INL/MIS-15-35009

INL Full-Scale Geo-Magnetic Disturbance Ground Induced Current LDRD

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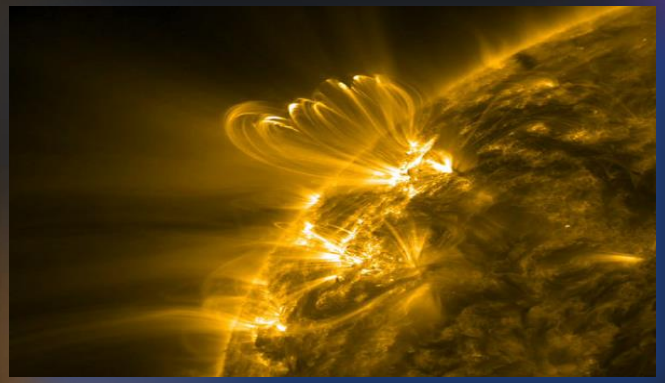
INL GMD Workshop

Date: April 8, 2015



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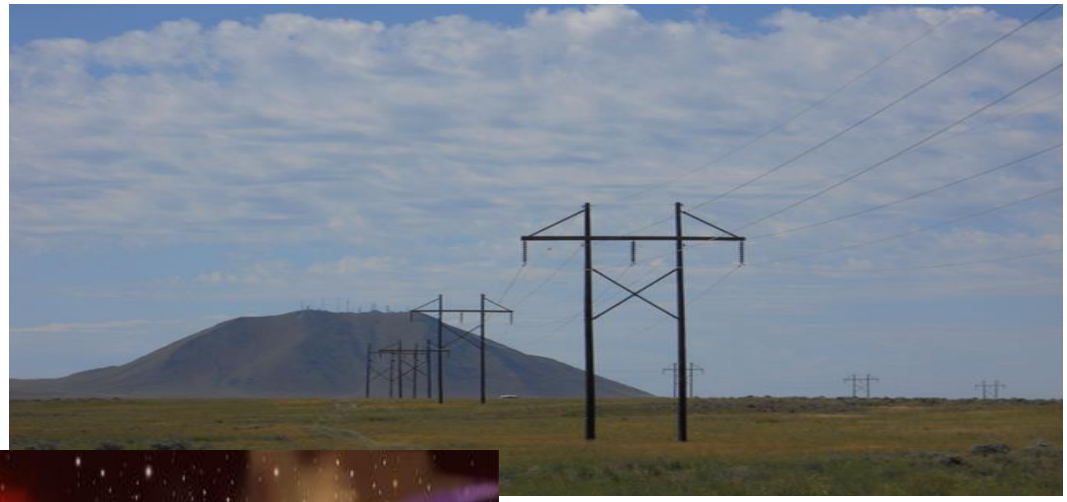
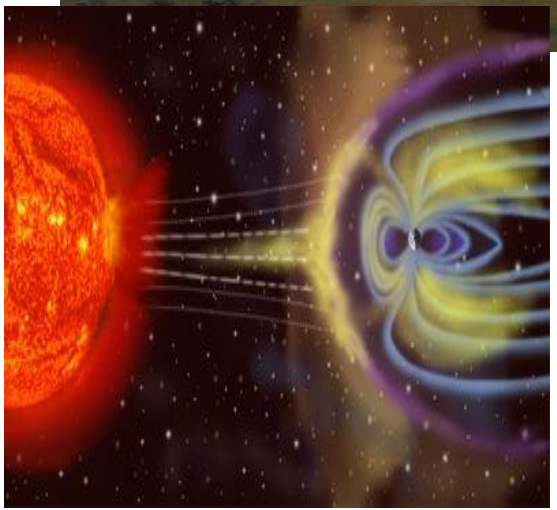
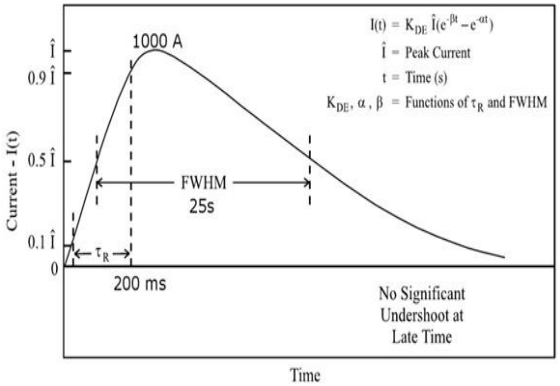
Outline

- General Description
- SANDAQ (SARA Alfred Node Data Aquisition)
  - Acquisition Hardware
    - Probes/Sensors
    - SANDAQ
    - RAID
  - Software
    - Continuous DAS
    - SANBeacon
    - RAID Eraser
    - Data Review
- GIC/GMD Modeling
- Next Steps and Future Work







General Description - INL LDRD Research

Infrastructure

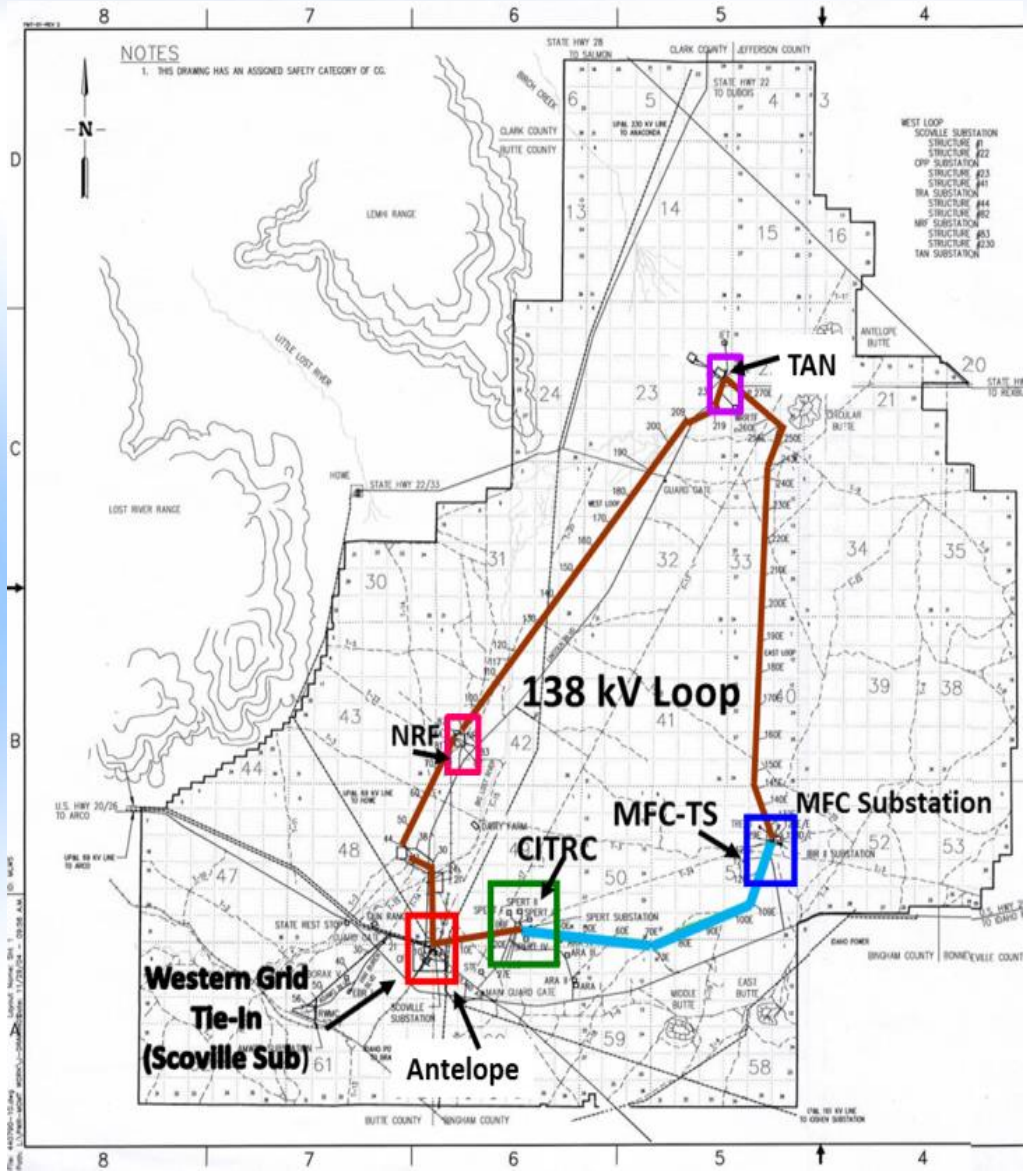
- INL utility scale grid with real-time GMD monitoring and located at INL's 890 square mile federal reservation

Instrumentation

- GIC, and 3-Axis Geo-Magnetic Sensors
- Data collection and analysis

Personnel

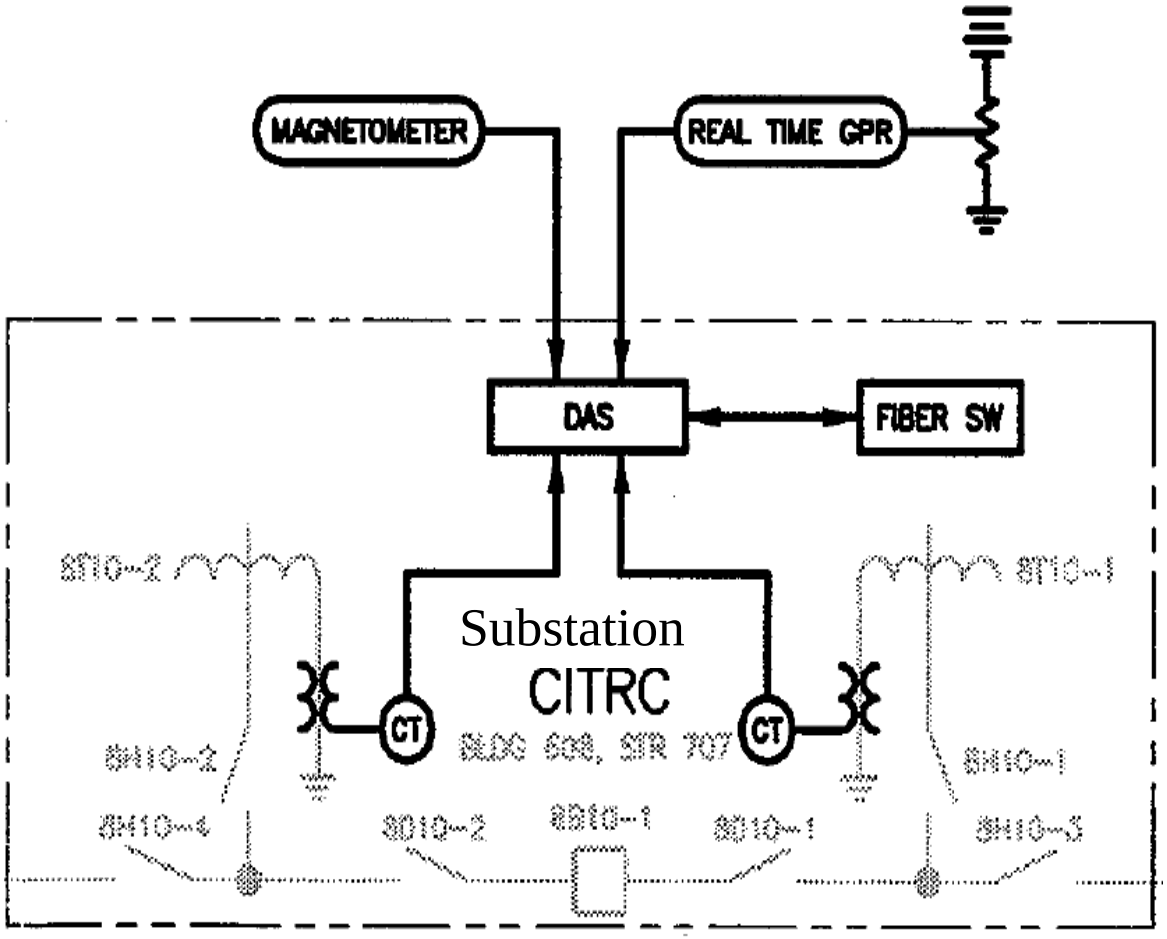
- Electrical/power engineers – PhD analysis, utility and research test design engineering, utility operations



INL GMD Typical Substation Layout

- CTs at Transformer Ground Locations
- Magnetometer ~600 m from substations
- Fiber Connectivity to all Substations

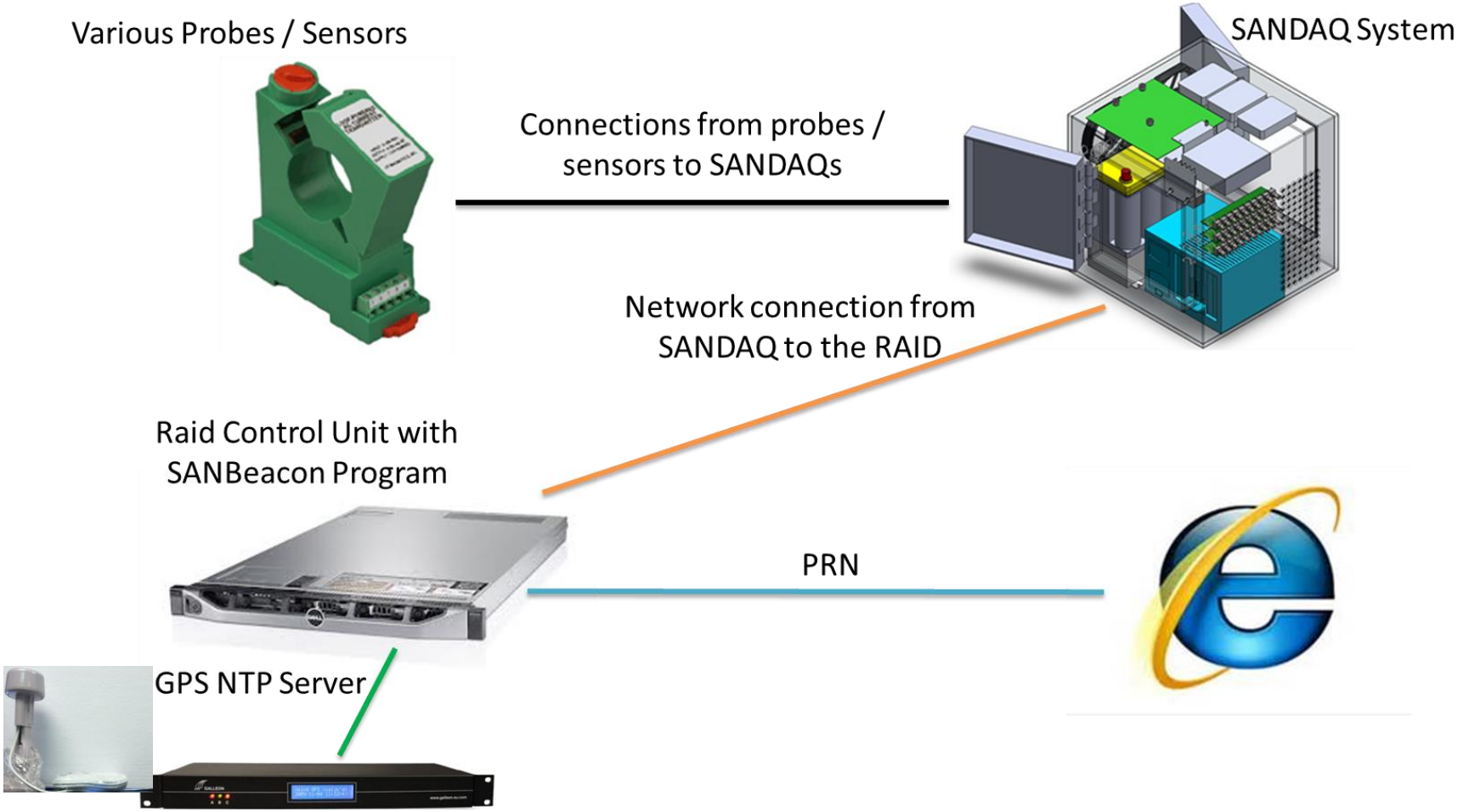
- Future –
  - 138kV Current Sensors
  - More Geomag units



SANDAQ Acquisition Description

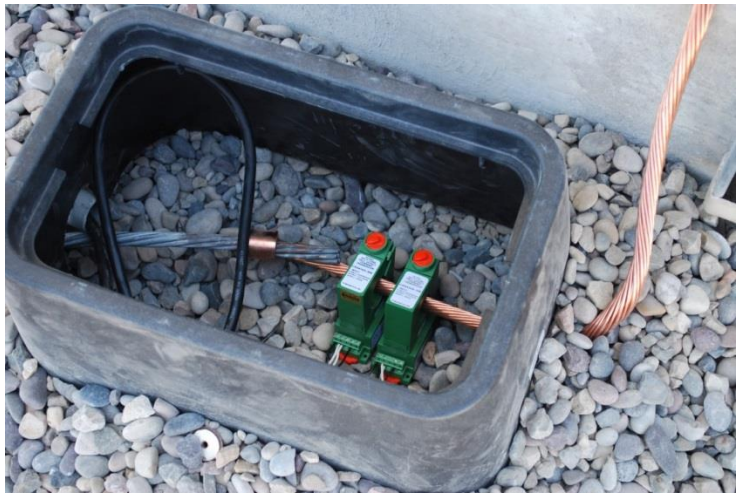
- Stand Alone Operation
  - 24/7 Acquisition and Monitoring
  - Redundant Data Storage-Local/Raid
  - UPS Protected
- Data Acquisition
  - National Instruments PCI-6143
  - 20 kSamples/Sec
  - 24 Channels per SANDAQ Unit
  - Field and Current Measurements
- System Monitoring and Alert Programs
  - SANDAQ Connectivity and Data Acquisition
  - Raid Capacity Monitoring and Automated Data Deletion
  - UPS Battery Lifetime Monitoring

INL-GMD Monitoring Overview



INL-GMD Field and Current Monitoring

- Field Sensors
  - 3-Axis Flux-gate Magnetometer
  - Potential for additional magnetic field sensors
- Current Probes
  - 0-100 A and 0-300 A CTs
  - Transformer Ground Instrumentation
  - Protective Housing



INL GMD SANDAQ

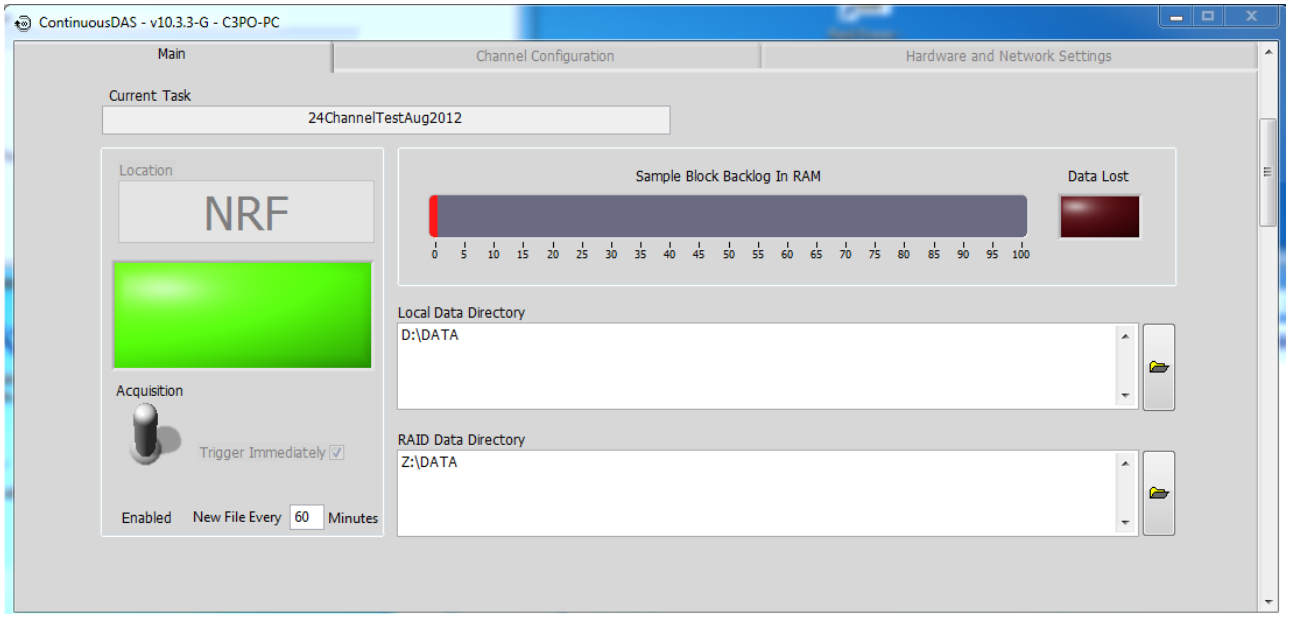
- Electromagnetically Shielded Enclosure
- Filtered 120 V Power
- Filtered E-net
- 24 Analog Channels
  - Static Range ±5 V
  - 16 bits
  - Max of 25 kSamples/sec
- External UPS Protection
  - 4-5 hours
- Adjustable Temperature Control Fans
- Fiber Isolation
- GPS Synchronized
- 1 TB Local Data Storage
- Ruggedized Computer

INL GMD RAID Control Unit

- 6 TB of Remote Data Storage
  - Redundant Storage for all SANDAQs
    - 3.3 GB of Data per Channel per Day
    - 42 Channels = >30 Days of Data Storage
  - USB 2.0 ~ 8hr/TB Data Retrieval (if manual download)
- Centralized Communication to all Remote SANDAQs
- GPS Time Server with Automated Time Synch to SANDAQS
- Capacity Monitoring
- Automated Data Deletion
  - Midnight Everyday after Capacity Threshold Exceeded

DAS Software Setup Screen

- Continuous DAS Software
  - Installed Locally at the SANDAQ
  - Manages Channel Configuration
  - Manages Hardware and Network Configurations
  - Displays Locally or Remotely at the RAID or other SANDAQs

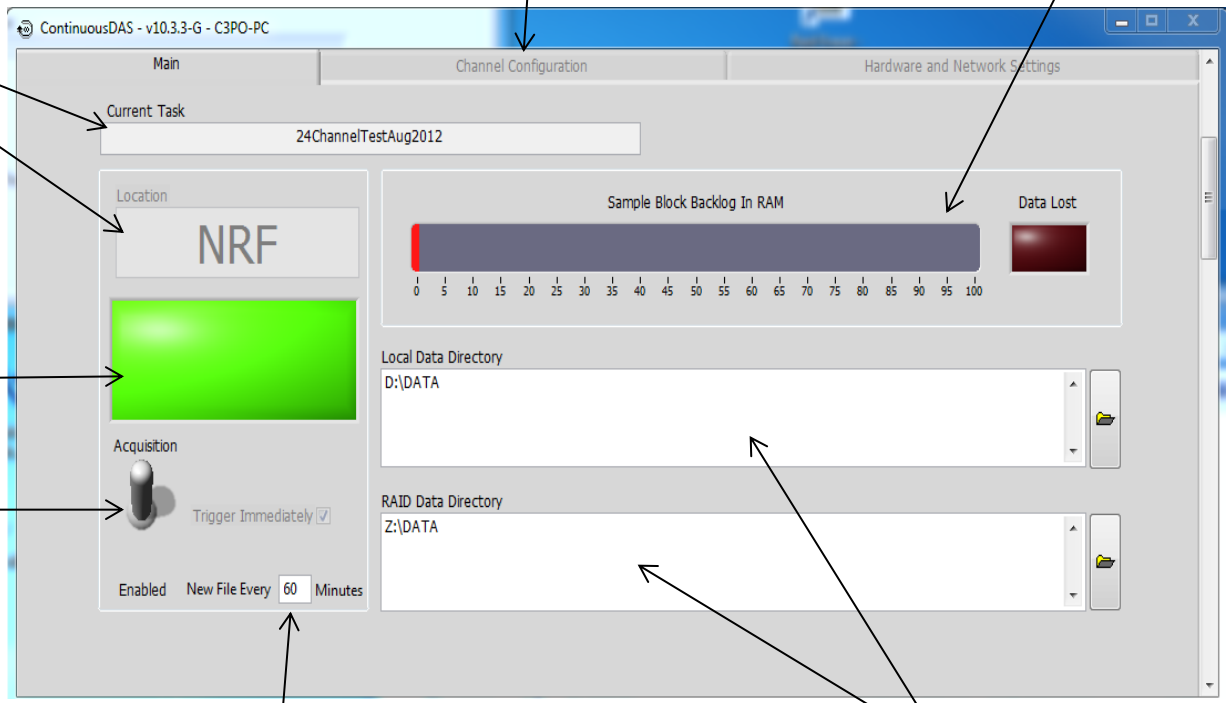


Continuous DAS Features

Channel Configuration
- Sampling Rate
- Sensor Location/Type
- Input Range

Unique Task and Location Names

Local RAM Capacity Monitor



Data Acquisition Indicator
Dark=Off
Green Light=Acquiring

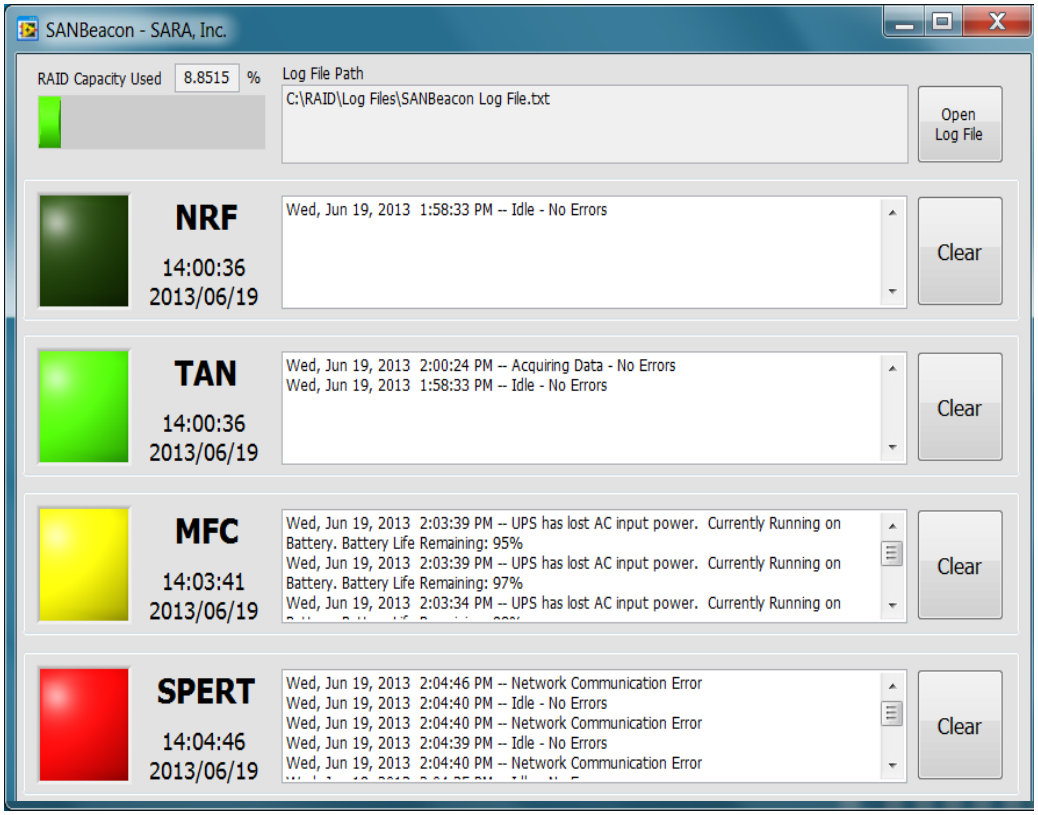
Acquisition
Toggle Switch

File Duration Selection
(Default File Length=60 min)

Local and RAID Directory Mapping

SANBeacon System Monitor

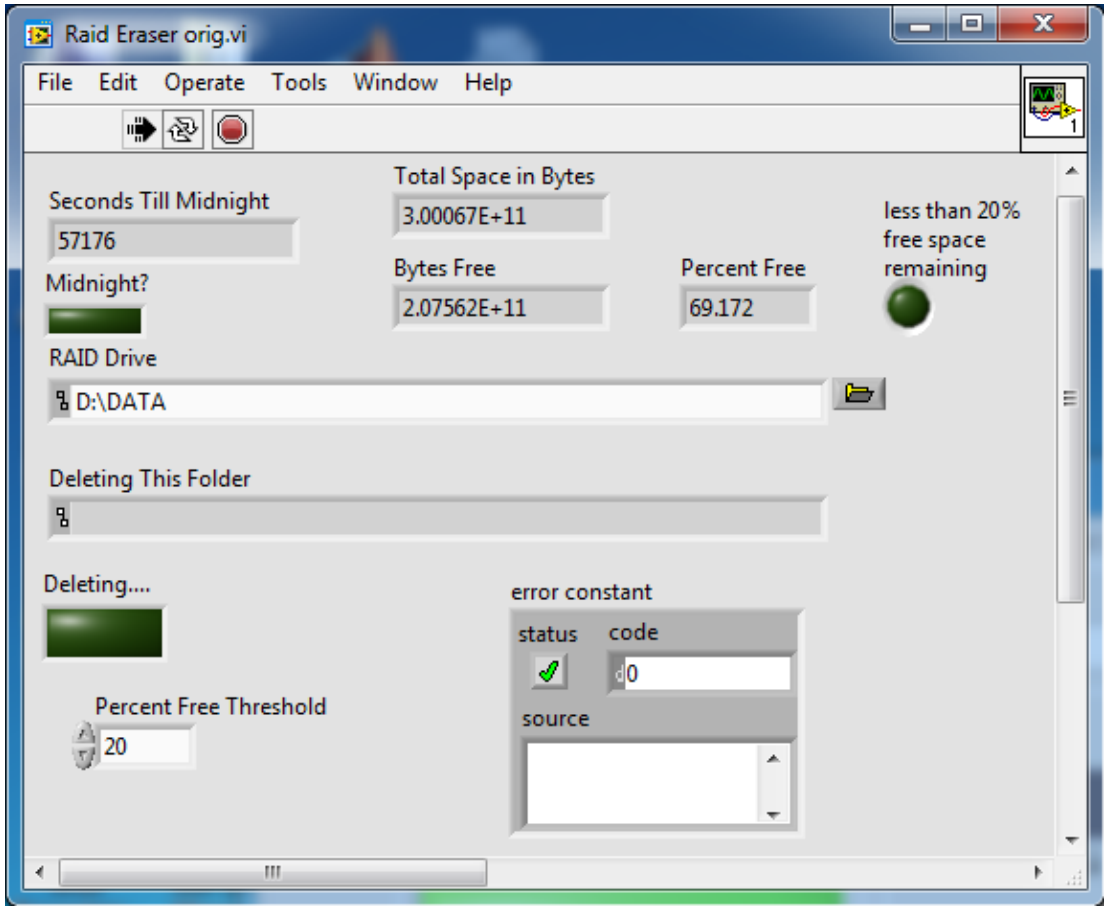
- Runs on the RAID
  - Status Reporting
    - RAID Capacity
    - Time code reporting
    - Network errors
  - UPS Diagnostics
    - Status
    - Battery life



- Dark Green=Comm Link Good-Data not Acquiring
- Green=Comm Link Good-Data Acquiring
- Yellow=System Requires Attention-Data Acquiring
- Red=Network Comm Error-Data not Acquiring

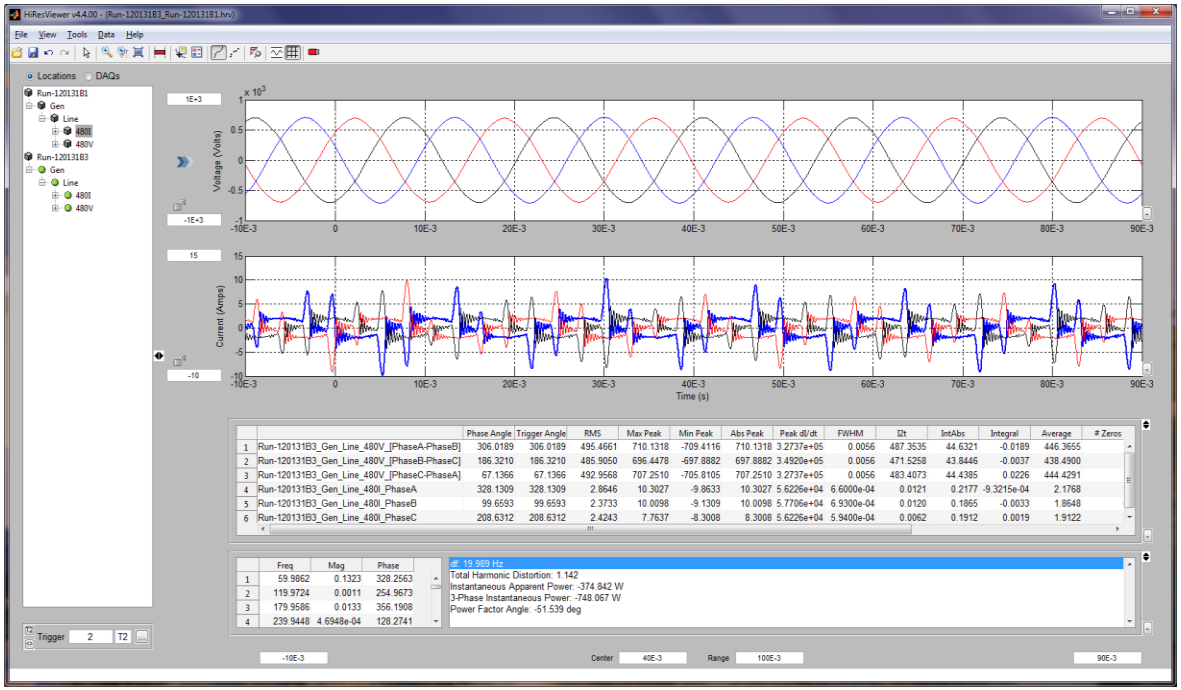
SANDAQ RAID Eraser

- Resident Background Program on the SANDAQs and RAID
  - Monitors RAID Capacity
    - Total Capacity
    - Bytes Free
    - Percentage Free
  - Performs Automatic Data Deletion
    - Begins after Capacity Threshold Exceeded
    - Occurs Daily at Midnight
  - Adjustable Threshold Setting
    - Default at 20%
    - Indicator Light



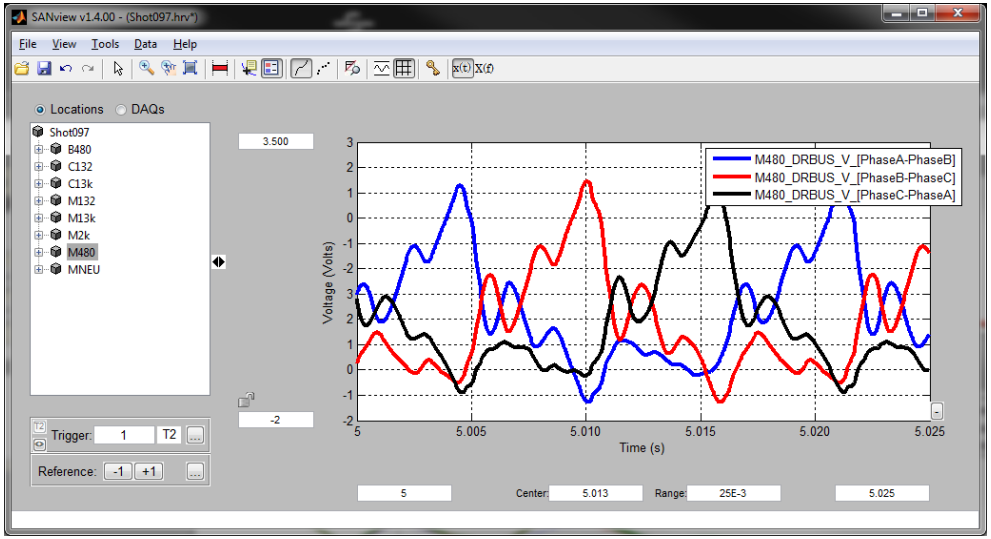
SANView

- SANDAQ Data Viewer
- Power Quality Visualization
- Data Analysis
- Customizable Plots and Displays



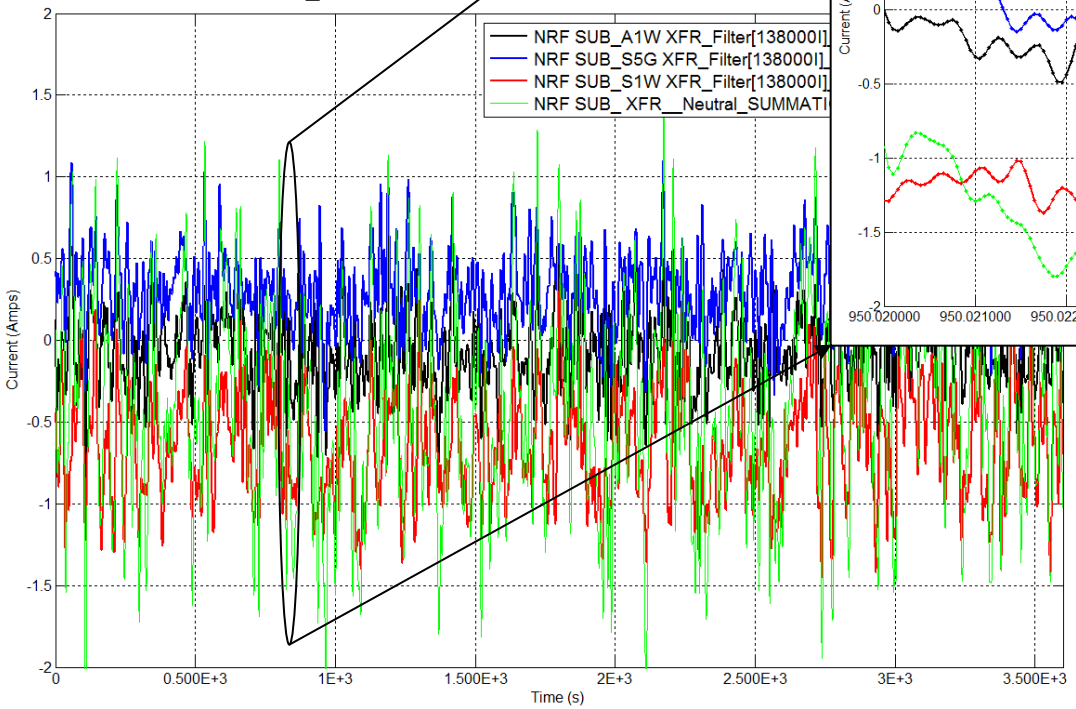
SANview Key Features

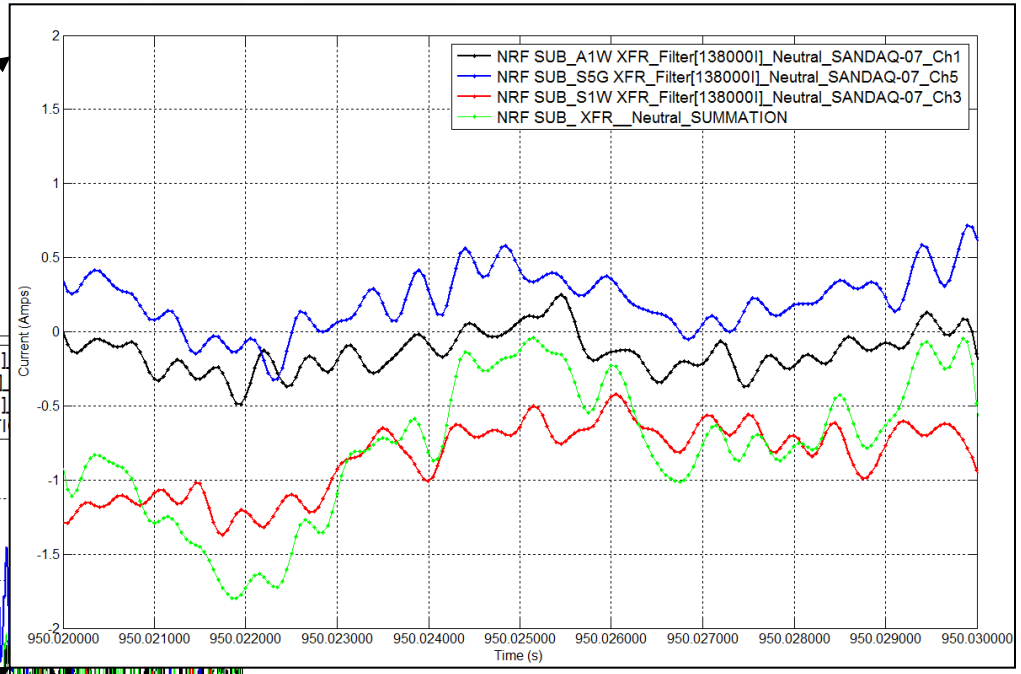
- Data Review
  - Import and View Multiple Files Simultaneously
    - Multiple Channels from Multiple SANDAQs
  - Intuitive Tree-View
  - Advanced Data Analysis
  - Zoom/Pan Options
- Data Export and Plotting
  - .TXT, .CSV
  - Various Image File Formats
  - Customizable Print Options
  - Annotations



SAMPLE SANDAQ DATA-NRF Substation

1 hour Sample





10 msec Sample

20 kSamples/sec

3.3 GB Data/Day

INL GMD/GIC RESEARCH GOALS

- 2013 Plan, Purchase, and Develop Installation Packages for Install on INL Grid
- 2014 Begin Installation of Data Acquisition Hardware and Field Sensors
- 2015 – Complete Installation
  - GIC and GeoMag Sensor Calibrations
  - Adding GIC related model elements to INL Power Grid EMTP/RV and RTDS Models
  - Use Collected Data to Validate Existing INL Models
  - Obtain Commercial GMD Effects Models to Begin Validation/Comparison
  - Establish Collaborations with Industry – Mitigation Developments
- 2016 – End of LDRD Investment--Industry Investment
  - Mitigation Development Continues
  - Apply Validated Models on Industry Partner Systems
  - Establish 138kV Scientific Class Power Measurement System
  - Test Partner System Mitigations Where Possible
- Future - Continue to Develop & Test GIC Mitigations
    - Operational and Model Based
    - Hardware Related Testing
  - Expand Commercial Utility Measurement and Modeling

Next Steps – INL GIC/GMD Measurement System

- INL SANDAQs
  - Additional GeoMag Sensors and 138kV Level Current Measurements
- Develop System Monitoring and Alert Programs
- Provide SANview Data Review and Export
- Process GIC and INL operational data through INL-specific models and combine with Geomag and Solar Weather data for predicted effects of GMD on INL's Grid.
- Expand our capabilities into our local utility provider systems.

- INL Ground Impedance – Measure and Map

Next up - INL GMD/GIC Model Development and Validation

Future Work – GIC/GMD Transformer Model Comparison and Validation

Goals:

- Understand the INL GMD test grid as completely as possible
- Expand testing, modeling and validation activities to neighboring utilities
- Help local utilities understand their GMD related issues/risks
- Consider EMP effects as well as GMD

Next Steps:

- Identify essential/desired transformer model features
- Select models which capture identified features
- Compare selected model simulations with results from tests run at INL GMD testbed
- Identify gaps in models and modify if necessary
- Design new testing to validate modified models and iterate

Future Work – Common Classes of Transformer Models

Transformer Model Parts:

Frequency Dependent

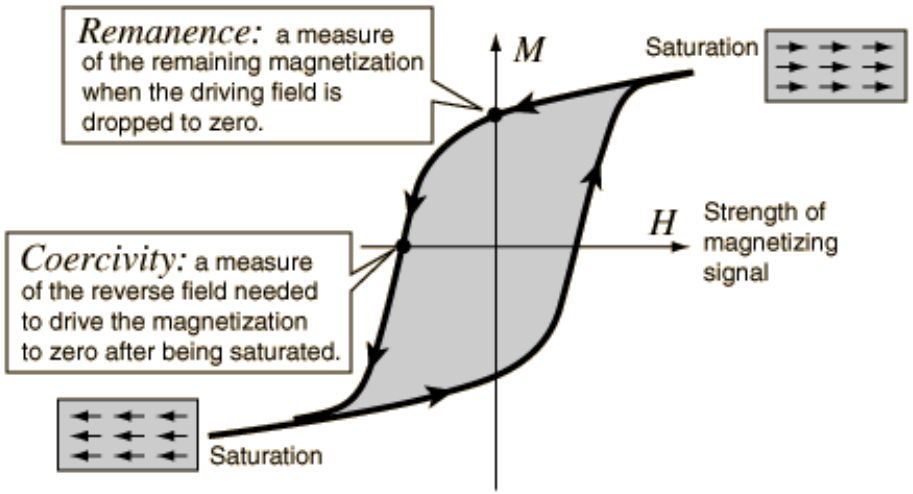
1. Windings ← Linear
2. Core ← Non-Linear

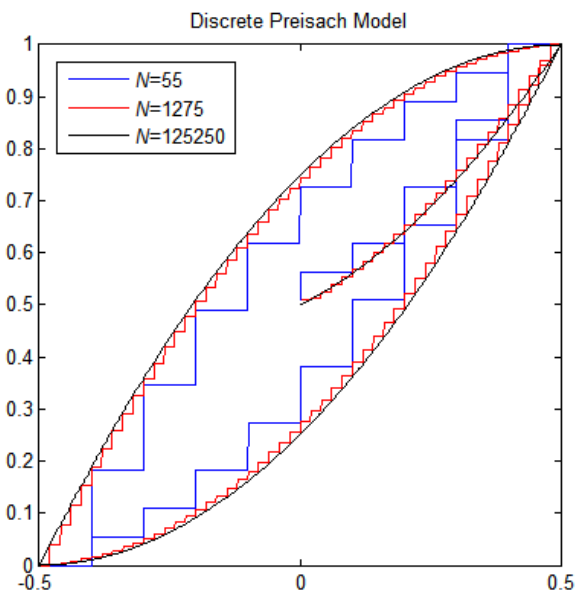
Common Classes of Transformer Models

- Matrix Representation
  - Uses either branch impedance or admittance matrix
  - Good results for leakage inductance but core topology not taken into account
  - Models are linear - do not include saturation/hysteresis
- Saturable Transformer Component
  - Similar linear form as matrix based approach
  - Saturation and hysteresis modeled by adding non-linear inductor at star point
  - Limited usefulness for three-phase units
- Topology-Based Models
  - Duality-Based: Derived entirely from magnetic circuit using principle of duality
    - Cores modeled as saturable reluctances, windings modeled as MMF sources
    - Does not accurately model leakage inductance
  - Geometric: Derived from magnetic circuit, but passed through mathematical formulation Hybrid Models (Matrix + Duality Representation)
  - Accurately represents core topology and leakage inductance

Future Work – Approaches to Modeling Ferromagnetic Hysteresis Loops

- Curve Fitting (Ignores behavior of magnetic material)
  - Linear
  - Piecewise Linear
- Macroscopic Magnetization Models
  - Preisach
  - Jiles-Atherton
- Micromagnetic Methods
  - Consider all known energies
  - Solve for domain configuration with minimum energy





Preisach

•Based on phenomenological description of ferromagnetic materials
•Fundamental unit is discrete 'hysteron' relay
•Potentially better agreement with measurement over wide excitation ranges

Jiles-Atherton

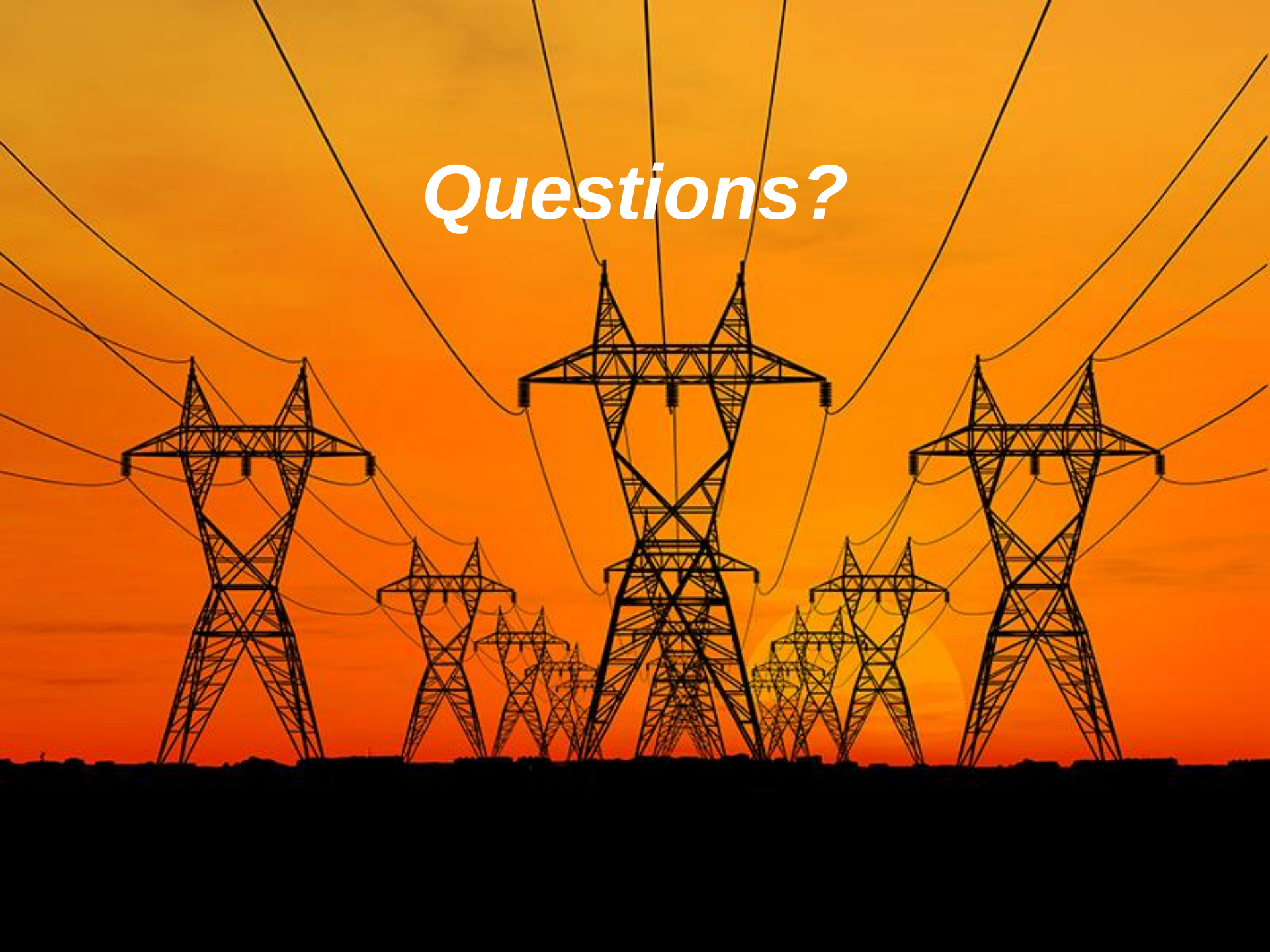
•Models hysteresis as a consequence of a frictional force opposing Bloch domain-wall motion
•Model parameters obtainable by fitting
•Potentially faster execution

Future Work – Motivating Questions and Considerations

- How are the GIC transformer modeling needs different from low/mid frequency transient modeling?
- How do the results from piecewise linear and macroscopic core models compare to experimental results?
- How sensitive is THD to ferromagnetic hysteresis loop modeling accuracy?
- Is ferroresonance an issue with GIC in transformers? What types?

Approaches:

- Real-time vs run-time simulations
- Incorporate finite element model with COMSOL-Simulink
- Patchwork approach may be necessary to capture required features


Questions?

BACKUP SLIDES

GIC Related Calculation Challenges:

Transformer:

Calculate core flux density shifts

Determine whether core is saturated

Calculate exciting current magnitude / wave-shape

Calculate resulting flux

In the core, windings, and structural parts

Calculate effective additional I^2R loss, eddy current loss, other circulating currents / losses, and hot spot rise in core, windings, and structural parts

Accounting for rich content of harmonics in flux, duration of exciting current pulse per cycle, and duration of the GIC

Determine allowed level of load for different levels of GIC

Assuming a limit on the hot-spot temperature

System

Model GIC effects on the Utility system

Find sensitive points related to system operations, resonances, ferro-resonance, mitigation requirements, and type (effect on capacitor banks, SVC's, relay sensitivity, timing/coordination, etc…)

Overall Summary

- INL 65-mile Long 138kV Loop with 5 Substations
  - DAS Recording GIC and GeoMag B-Field
  - 24/7 Acquisition and Monitoring
  - 20 kSamples/sec at 16 bit resolution - Redundant Data Storage
- SANview Provides Data Review and Export
  - Combine with B-Field Measurements to Provide Predictive GMD Impact to INL Power Grid.