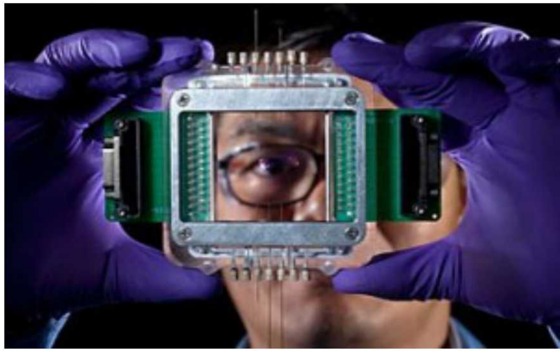
SAND2019-10084PE

Exceptional service in the national interest



Electromagnetic Pulse Grand Challenge

NERC EMP Workshop

Ross Guttromson, PI

July 25, 2019

Acknowledgements

Sandia Researchers

- Alfred Baughman
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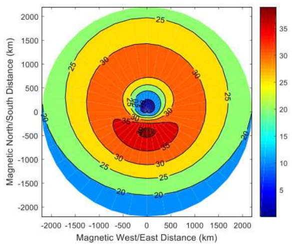
External Partners

- ABB
- Public Service Co. of NM (PNM)
- National Grid
- ITC
- Electric Power Research Institute
- Texas A&M
- University of NM
- Los Alamos and Lawrence Livermore National Laboratories
- Department of Energy
- Federal Energy Regulatory Agency
- Defense Threat Reduction Agency

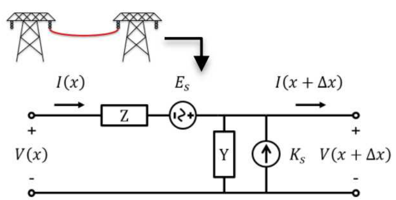
Sandia's Lab-Directed R&D Approach: Three Integrated Thrusts

Sandia National Laboratories

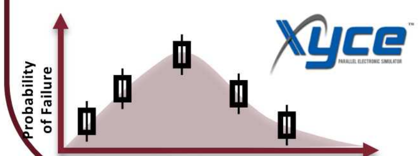
Thrust 1
Vulnerability Assessment



Environments

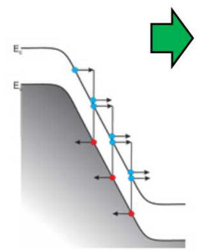


Coupling



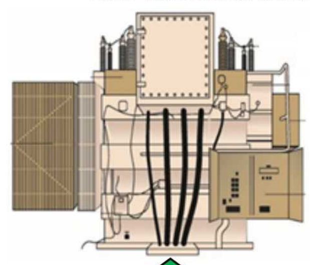
Failure Analysis

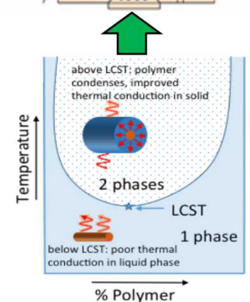
Thrust 2
Material & Device Innovation



Avalanche Breakdown in a Wide Band-Gap diode

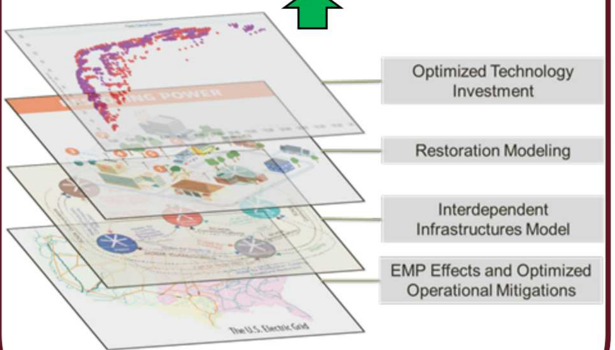
EMP hardened assets





Design New Component Materials to Withstand EMP Effects

Thrust 3
Optimal Resilience Strategies



Modular Multi-Layered Modeling Approach

R&D

- **Large scale coupling modeling with significant number of unknowns**
- **Component response and failure estimation to EMP waveforms**

R&D

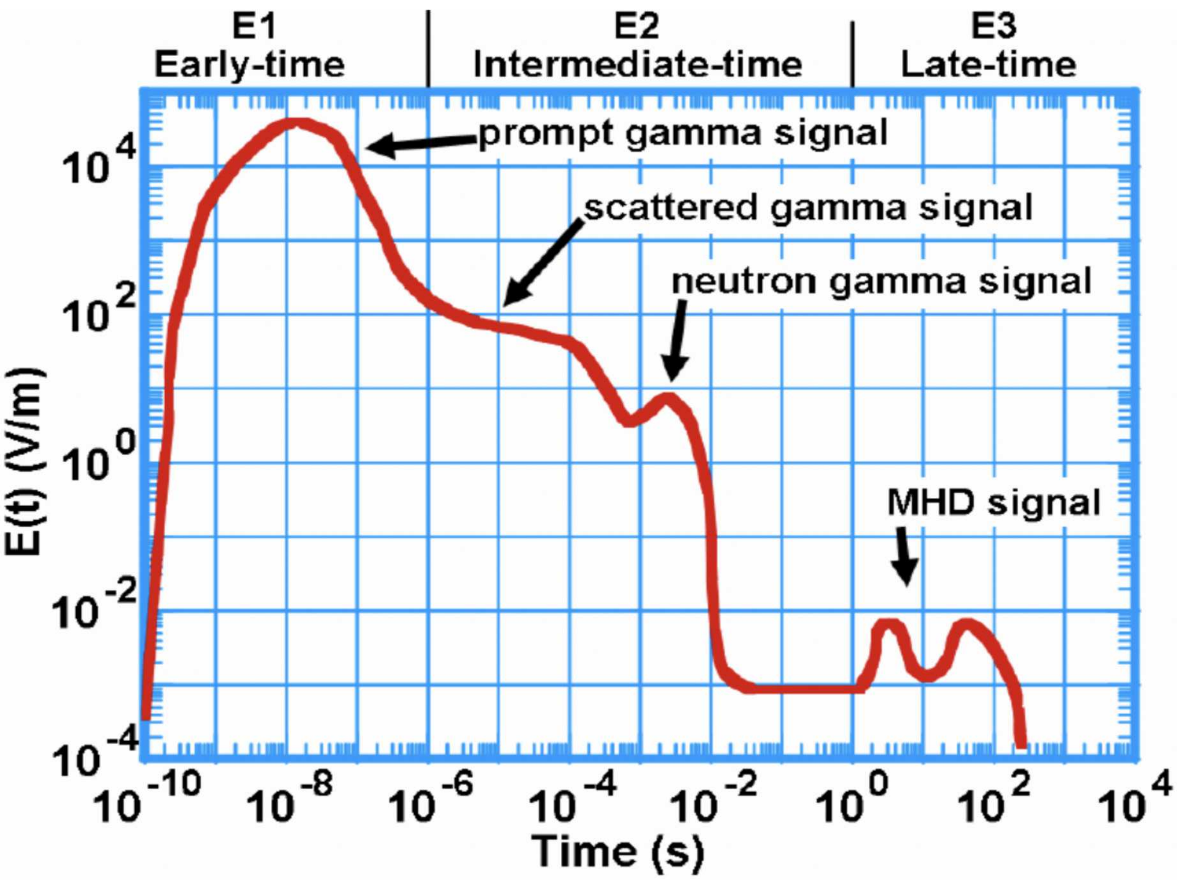
- **Develop Wide Band-Gap EMP arrestor**
- **LCST Polymers for thermal management during E3/GMD**

R&D

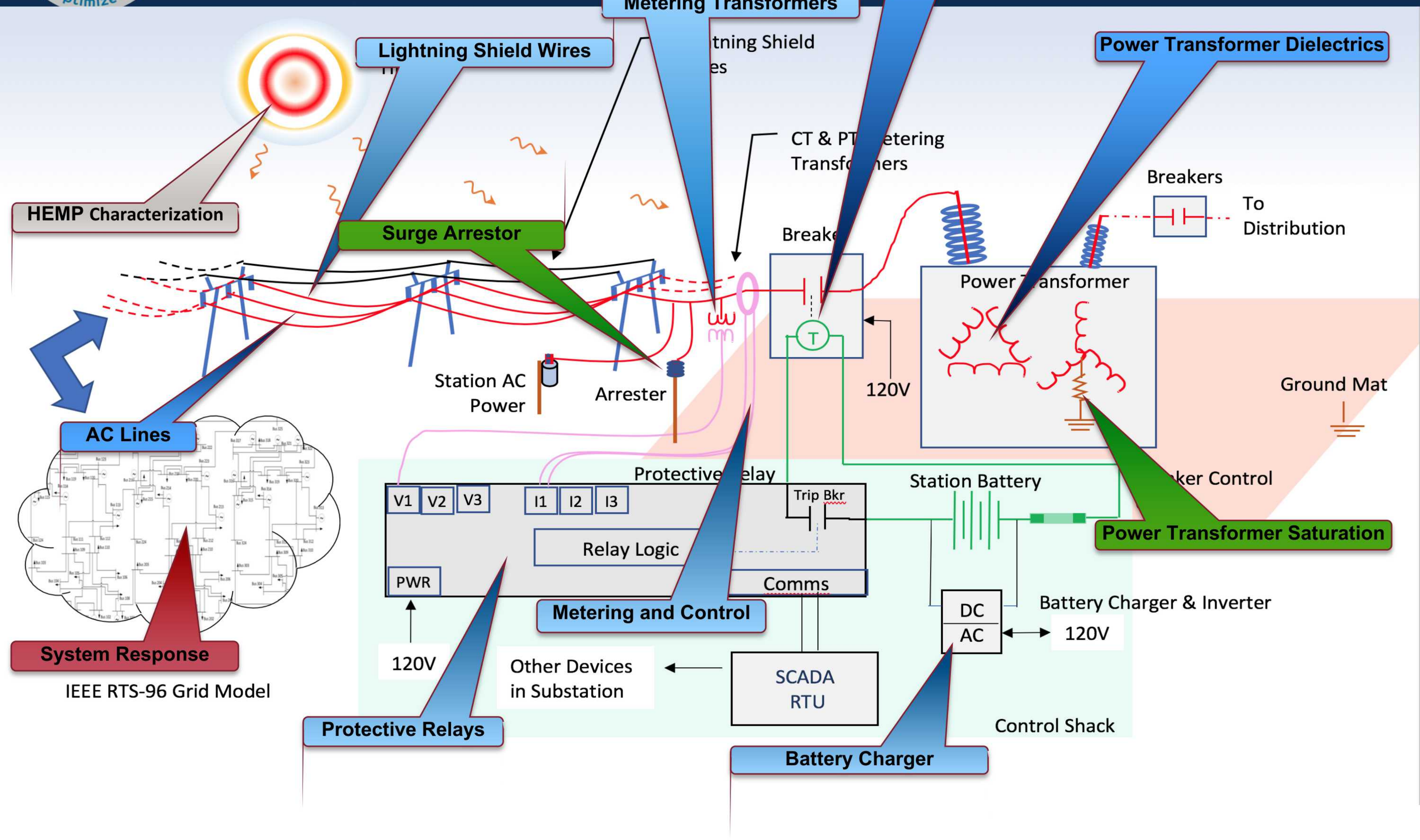
- **Baseline assessment of EMP Effects w/ Large Scale Stochastic, AC Dynamic Optimization**
- **Risk mitigation by Tech Deployment, Operational Mitigation & Optimal Restoration**

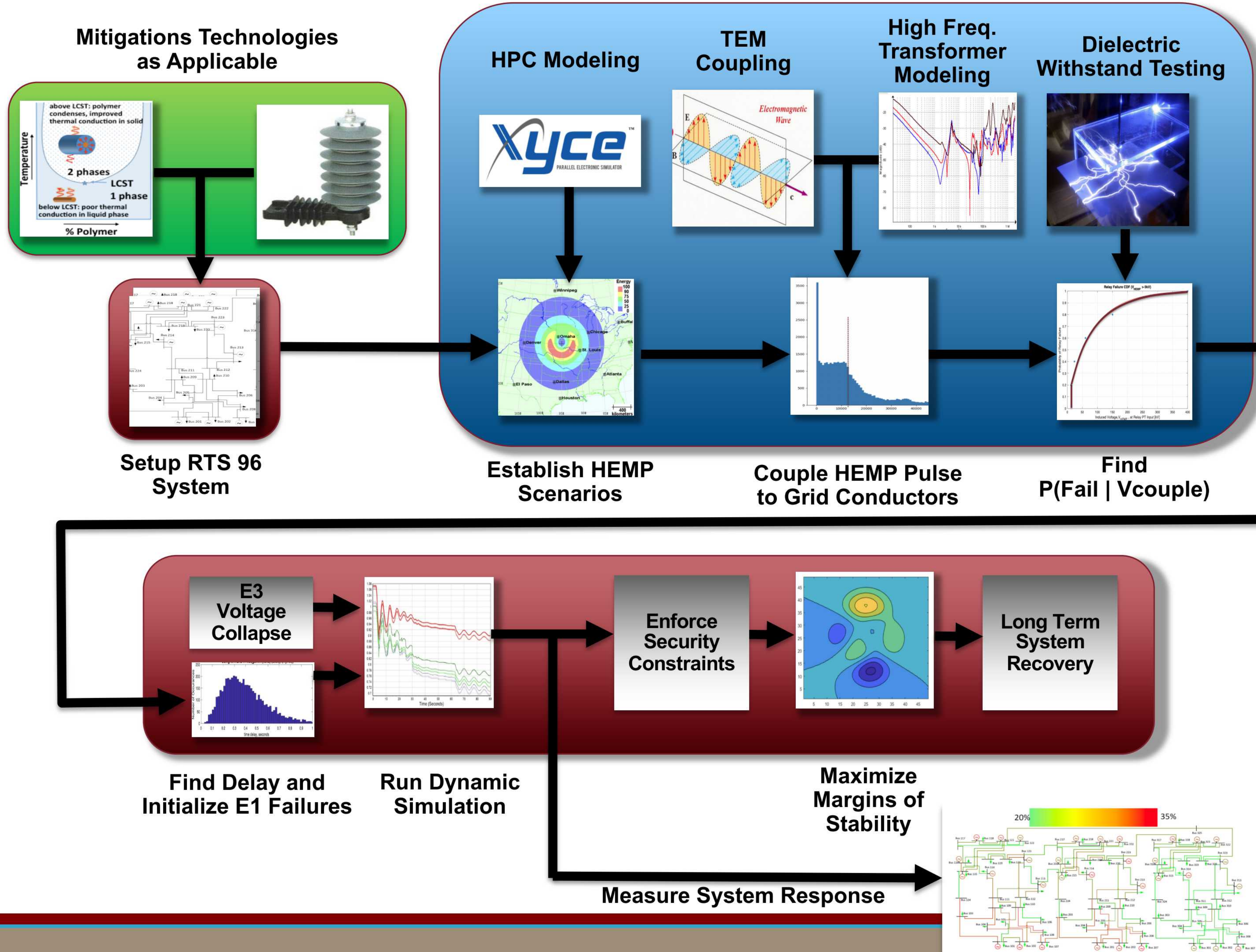
HEMP Waveform

- Openly available curve from IEC and Mil-Spec
- Polarization must be assumed
- LANL provided E1 and E3 data
- E2 data is not well known but thought to have less significant impact

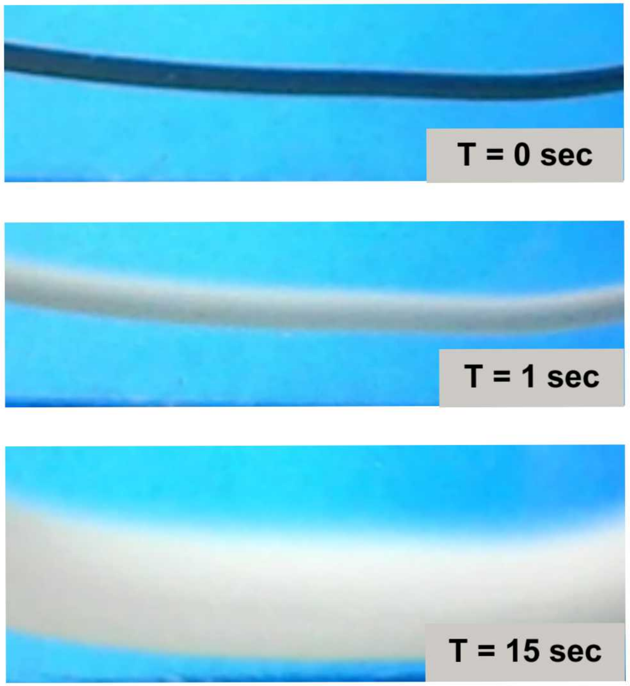


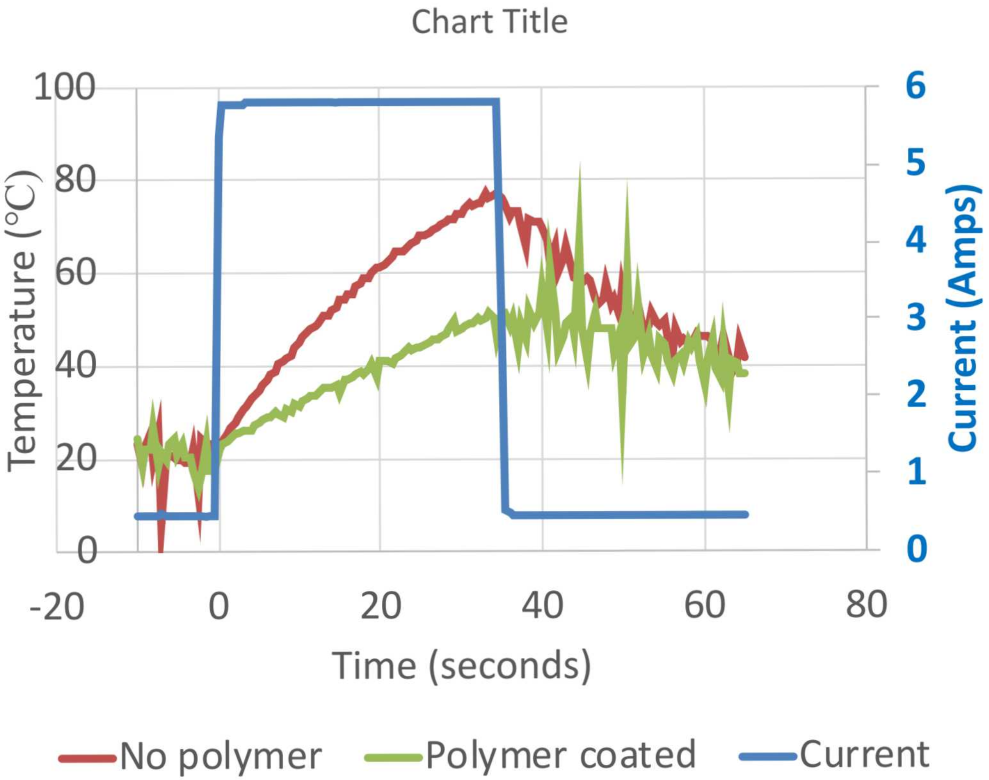
Investigating Potential Grid Vulnerabilities



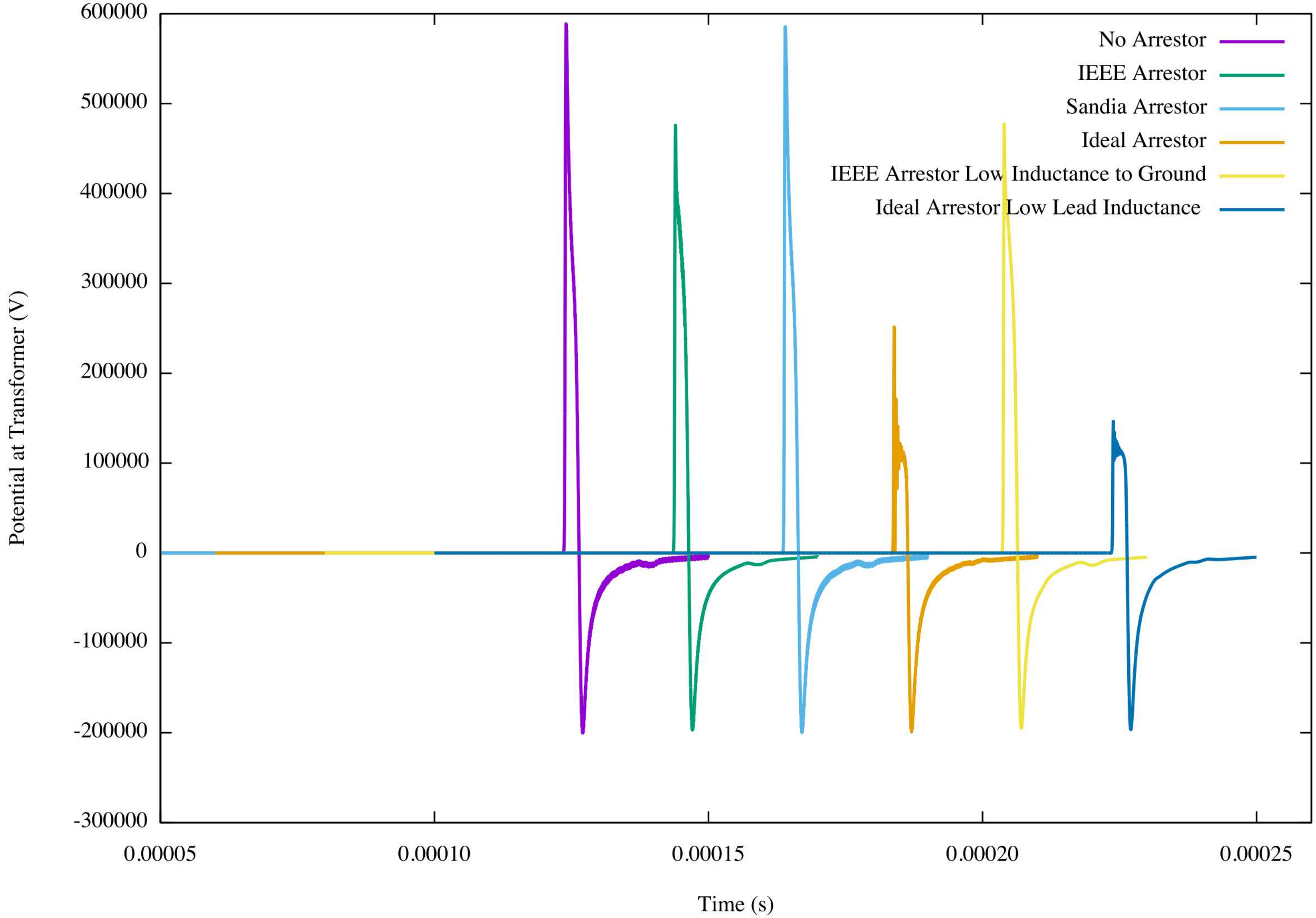

Mitigations Technologies as Applicable
above LCST: polymer condenses, improved thermal conduction in solid
Temperature
2 phases
LCST
1 phase
below LCST: poor thermal conduction in liquid phase
% Polymer
Setup RTS 96 System
HPC Modeling
Xyce
PARALLEL ELECTRONIC SIMULATOR
TEM Coupling
Electromagnetic Wave
High Freq. Transformer Modeling
Dielectric Withstand Testing
Establish HEMP Scenarios
Couple HEMP Pulse to Grid Conductors
Find P(Fail | Vcouple)
E3 Voltage Collapse
Find Delay and Initialize E1 Failures
Run Dynamic Simulation
Enforce Security Constraints
Maximize Margins of Stability
Long Term System Recovery
20%
35%
Measure System Response

Transformer Oil Polymer Additive





Effectiveness of Surge Arrestors Including Parasitic Inductance



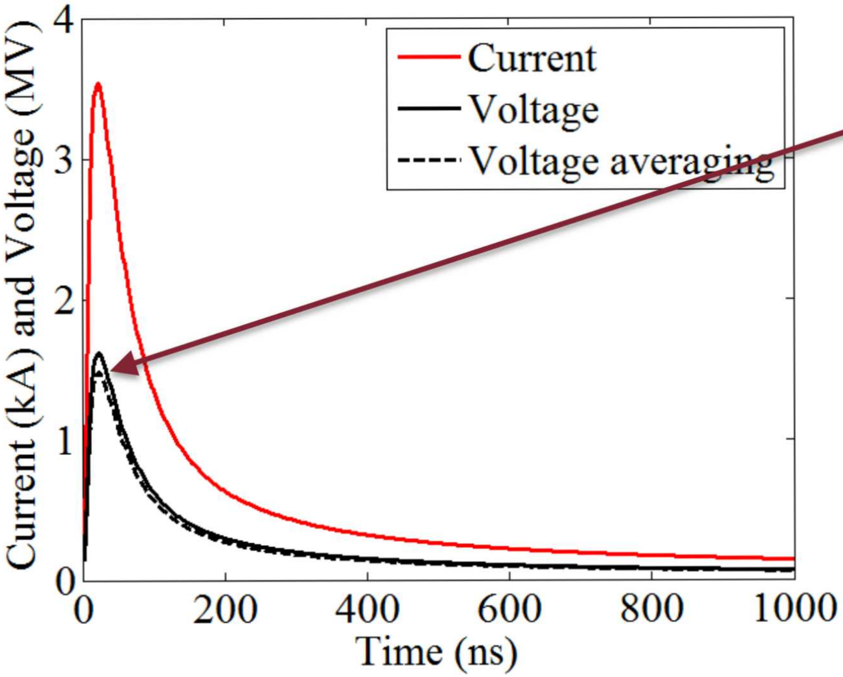
Coupling Physics of Interest

- Single line (equivalent conductor)
- Multiple lines (3-phase systems)
- Substation transition
- Tower impact
- Corona damping
- Instrumentation cable coupling
- Shield wire impact
- Line sag
- Insulator flashover/breakdown
- Substation meshed ground modeling

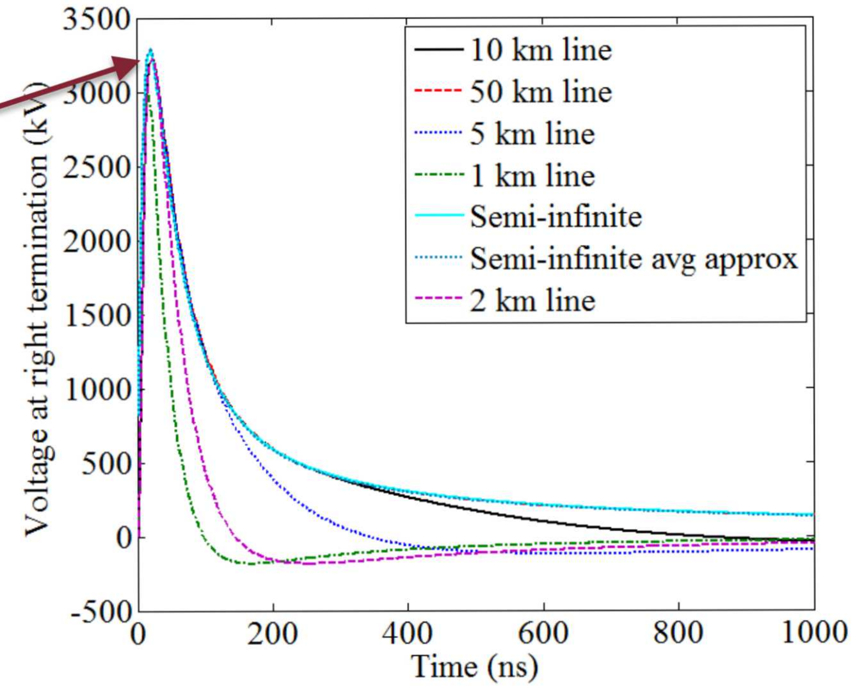
Investigated Work (Single line (equivalent conductor); Multiple lines (3-phase systems); Substation transition)

Ongoing or Future Work (Tower impact; Corona damping; Instrumentation cable coupling)

EMP Coupling to Transmission Lines



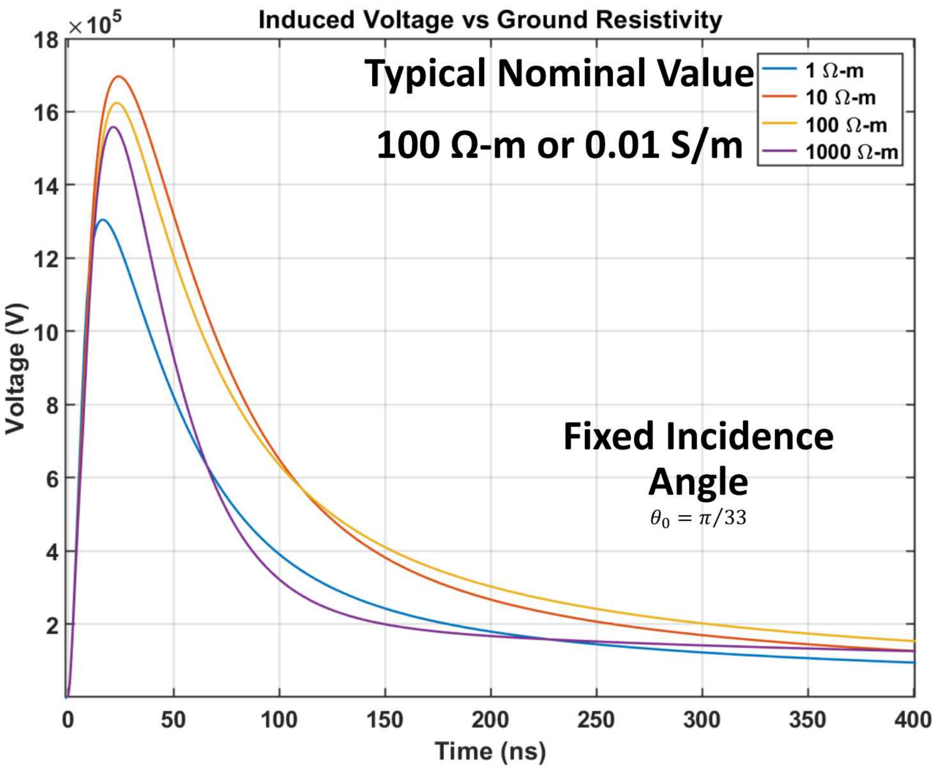
Matched Impedance Termination

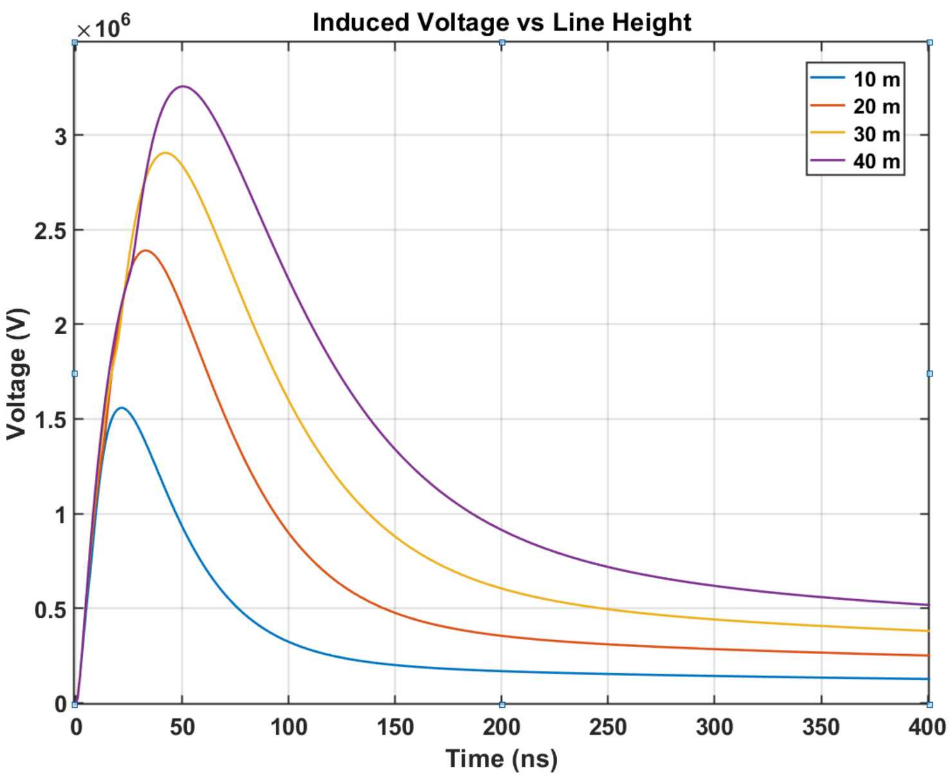


Open Termination

1. Long lines have little affect on coupled voltages
2. Terminating Impedance has a large effect on coupled voltages

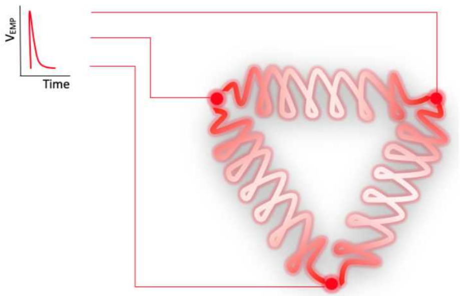
Coupling Sensitivity Analysis Results





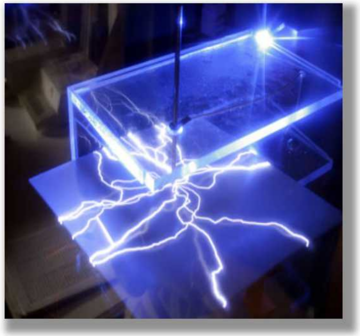
Coupling is sensitive to many variables, which are often not precisely known

Finding Risk of Dielectric Failure to HV Transformers Caused by HEMP



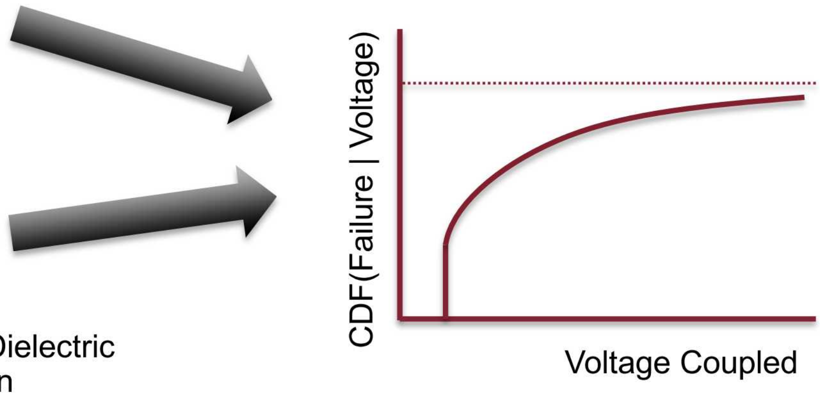
1. Develop High Frequency Winding Model, then Find Winding Voltage Due to HEMP

2. ABB will Calculate Dielectric Stress on Winding Insulation



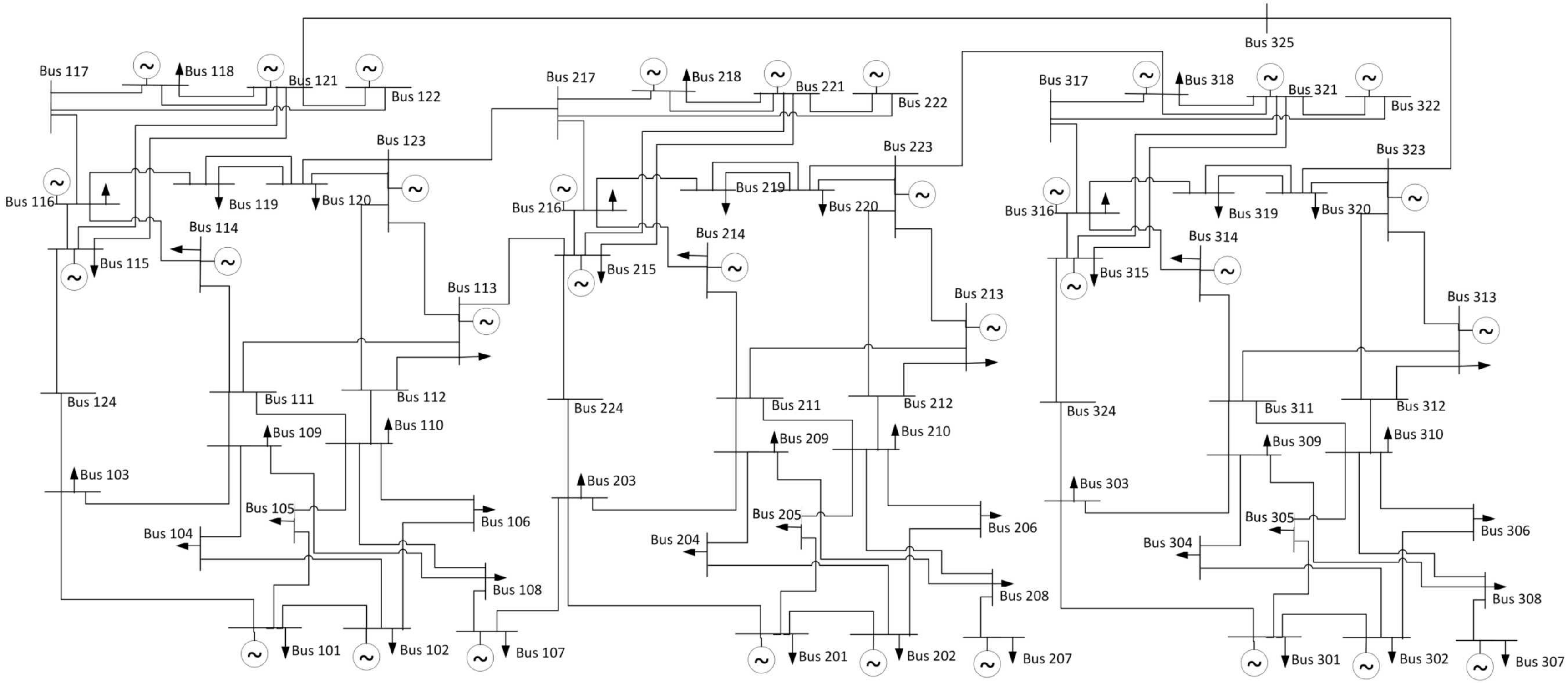
3. Test to find Probability of Dielectric Failure of Paper-Oil Insulation

Prediction of Transformer Failure Due to HEMP Event

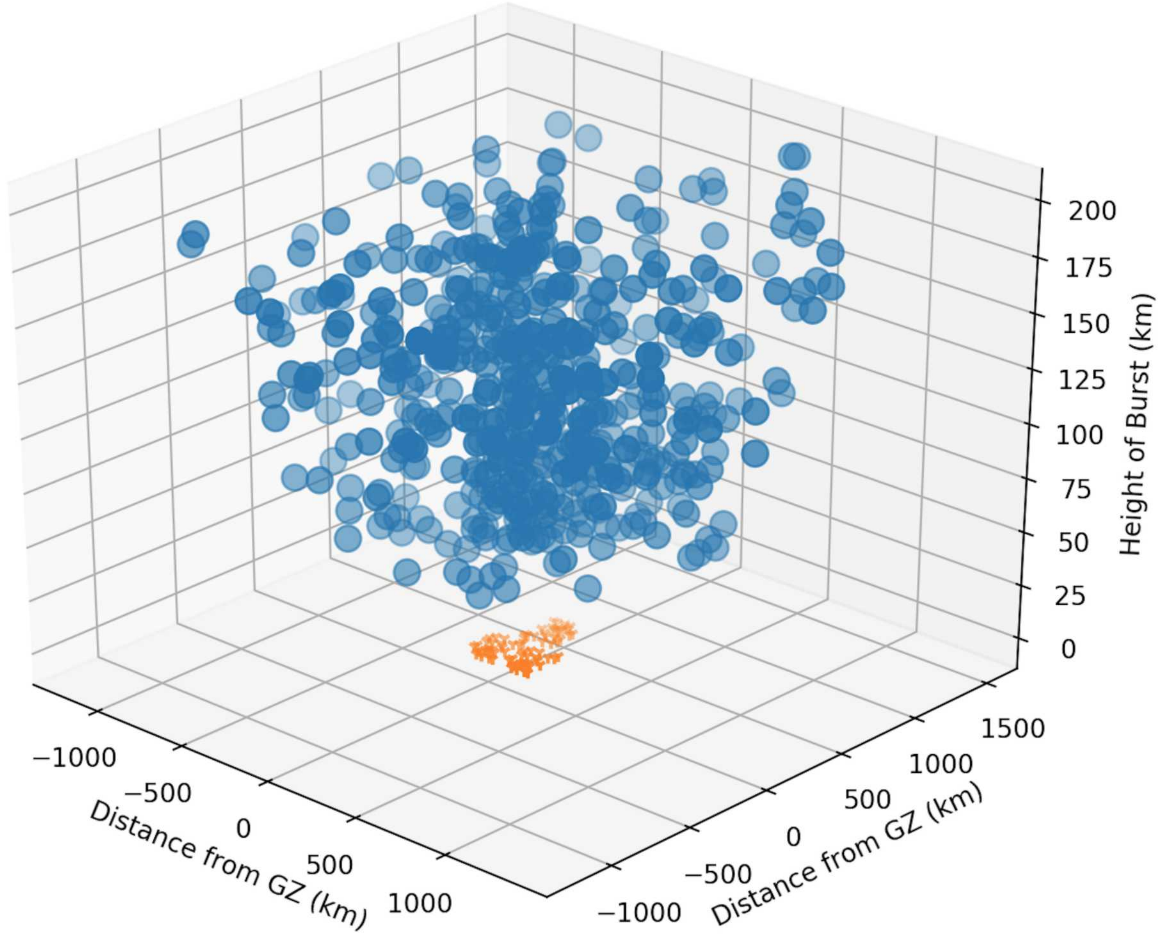


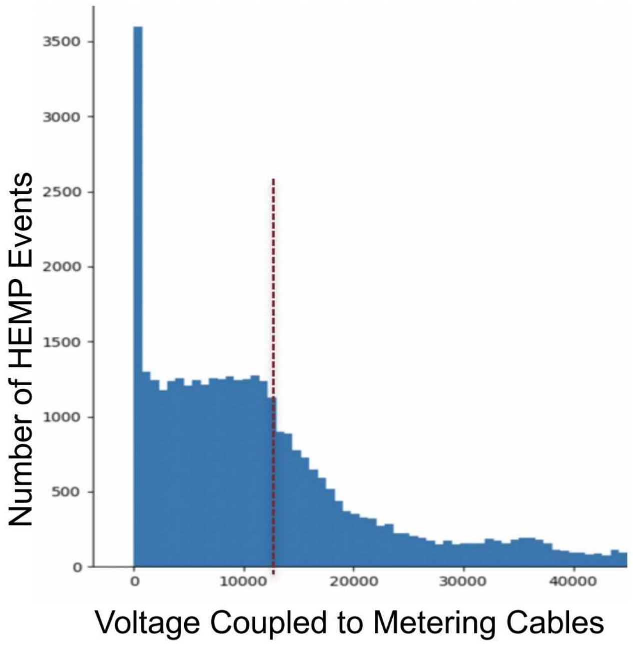
IEEE RTS-96 Grid System
Purpose: Identify System Effects

- Used by the NERC Cascading Outage Study Team
- Provides a Point of Comparison With Published Study Results
- Shows the Combined System Effects Expected From E1 and E3



HEMP Events Above the RTS 96 Grid Model and Coupled Voltages



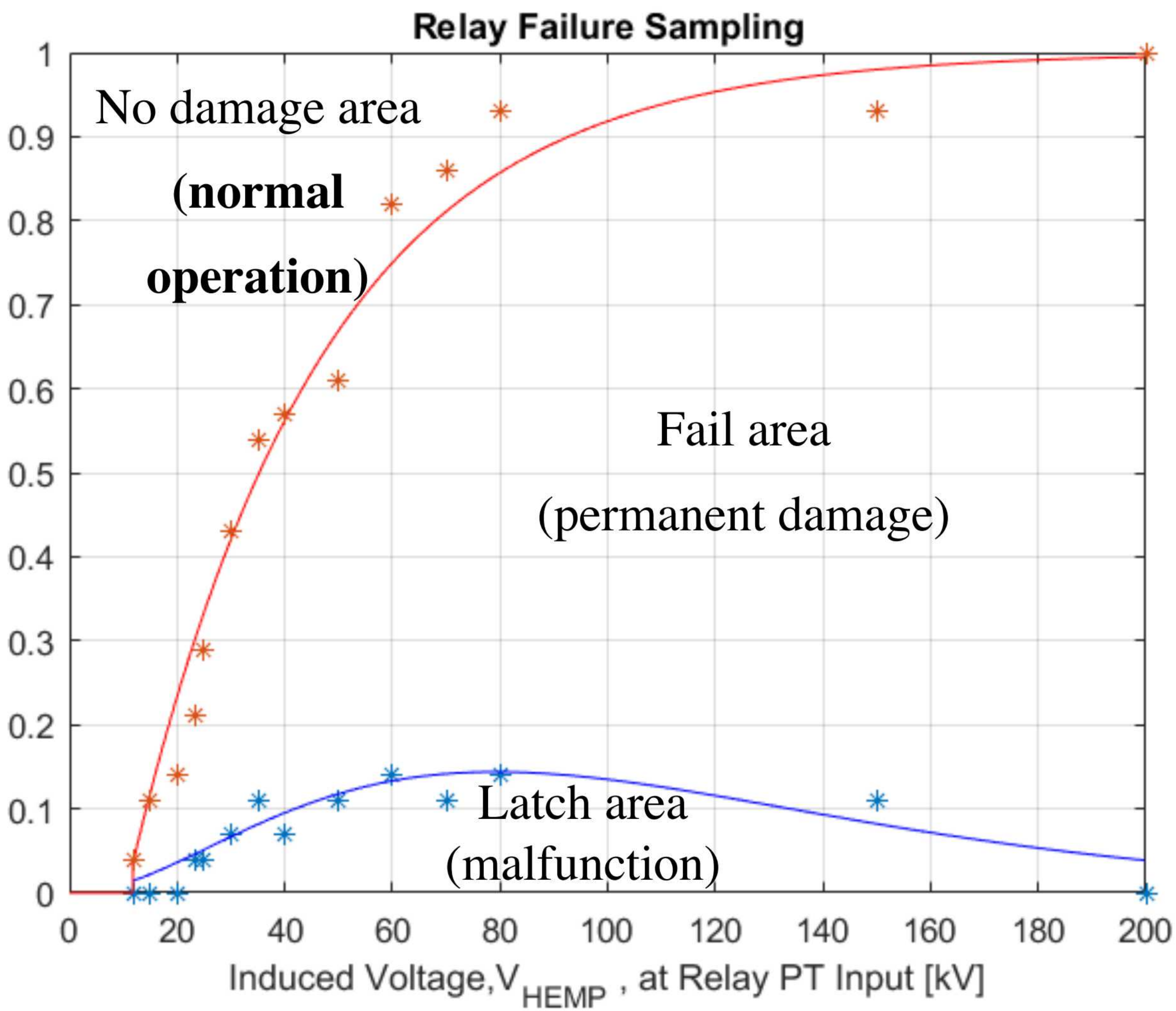


Failure of relay due to terminal voltage

Relay failures caused by the induced voltage from a HEMP at the relay's input terminal

Data from recently released EPRI report and DTRA report.

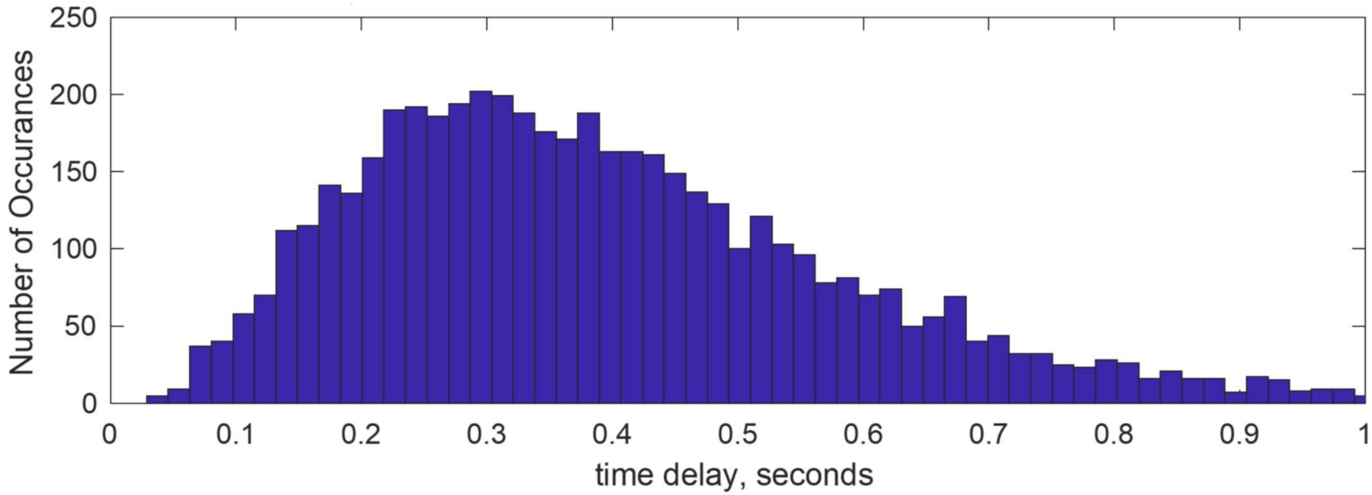
With more data, similar figures will be made for other components.



Delay of Component Trip

Once a relay fails, the component it is protecting does not trip offline immediately, and is not a constant time for all relays.

For this reason, the component trip time is varied, t=0 is the time the EMP voltage hits the relay. Component trip varies from t=0 to t=1 second based on a gamma distribution.



Final Report

- Report Will Include:
  - Voltage Coupling Calculations
  - Test Results
    - Insulation Withstand Test Results
    - Impedance Test Results at High Frequencies
    - Material EMP Withstand Test Results
    - Limited Component EMP Withstand Test Results
  - HV EMP Arrestor Design Information
  - Transformer Polymer Oil Additive Information
  - System Analysis Methods and Results
    - Effects of Combined Failure Modes
    - Effects of System Mitigation Technologies
    - Optimal Planning and Operations Methods to Enhance EMP Resilience

Outcomes at the End of the Project

- Modeling Methodologies That Will:
  - Identify Failure Probabilities for Key Components
  - Calculate Voltage Stresses Inside Large Power Transformers
  - Incorporate E1 and E3 Failures into Dynamic System Simulations
    - Broadly Identify System Response to a HEMP
    - Identify Key System Vulnerabilities
- Critical Test Results
  - Impedance Testing for PTs and Power Transformers
  - Probabilistic Dielectric Withstand Tests for Paper-Oil
  - Combined Test-Analytic E1 Vulnerability Assessments for Large Power Transformers
  - Limited Component Testing for E1
- New Technologies
  - LCST Polymer Oil Additives for Thermal Management of Transformers
  - EMP Sub-Nanosecond Surge Arrestors
- New Analytic Methods
  - Methods to Calculate EMP Coupling, Shielding, and Shield Grounding Effectiveness
  - Methods to Apply Limited Test Results Across Broad Populations

Select Publications

- Oleksiy Slobodyan, Jack Flicker, Robert Kaplar, and Mark Hollis, "Analysis of Dependence of Critical Electric Field on Semiconductor Bandgap," *Journal of Applied Physics (Submitted)*, 2019.
- S. Campione, L. K. Warne, M. Halligan, O. Lavrova, and L. San Martin, "Decay Length Estimation of Single-, Two-, and Three-Wire Systems Above Ground Under HEMP Excitation," *Progress In Electromagnetics Research B*, Vol. 84, 23-42, 2019.
- Matt Halligan et. al., "Transmission Lines Above Ground: Circuit Models for the Open, Short, and Ground Rod Terminating Loads," *Progress In Electromagnetics Research B* (Accepted), 2019.

Thank You

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