience Participation: GMD Background

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- Using the “Raise Hand” button 

at the bottom of your screen, please raise your hand if you:
    - Have at least a rudimentary knowledge of geomagnetic disturbances (GMDs), geomagnetically induced currents (GICs) and their effect on the grid
    - Conducted a TPL-007 study (leave your hands up)
    - Assisted with a TPL-007 study (leave your hands up)
    - Have read the results of a TPL-007 study, or any other GMD assessment study (leave your hands up)
    - Have read at least parts of the NERC TPL-007 standard (leave your hands up)
    - Know what NERC TPL-007 is? (you can put your hands down)
    - Attended my GMD webinar a year ago (if you remember)

GMD Analysis Components

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- Modeling
- Data
- Simulations
- Mitigation

GMD Analysis: TPL-007

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- Modeling
    - Geocoordinates, and additional modeling parameters for transmission lines, transformers and substations
- Data
    - E-field information
- Simulations
    - Steady State “worst case”
    - Thermal and Harmonics analysis if needed
- Mitigation
    - If needed

GMD Research at A&M

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- Modeling
    - Geocoordinates, and additional modeling parameters for transmission lines, transformers and substations
    - Transient stability models
    - Transformer thermal models
- Data
    - Spatiotemporally varying e-field waveforms
    - Magnetic field waveforms
    - Earth conductivity

GMD Research at A&M

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- Simulations
  - Power flow time step simulation
  - Transient stability
  - Integrated harmonics and thermal analysis (with EPRI)
  - GIC state estimation

- Mitigation
  - Ongoing work to determine best strategies to mitigate GICs
    - GIC blockers
    - Topology changes
    - Relaying changes to accommodate harmonics

Overview

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- Introduction: What are Geomagnetic Disturbances?
- Geomagnetically Induced Current State Estimation
- Integrated assessment tool in collaboration with EPRI

GMD Short Course: March 18-19, 2025

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- Location: Texas A&M University RELLIS Campus
- Instructors: Tom Overbye, Bob Arritt, Jonathan Snodgrass
- This webinar gives a brief introduction to the topics covered in the GMD short course
- https://epg.engr.tamu.edu/electric-grid-impacts-of-geomagnetic-disturbances/

What is Space Weather?

- Like Earth, the sun has its own weather
  - The solar cycle is around 11 years, compared to earth’s weather cycle of 12 months
  - It has a continuous stream of plasma called the solar wind
  - There are periodic releases of billions of tons of matter in what are called coronal mass ejections (CMEs)
    - When directed towards Earth, they can cause large magnetic storms in the space environment around Earth (the magnetosphere and the upper atmosphere)

Geomagnetic Disturbances

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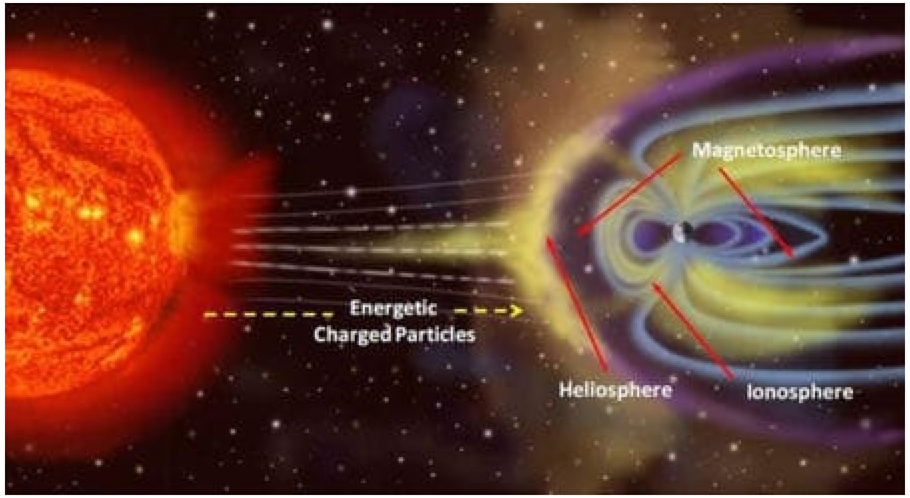
A Geomagnetic Disturbance (GMD) occurs when a CME (Coronal Mass Ejection) hits earth.

A GMD severity is from G1-G5



https://www.naes.com/news/what-is-a-geomagnetic-disturbance-and-how-can-it-affect-the-power-grid/#:~:text=Solar%20flares%20followed%20by%20CMEs,orientation%20of%20the%20magnetic%20field.

Scale	Descriptor	Effect on Power systems	Avg. Frequency (1 cycle = 11 years)
G5	Extreme	Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage.	4 days per cycle
G4	Severe	Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid.	60 days per cycle
G3	Strong	Voltage corrections may be required, false alarms triggered on some protection devices.	130 days per cycle
G2	Moderate	High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage.	360 days per cycle
G1	Minor	Weak power grid fluctuations can occur.	900 days per cycle

https://www.swpc.noaa.gov/noaa-scales-explanation

Effects of Space Weather

Coronal mass ejections (CME's) result from solar activity

High-energy charged particles interact with Earth's magnetic field

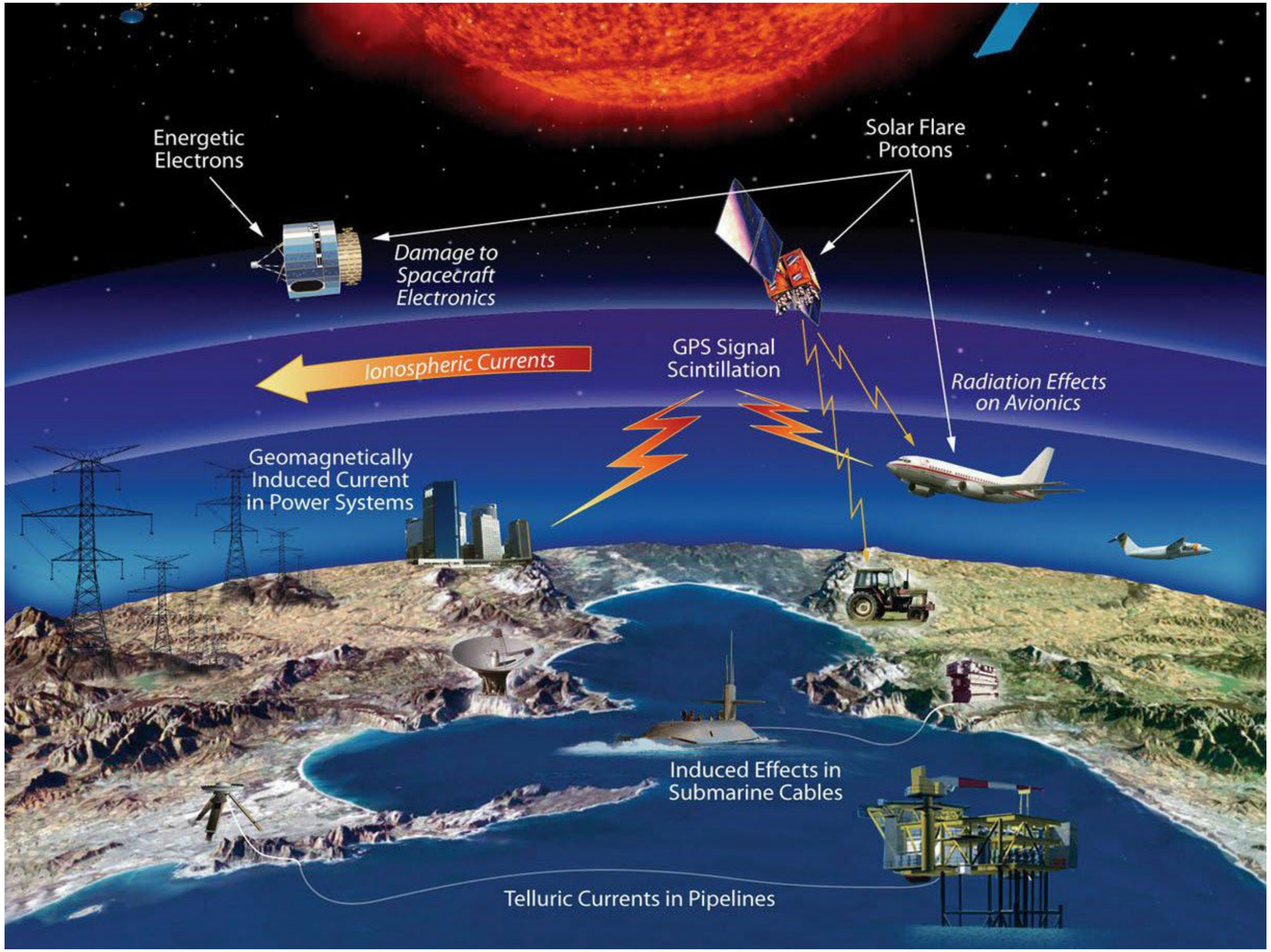
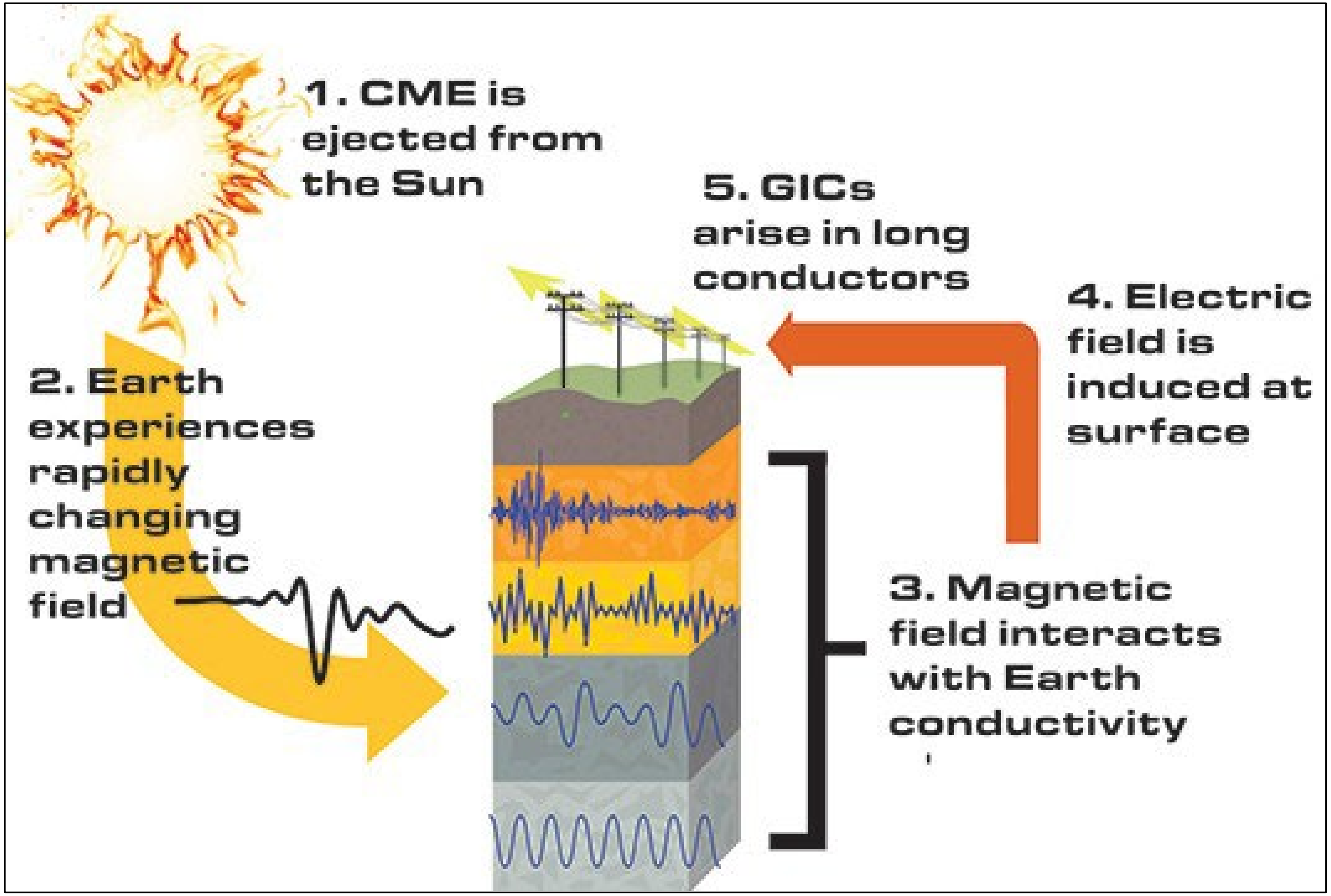


Image Source: https://www.nasa.gov/mission_pages/sunearth/spaceweather/index.html

What causes GICs?



GICs (<0.1 Hz) flow through transmission lines, grounded transformers, and the Earth

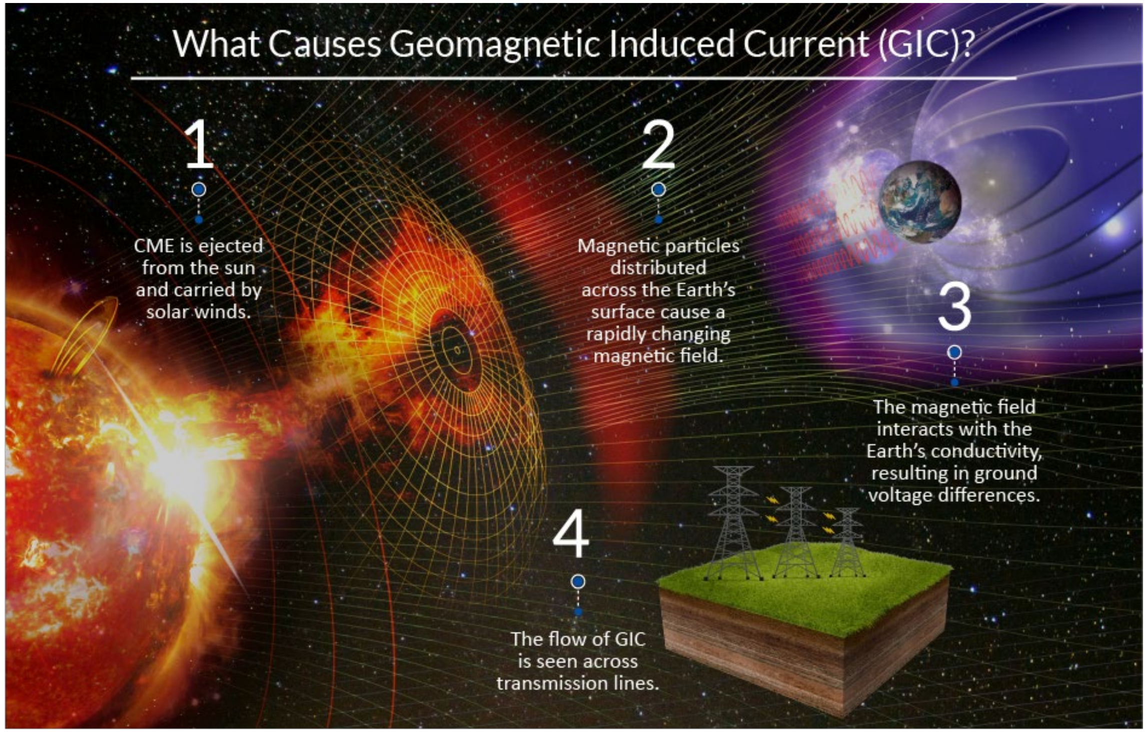
Electric fields are vectors, i.e. have magnitude and direction

Image Source: Dr. Jennifer Gannon, CPI

Geomagnetically Induced Currents

A GMD causes Geomagnetically Induced Currents (GIC)

- GIC are low-frequency, quasi-DC
- GICs can saturate transformers, creating harmonics
- Harmonics can cause nuisance tripping of relays
- Harmonics are modeled by increasing the VAR losses of the transformer
- Increased VAR losses can cause voltage instability



https://www.dynamicratings.com/solutions/geomagnetic-induced-current-monitoring/

G5 Storm, May 10th, 2024

- A G5 storm occurred from May 10-11, 2024
- This was the largest storm to occur since 2000
- Several relays tripped due to harmonics
- Analysis is still ongoing from this storm

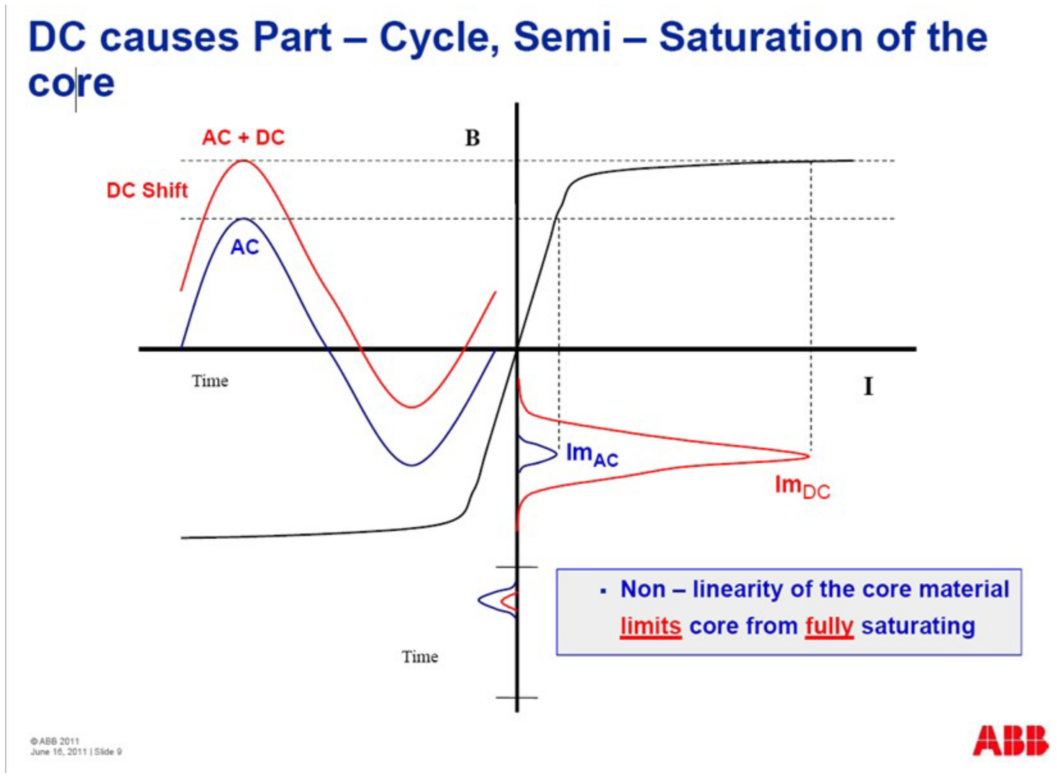
Photo of Aurora Borealis in College Station, Tx on May 10th, 2024
Photo Credit: Rhett Guthrie

G5 Storm, May 10th, 2024; E-Field

Youtube Link to be added

What are the impacts?

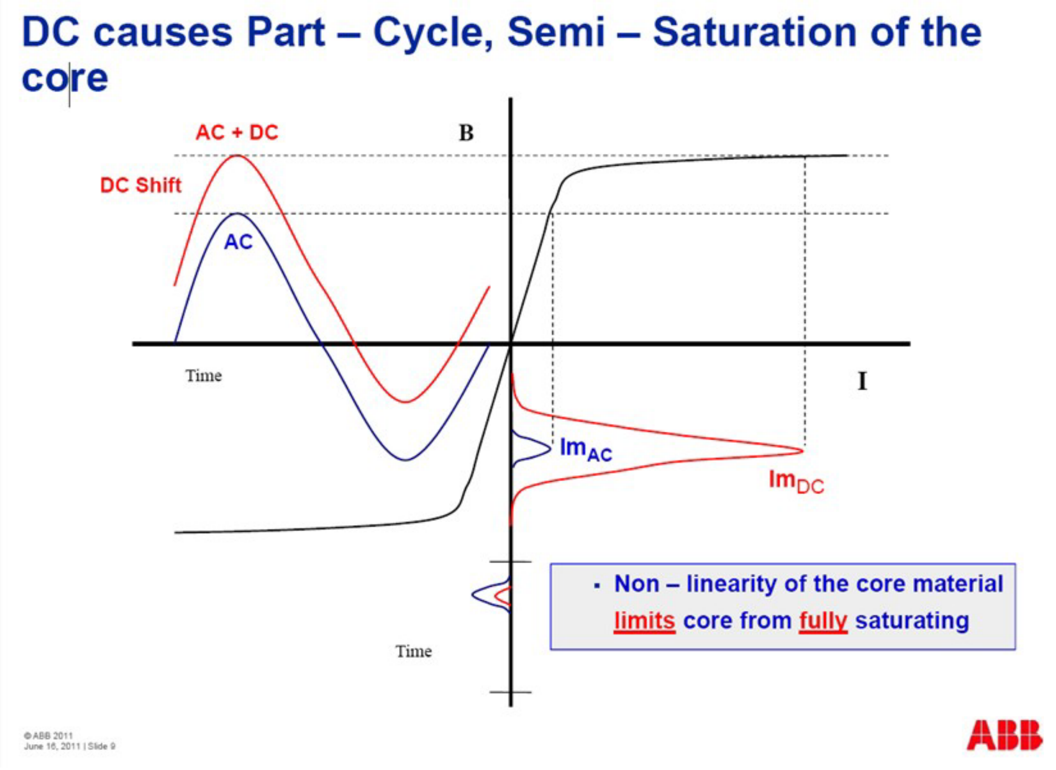
- Superimposition of DC GICs on normal AC grid currents can push transformer flux into saturation for a half-cycle
- This can cause harmonics
  - Why?
  - Fourier series: all waveforms can be represented by a sum of sine and cosine waves
  - Square wave:



$$f(x) = \frac{4}{\pi} \sum_{n=1,3,5,\ldots}^{\infty} \frac{1}{n} \sin\left(\frac{n \pi x}{L}\right).$$

What are the impacts?

- In the positive sequence (e.g., PF and TS) these harmonics can be represented by <u>increased reactive power losses on the transformer</u>
  - Why?
  - $Z_L = j\omega L$ so transformer impedance increases with frequency
- Harmonics can also cause relays to trip devices such as SVCs
  - $Z_c = \frac{1}{j\omega C}$ so capacitors are a low impedance path for harmonics
- Transformer heating and damage



What are the impacts?

- Two major possible impacts
  - Voltage collapse due to:
    - Increased transformer reactive losses
    - Tripping of reactive power support devices
  - Transformer damage (including GSUs)
- A GMD event in March 1989 caused a major blackout in Quebec
  - 7 SVCs tripped within 59 seconds, causing voltage collapse 25 seconds later.
    6 million people without power for 9 hours.
  - In US: New York Power lost 150 MW,
    New England Power Pool lost 1,410 MW, service to 96 electrical utilities in New England was interrupted. Over 200 grid issues problems erupted within minutes of the start of the storm. Luckily, there were no blackouts.

March 13, 1989 Geomagnetic Disturbance

Hydro-Québec Blackout

Summary

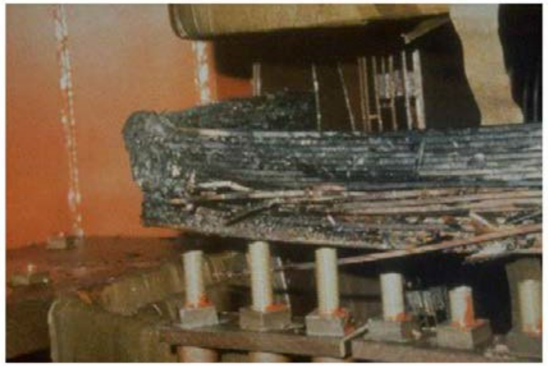
Just before 0245 EST on March 13, 1989, an exceptionally intense magnetic storm caused the shutdown of seven static compensators on the La Grande network. This equipment is essential for control of the Hydro-Québec grid and its loss caused voltage to drop, frequency to increase, and the resultant instability caused the tripping of the La Grande transmission lines.

The rest of the Hydro-Québec system, supplied by the Manicouagan and Churchill Falls complexes, collapsed within seconds of the loss of the 9,500 MW of generation from the La Grande

automatic rejection of the generation of two La Grande 4 generating units.

Three other 735 kV lines of the La Grande transmission network tripped next, and faults occurred in two single-phase units of two La Grande 4 transformers and in the surge arrestor of a shunt reactor at Nemiscau substation. The remaining line of the La Grande transmission network tripped next. Thus, the La Grande network was separated completely from the Hydro-Québec transmission network.

With separation of the La Grande network, the frequency fell rapidly. In response, automatic load-



Texas A&M GMD Work

- Developed synthetic but realistic large scale test systems, which include GMD parameters
  - https://electricgrids.engr.tamu.edu/electric-grid-test-cases/
- Real-time GIC Monitoring and Control Environment
  - Texas Magnetometer Network
  - GIC "State Estimation" (GIC Estimation)
  - Interactive GMD simulations and scenarios for visualization, control, and mitigation applications

Texas Magnetometer Network

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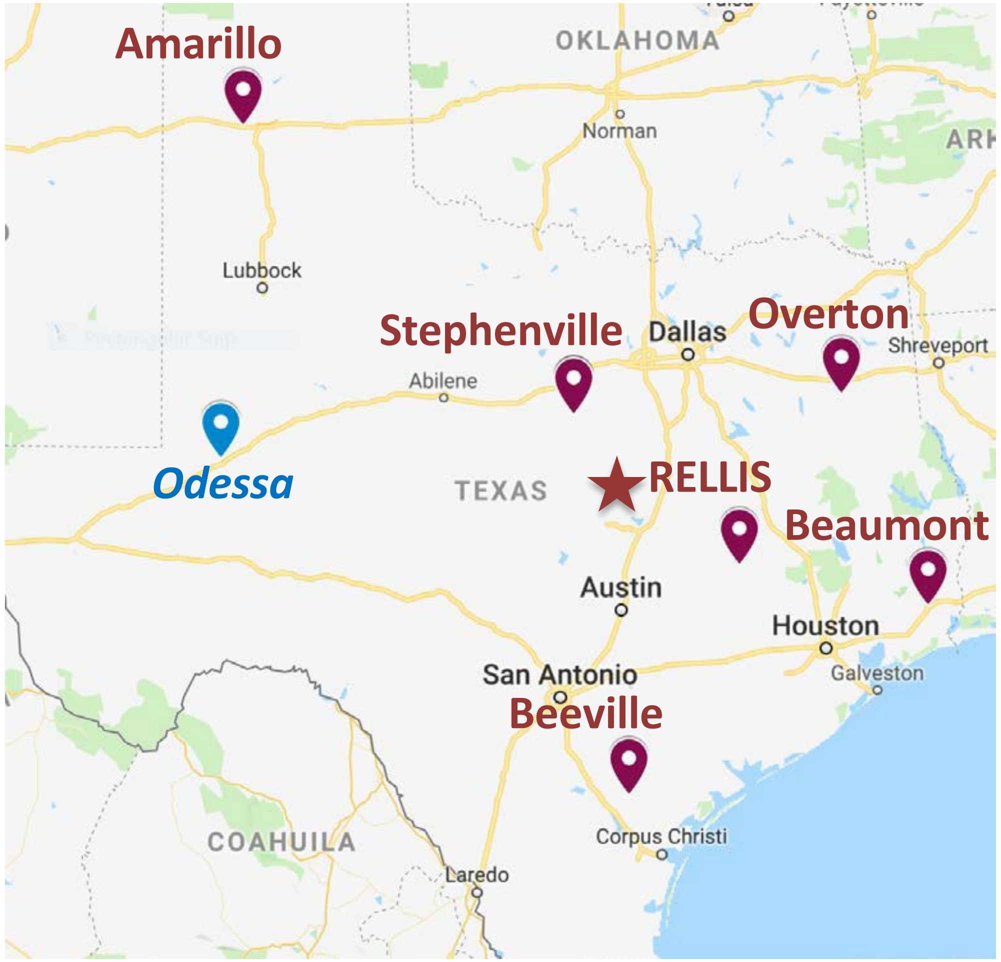
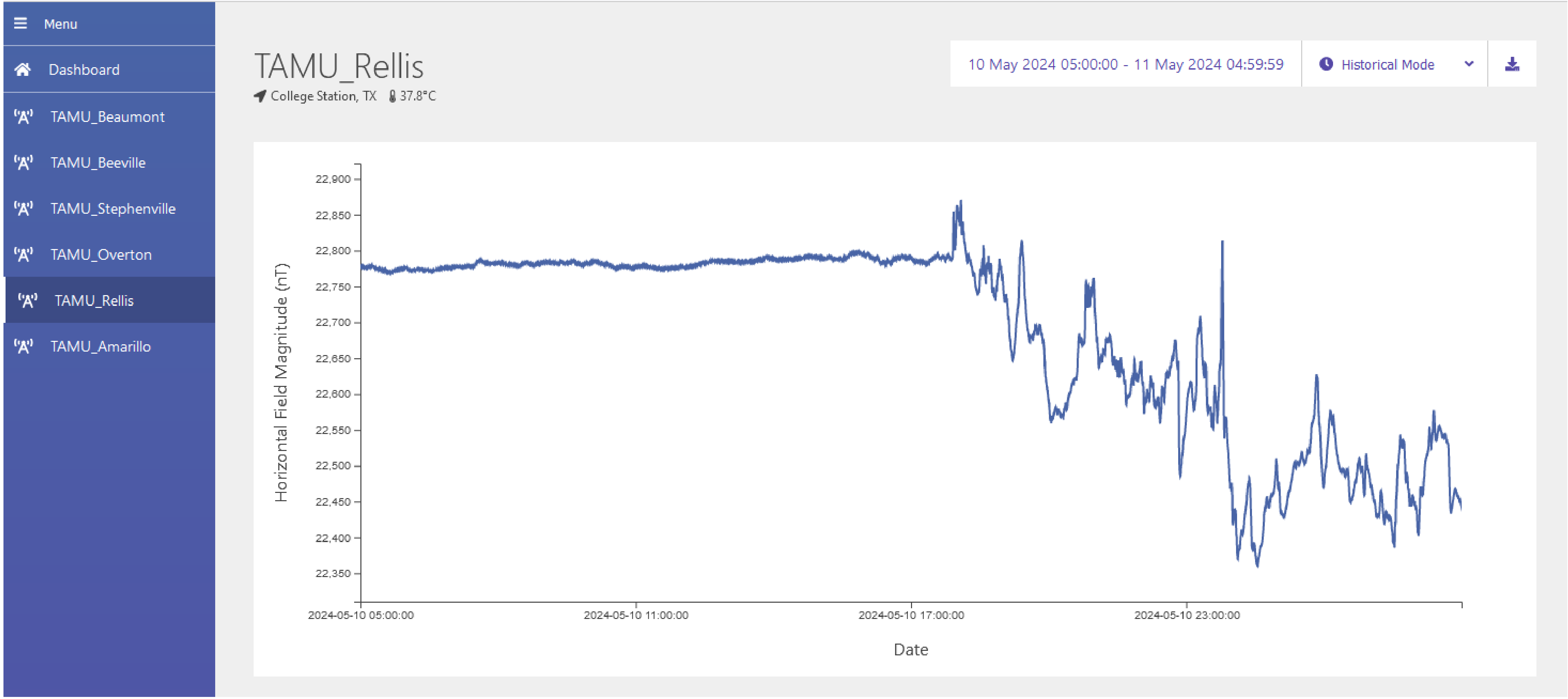


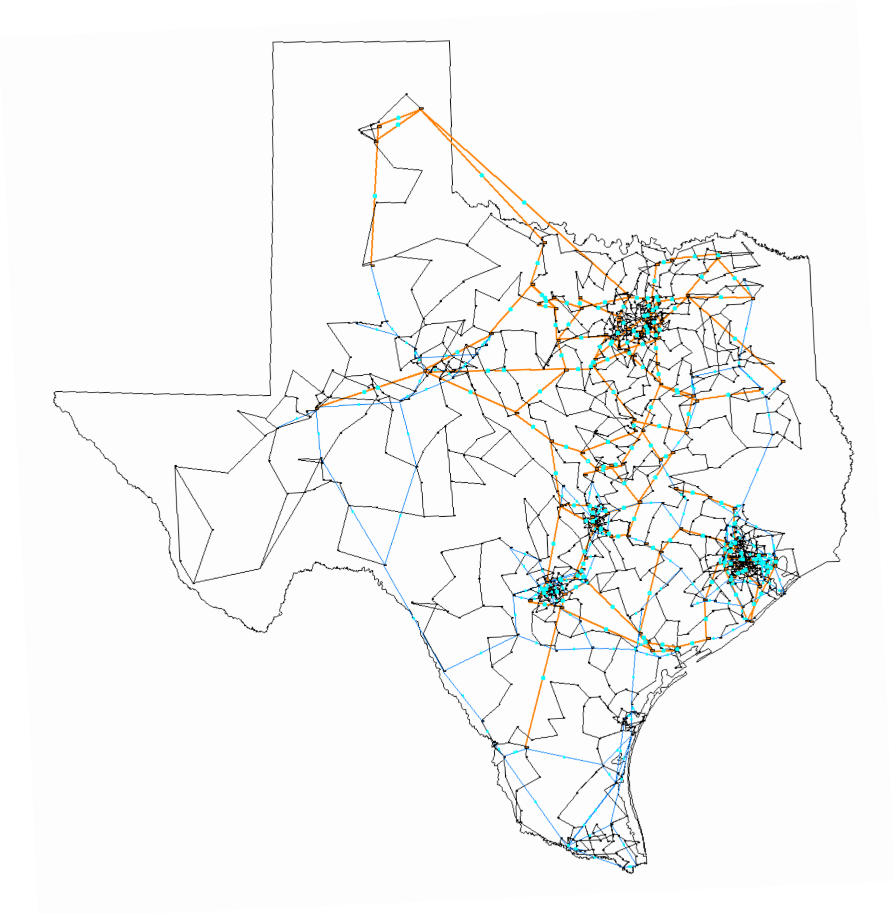
- 6 magnetometers installed by Texas A&M and Computational Physics Inc. (CPI)
  - **Completed** Dec 2019
  - Building on the results of our NSF project design
- Locations
  - 5 Texas A&M AgriLife Research sites (Amarillo, Beaumont, Beeville, Overton, Stephenville)
  - 1 local on RELLIS Campus (Bryan, TX)
- 1 mag installed under prior NSF project at Odessa

Online Dashboard



Hypothesis

- GIC measurement devices can be used to estimate the electric field.
  - This is done through a weighted least squares state estimation



Weighted Least Squared (WLS) State Estimation

- State estimation is traditionally used for estimating voltages throughout the electrical grid.
  - The relationship between GICs and a semi-DC electric field is linear, so a linear state estimation can be used.

- WLS Linear State Estimation:

$$\boldsymbol{x} = \left(\boldsymbol{h}^{T}\boldsymbol{R}^{-1}\boldsymbol{h}\right)^{-1}\boldsymbol{h}^{T}\boldsymbol{R}^{-1}\boldsymbol{z}$$

  - **z**: measurements – GICs
  - **x**: states – electric field
  - **h**: of the relationship between measurements and states
  - **R**: measurement error

Electric Field to GICs

$$\boldsymbol{I_n = \Phi_n G^{-1} H E}$$

- $\boldsymbol{I_n}$: Geomagnetically Induced Currents
- $\boldsymbol{\Phi_n}$: Transformer conductances, altered to include different transformer types
- $\boldsymbol{G^{-1}}$: Line conductance values that include substation grounding resistances
- $\boldsymbol{H}$: Matrix that depicts the length, resistance, and orientation of the lines in the North/East direction.
- $\boldsymbol{E}$: Electric Field

Overview of Electric Field State Estimator

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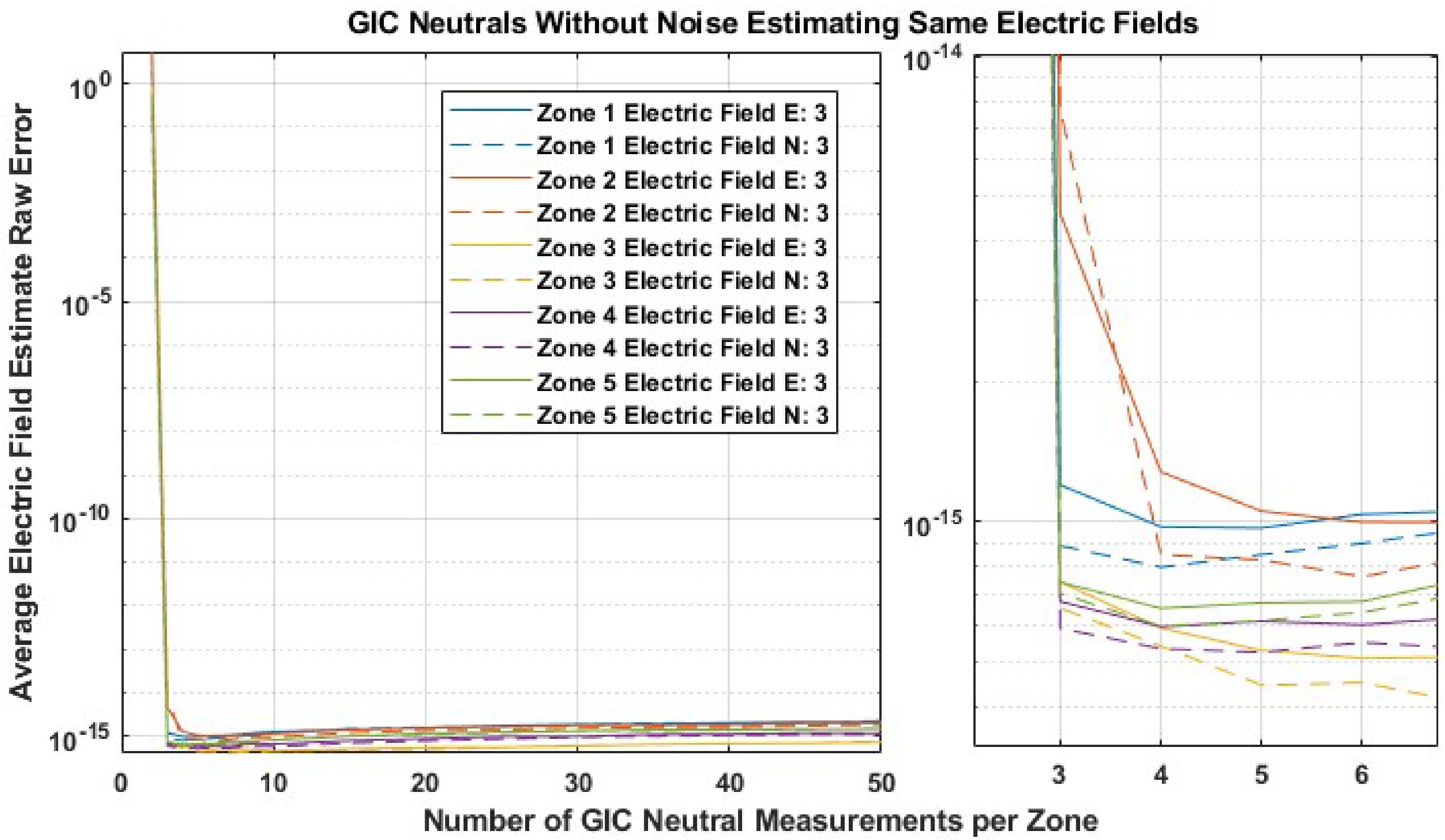
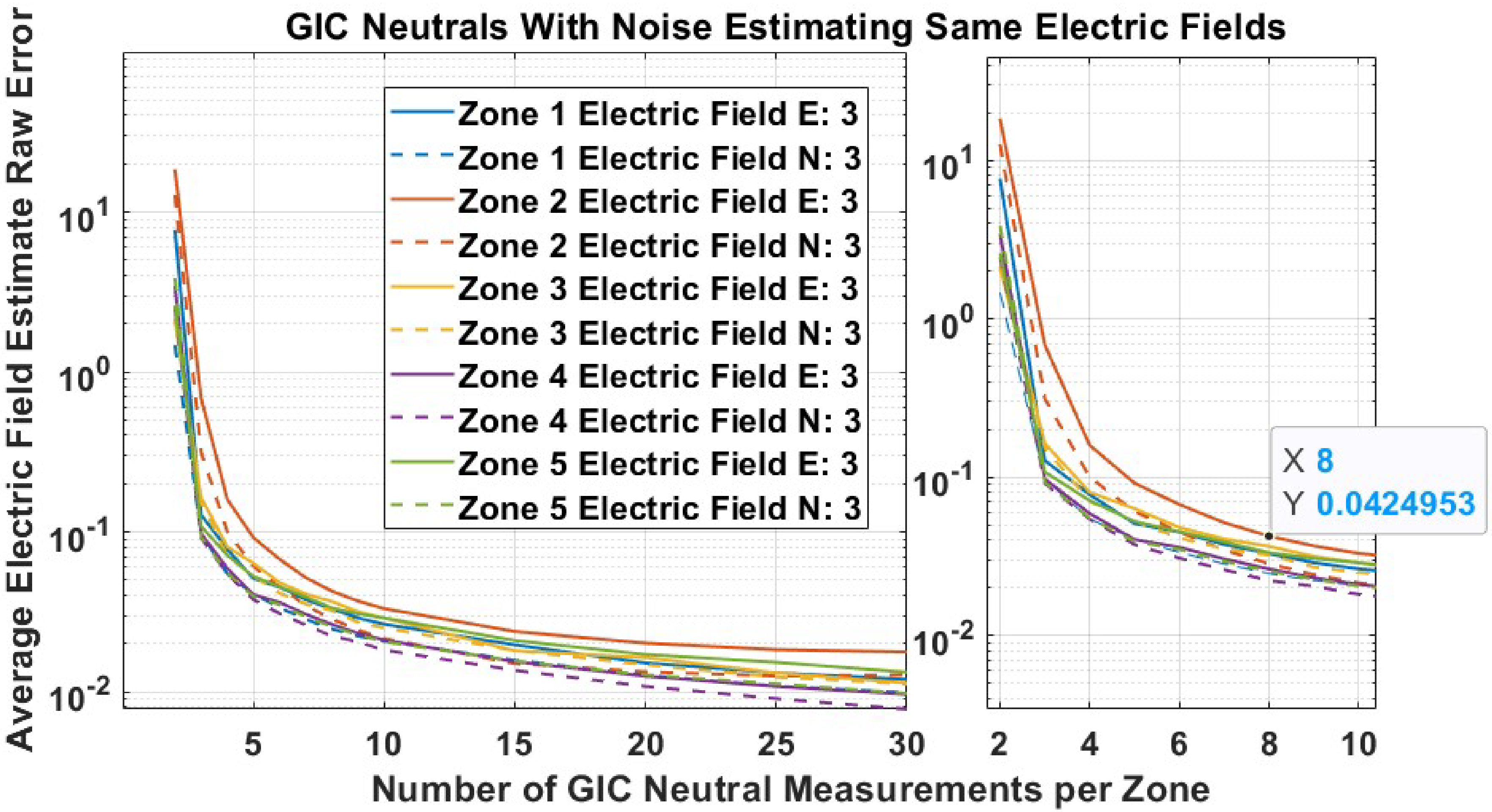
- Estimates the Northern and Eastern electric field magnitudes for five different zones across Texas.
  - Utilizes transmission line and transformer data to map GICs to electric fields.
- Determines the number of GIC measurements within each zone required to accurately estimate the electric field.

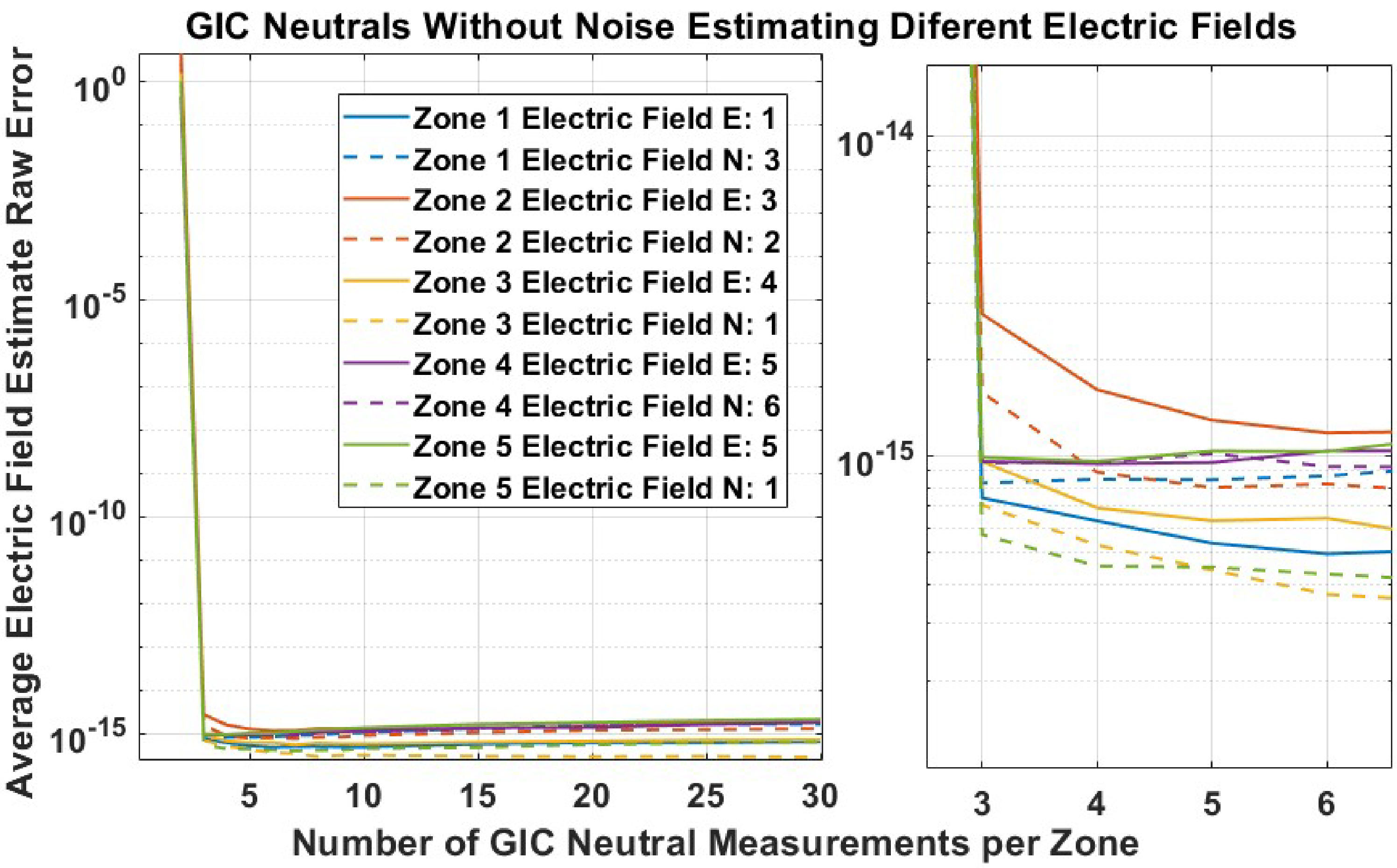
Same Electric Field Without Noise



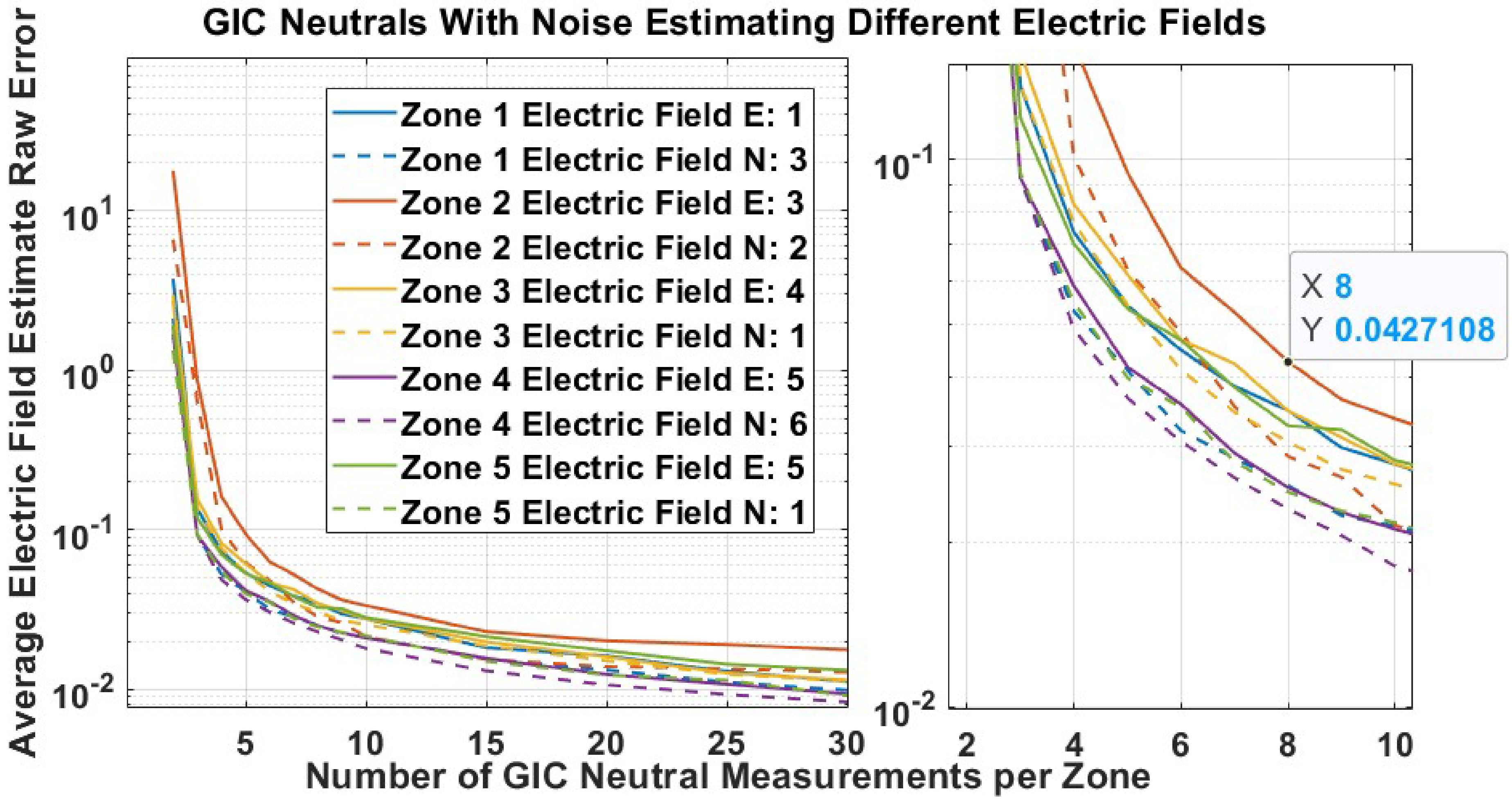
Same Electric Field With Noise



Different Electric Field Without Noise



Different Electric Field With Noise

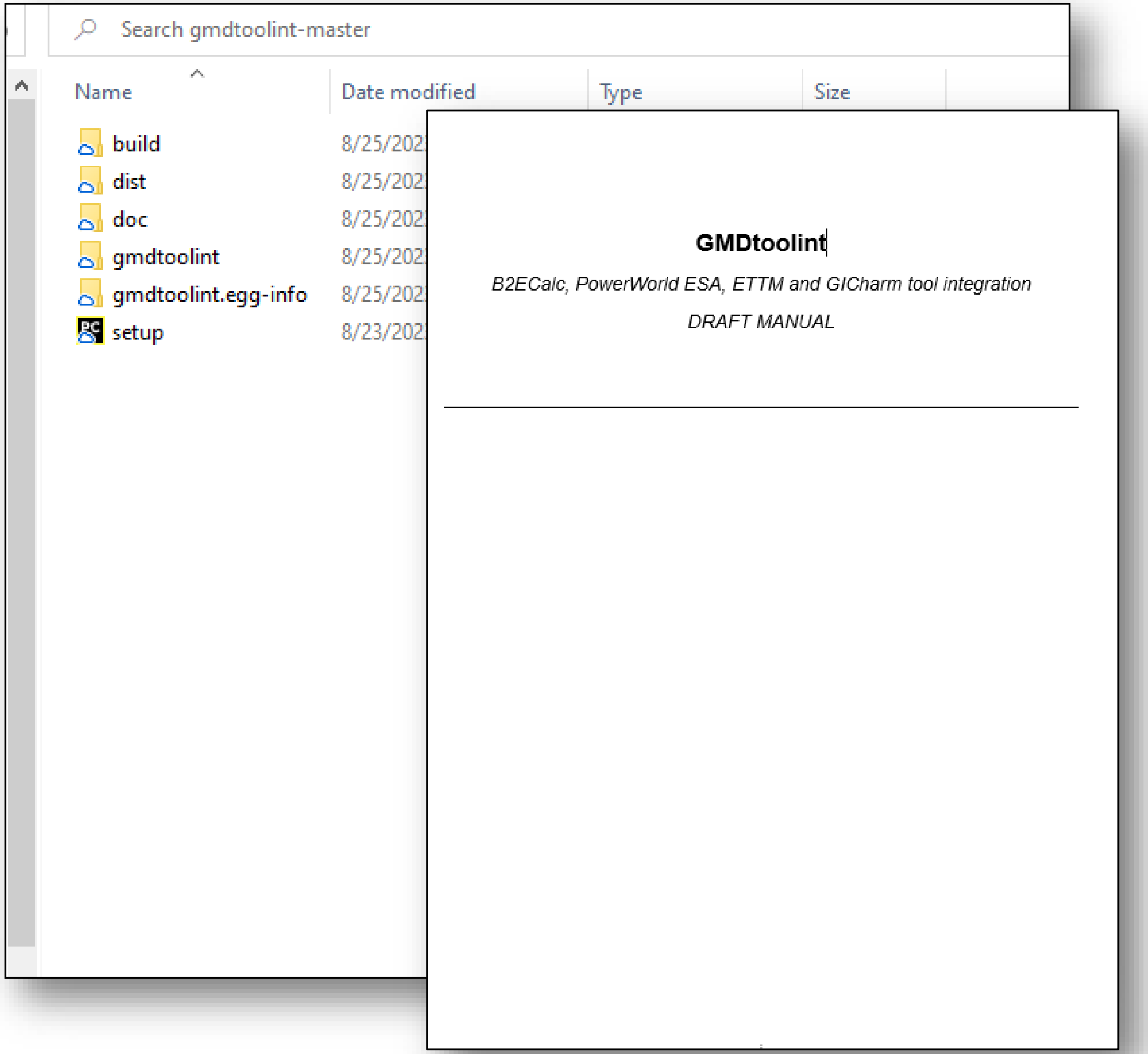


Results Summary

- Three measurements are required regardless for estimating the electric field from GIC measurements.
- Eight measurements are required to ensure an error of less than 0.05 V/m over 1000 iterations when noise is added to the measurements.
  - Changing the direction/magnitude of the electric field does not affect the estimation to a significant degree.
  - Some zones may require more measurements to acquire the same level of accuracy as the other zones regardless of the electric field.

Integrated Assessment Tool

- EPRI has integrated GIC modeling tools for GMD vulnerability assessments. (GMDToolINT)
- Integrated Platforms include:
  - B2E Tool (Earth Conductivity E-Field solver)
  - ETTM (Transformer Thermal Module),
  - GICharm (GIC-harmonic Analysis Tool), and
  - GIC Power flow (PowerWorld GMD Vulnerability Software Platform)
  - Integrated Tool includes relevant improvements
    - GIC unbalance and improved responses
  - The new source code, executables, examples and documentation are available on a PNNL open-source software site, and GICharm and ETTM are available on EPRI-member site with access provided.



Model Integration

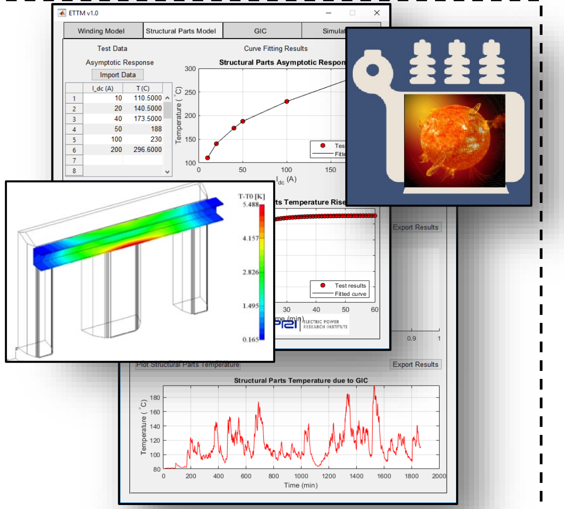
- Integration of GIC tools

EPRI

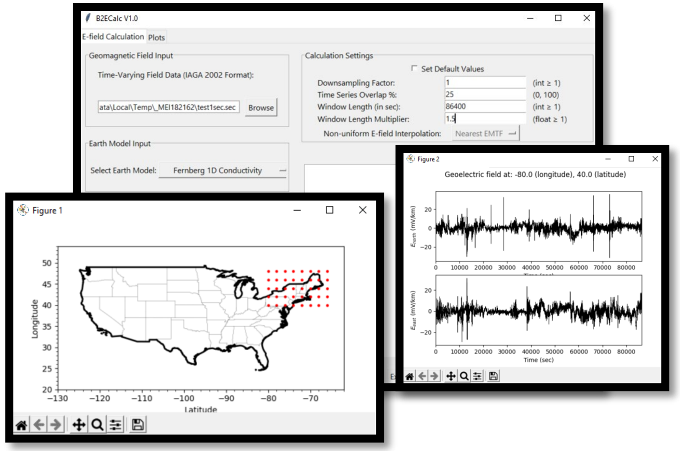
Integration tool overview

- Tool integrates functionalities of B2eCalc, PowerWorld ESA, ETTM and GICHarm.
- Tool manual indicates installation instructions, module functions and input data file description.

ETTM: Transformer Thermal Analysis

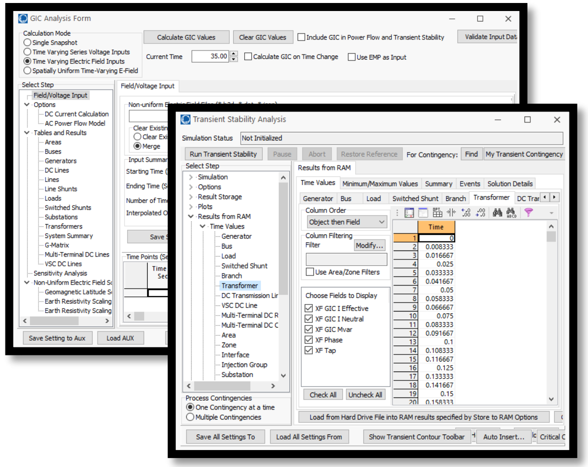


B2ECalc: E-field computation



E-field (.b3d)*

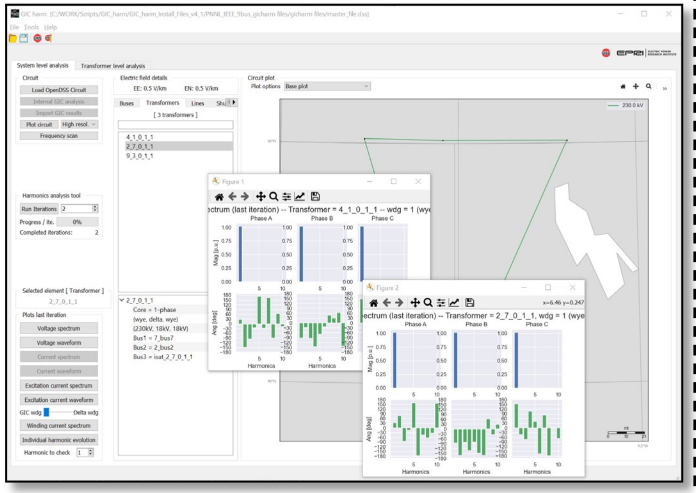
PowerWorld: GIC calculations



GIC (.txt)*

GIC (.xlsx)*

GICHarm: Harmonic Analysis



* File format in parenthesis.

GMD Short Course: March 18-19, 2025

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Thank you!

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Questions?