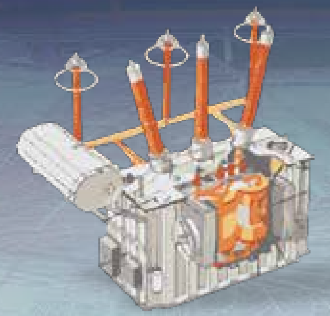
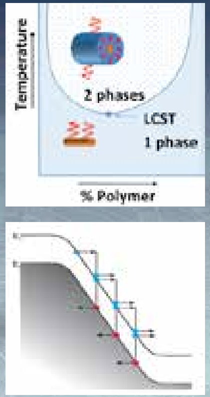




EMP-Resilient Electric Grid: GC LDRD Presentation

August 22, 2018

Olga Lavrova (PI), Craig Lawton (PM), Charles Hanley, Matt Halligan, Jack Flicker, Dale Huber, John Eddy, Ross Guttromson, Rich Schiek, Jon Rogers, Steve Glover, Bob Kaplar, Larry Warne, Salvatore Campione, Brian Pierre, Bryan Arguello, April Zwerneman, Matt Hoffman, Andrea Staid

Exceptional service in the national interest

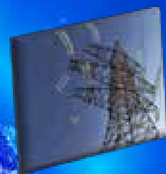
Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA

Sandia's Grid Modernization Program Approach

Crosscut Initiatives



Transmission Planning & Operations

Renewable Energy & Distributed Systems Integration

Energy Storage

Defense Energy

Cyber and Physical Security

- Grid Resilience
- Microgrids
- Grid Modernization Laboratory Consortium
- Laboratory Directed Research & Development

Defining Resilience

"The term 'resilience' means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents." –

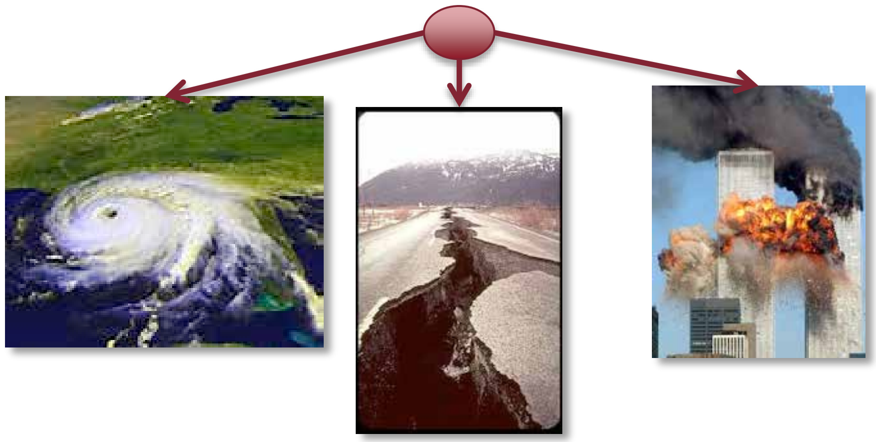
Resilience definition from Presidential Policy Directive-21

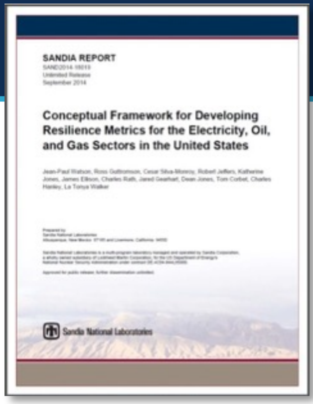
Sandia adds two words: "system" and "measure."

"Without some numerical basis for assessing resilience, it would be impossible to monitor changes or show that community resilience has improved. At present, no consistent basis for such measurement exists…"

-Disaster Resilience: A National Imperative, National Academy of Sciences

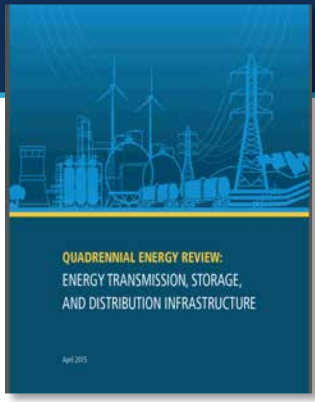
Resilience Analysis Approach is Threat-Based, Rigorous, and Quantifiable

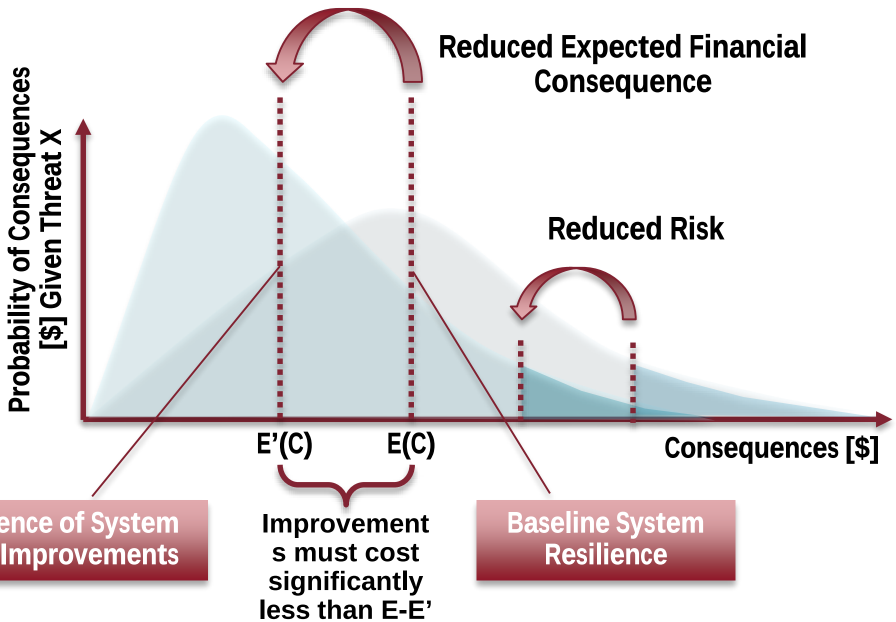


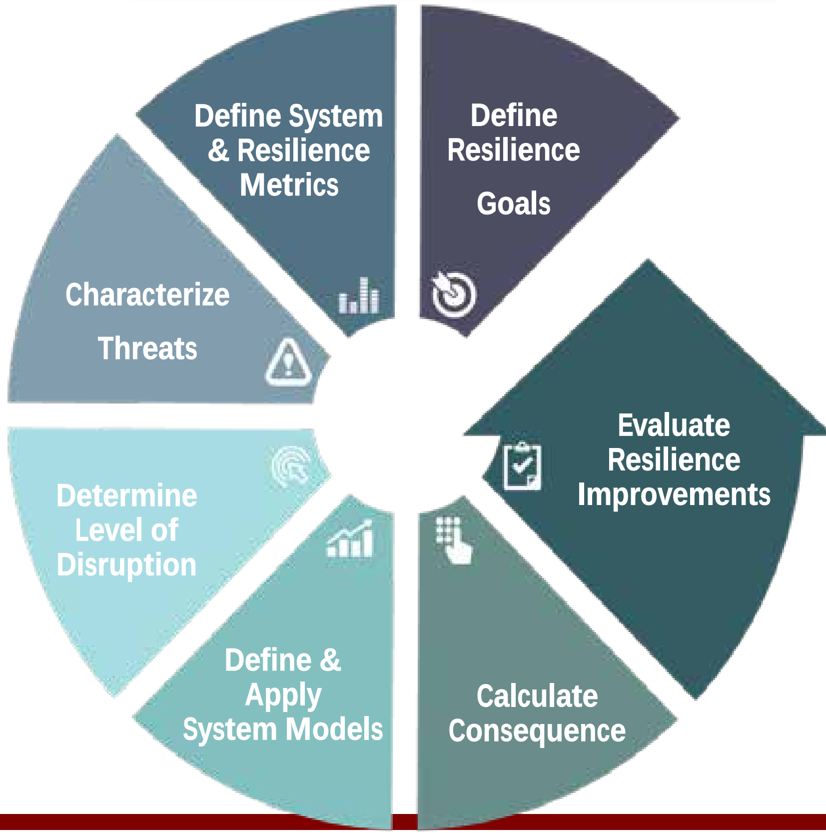

SANDIA REPORT

Conceptual Framework for Developing Resilience Metrics for the Electricity, Oil, and Gas Sectors in the United States

Sandia National Laboratories







EMP: Growing concern by US Government Agencies

1. **2016 Electric Subsector Coordinating Council visit to Sandia**
2. **2016 DOE visits to Sandia (Liz Sherwood Randall, Pat Hoffman, John Ostrich)**
3. **2008 EMP Commission report; 2017 revitalization of commission**
4. **DOD and DHS policy drivers**
5. **May 2017 US Senate hearings (Murkowski)**

156 FERC ¶ 61,215
UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COM

18 CFR Part 40

[Docket No. RM15-11-000; Order No.

Reliability Standard for Transmission System Plann
Geomagnetic Disturbance Events

(Issued September 22, 2016)

AGENCY: Federal Energy Regulatory Commission.

ACTION: Final rule.

SUMMARY: The Federal Energy Regulatory Commission (Commission) approves Reliability Standard TPL-007-1 (Transmission System Planned Performance for Geomagnetic Disturbance Events). The North American Electric Reliability Corporation (NERC), the Commission-certified Electric Reliability Organization, submitted Reliability Standard TPL-007-1 for Commission approval in response to a Commission directive in Order No. 779. Reliability Standard TPL-007-1 establishes requirements for certain registered entities to assess the vulnerability of their transmission systems to

The White House
Office of the Press Secretary

For Immediate Release — October 13, 2016

Executive Order -- Coordinating Efforts to Prepare the Nation for Space Weather Events

EXECUTIVE ORDER

\- - - - - - -

COORDINATING EFFORTS TO PREPARE THE NATION FOR SPACE WEATHER EVENTS

By the authority vested in me as President by the Constitution and the laws of the United States of America, and to prepare the Nation for space weather events, it is hereby ordered as follows:

Section 1. Policy. Space weather events, in the form of solar flares, solar energetic particles, and geomagnetic disturbances, occur regularly, some with measurable effects on critical infrastructure systems and technologies, such as the Global Positioning System (GPS), satellite operations and communication, aviation, and the electrical power grid. Extreme space weather events -- those that

HEARINGS AND BUSINESS MEETINGS

Home / Hearings / Hearings and Business Meetings

May 04 2017

Hearing to examine the threat posed by electromagnetic pulse and policy options to protect energy infrastructure and to improve capabilities for adequate system restoration.

366 Dirksen 10:00 AM

The hearing will be held on **Thursday, May 4, 2017, at 10:00 a.m. in Room 366 of the Dirksen Senate Office Building in Washington, DC.**

- **Sen. Lisa Murkowski**
  Chairman
  Senate Committee on Energy and Natural Resources
- **The Honorable Cheryl LaFleur**
  Chairman
  Federal Energy Regulatory Commission
- **The Honorable Newt Gingrich**
  Chairman of the Board

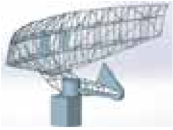
Sandia Has a Long History in Characterizing Electromagnetic Pulse (EMP)

Sandia's primary mission is ensuring the U.S. nuclear arsenal is safe, secure, and reliable in all operating environments

- **Normal Operating Environments**
  - Electromagnetic Radiation (DC to >50GHz)
  - Electrostatic Discharge
  - Nearby Lightning
- **Abnormal Environments**
  - Direct Strike Lightning (200kA, multi-pulse)
  - Contact with Unintended Electric Power
- **Hostile Environments**
  - Nuclear Weapon Fratricide / Counter-Measures
  - High Power Microwaves

Weapon External EM/Rad Environments Examples:

High Power Radars



High Power Microwaves

RF Communications

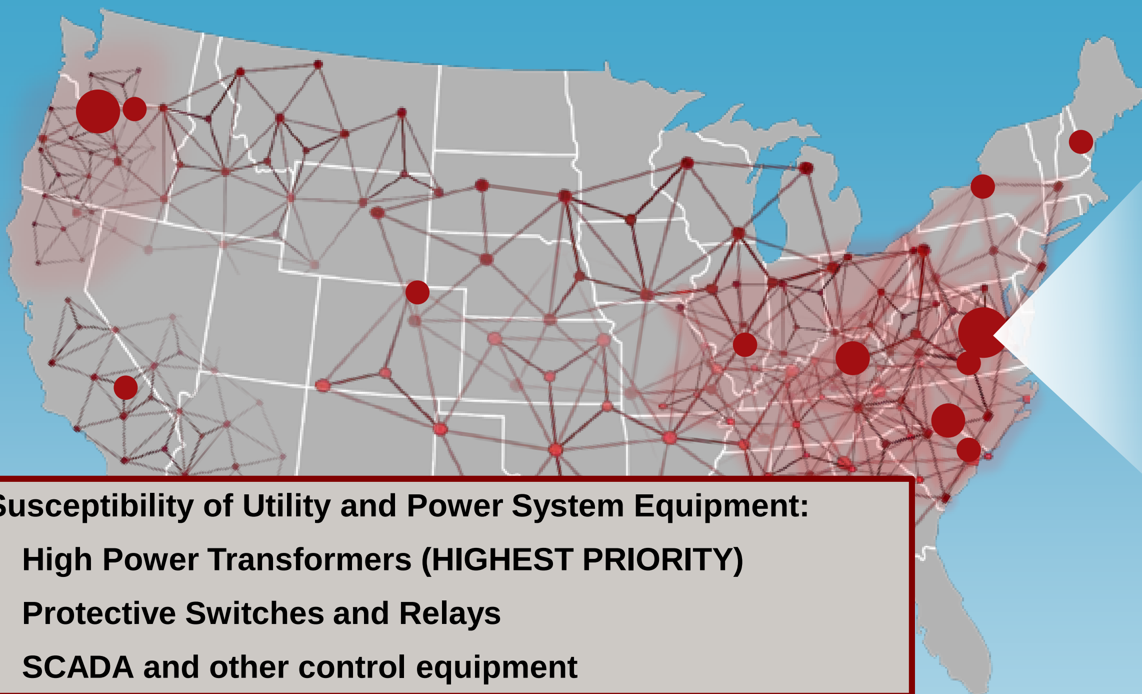
Lightning

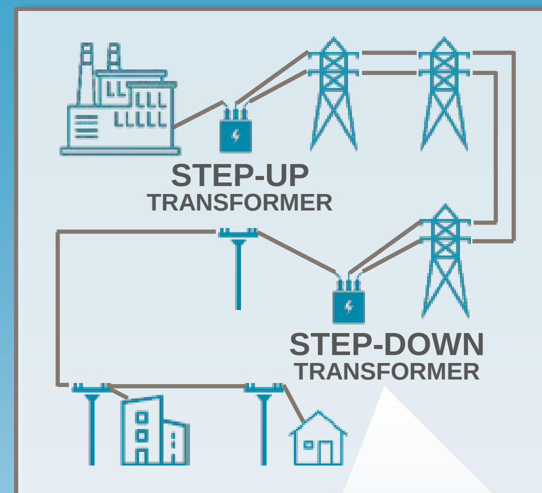
Electrostatic Discharge

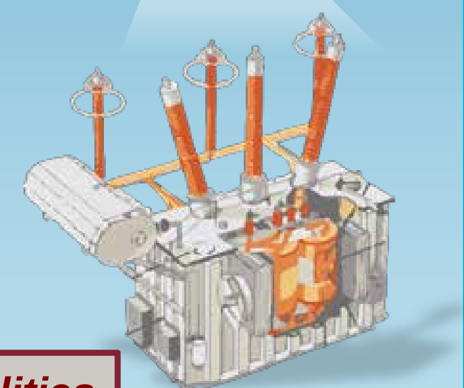
Submarine B-field degaussing

Nuclear fratricide/ counter-measures

Biggest Electric Grid Vulnerabilities to EMP







Susceptibility of Utility and Power System Equipment:

- **High Power Transformers (HIGHEST PRIORITY)**
- **Protective Switches and Relays**
- **SCADA and other control equipment**

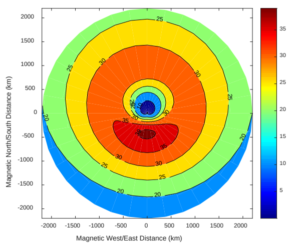
Two Primary coupling mechanisms:

- **Directly through radiated fields**
- **Through coupling on transmission and distribution lines**

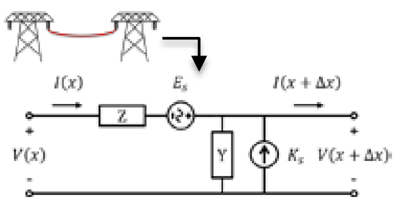
BOTTOM LINE: ***We do not fully understand the vulnerabilities of the grid network nor of its individual components – but EHV transformers are believed to be the most critical***

Our Approach: Three Integrated Tasks

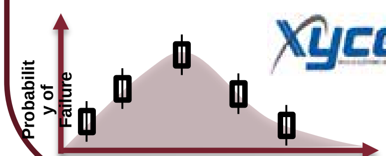
Task 1
Vulnerability Assessment



Environments



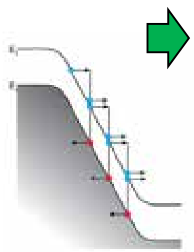
Coupling



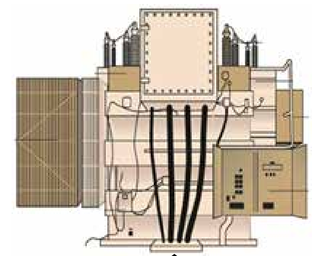
Failure Analysis

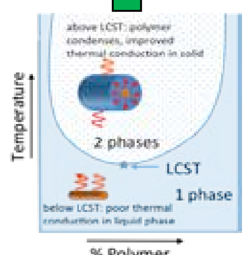
Task 2
Material & Device Innovation

EMP hardened assets



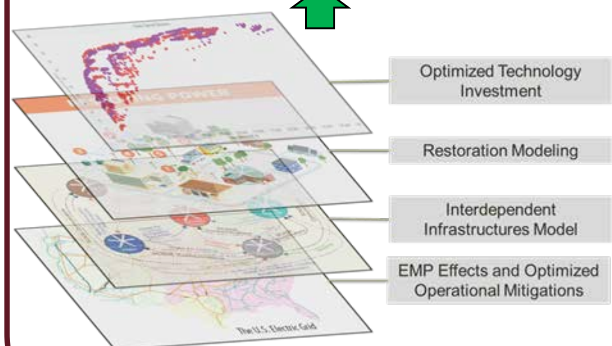
Avalanche Breakdown in a Wide Band-Gap diode





Design New Component Materials to Withstand EMP Effects

Task 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

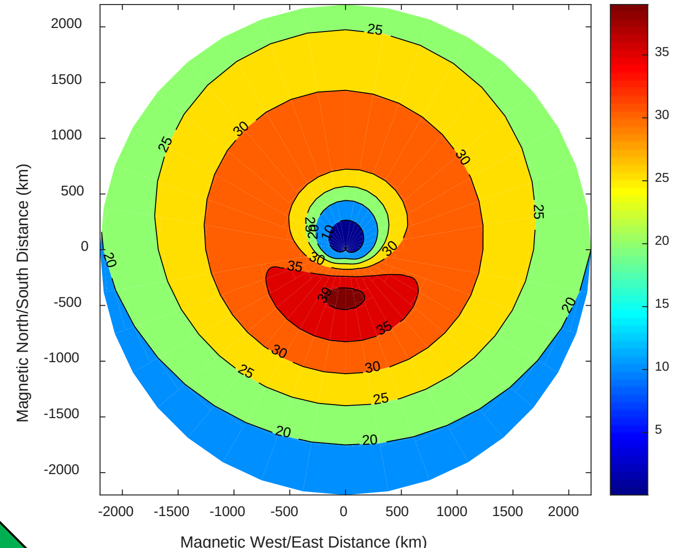
- Develop Wide Band-Gap EMP arrestor
- LCST Polymers for thermal management during E3/GMD

R&D

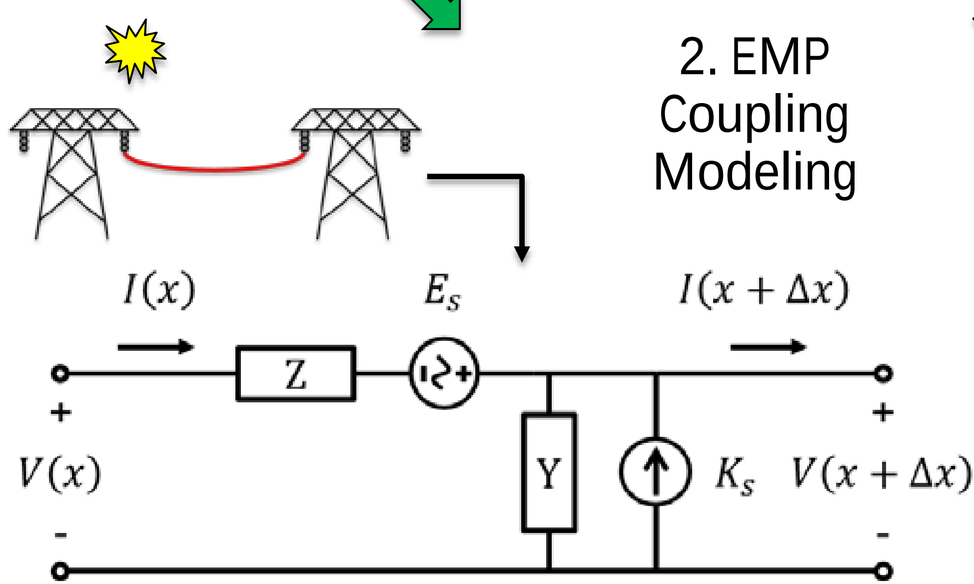
- Baseline assessment of EMP Effects w/ Large Scale Stochastic, AC Dynamic Optimization
- Risk mitigation by Tech Deployment, Operational Mitigation & Optimal Restoration

Task 1 Overview

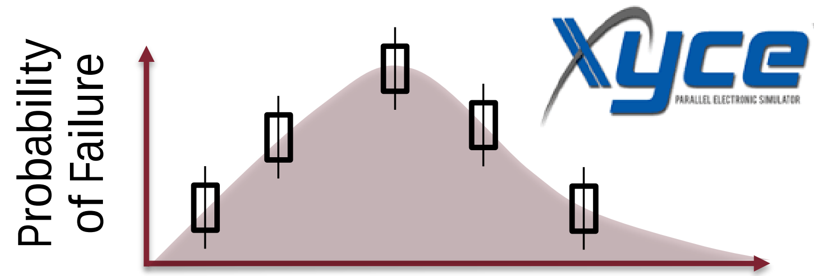
1. EMP Environment Definition



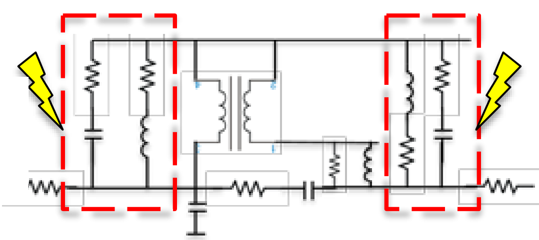
2. EMP Coupling Modeling



3. Component Failure Modeling and Experimental Characterization

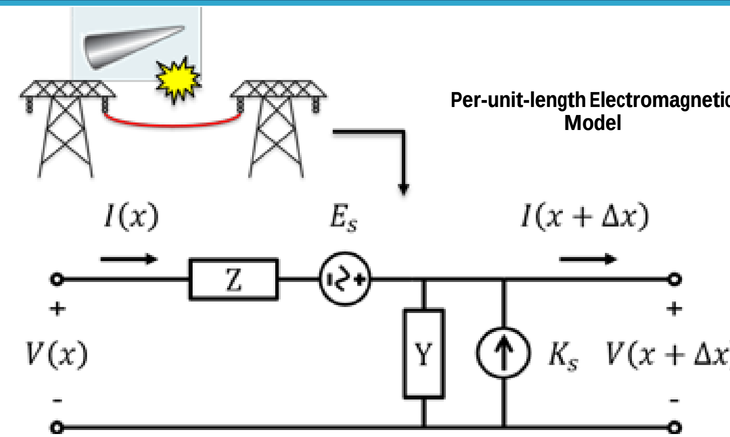


Model Extraction

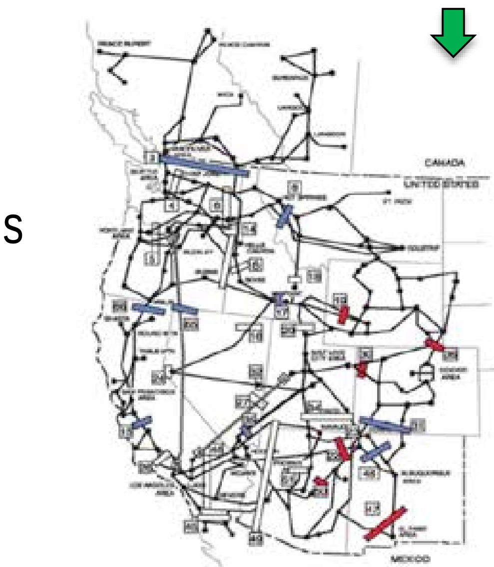


EMP Coupling Modeling

- Focus: coupling to power lines and effects
- Challenges
  - Large scale electromagnetic calculations
  - Many boundary conditions unknown
- Analysis approach
  - Simplified grid representations
  - Formulating coupling estimates and bounds
  - Solutions leveraging analytic analysis, full wave simulations, ATLOG, and Xyce
- Outputs: conducted environment definitions



Per-unit-length Electromagnetic Model



Large Scale, Simplified Electromagnetic Grid Model

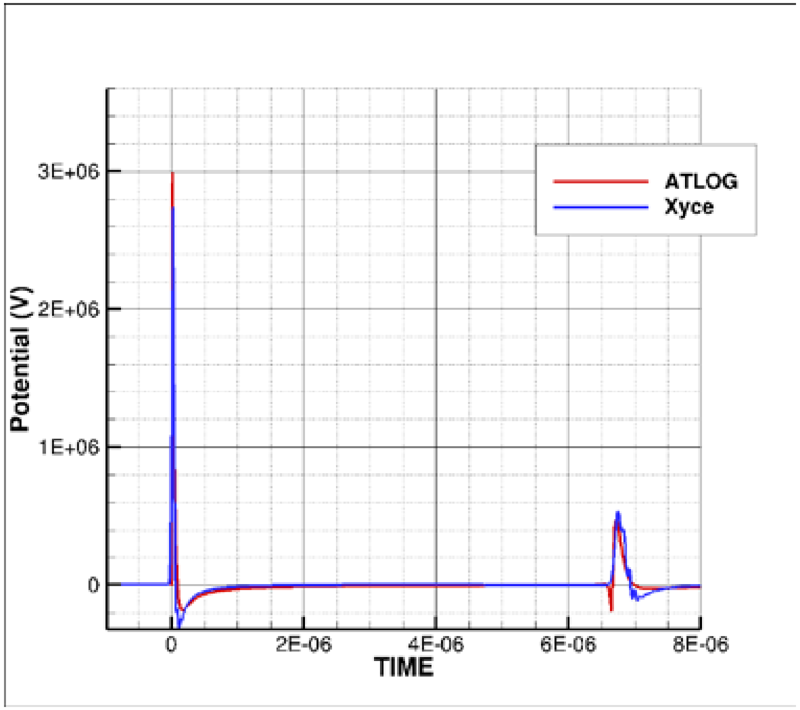
Xyce

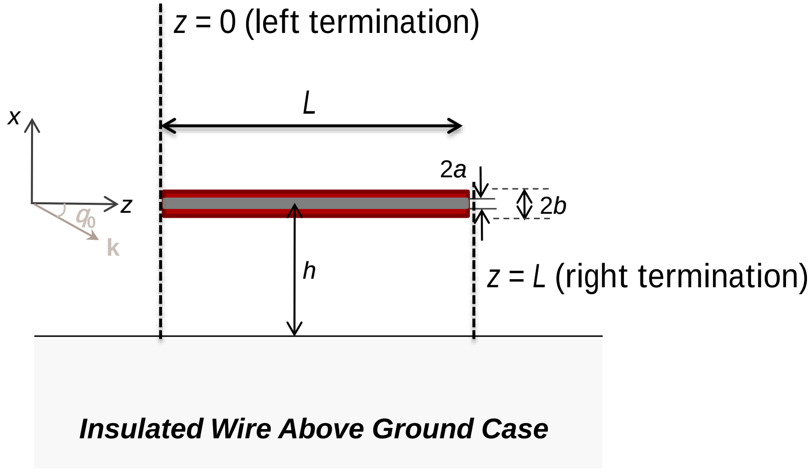
ATLOG

This task enables the first large-scale, high-fidelity grid coupling estimates for grid impact assessment

Single Line Simulation Comparisons

- Single line simulation comparisons to validate coupling calculations
- Decay length assertions from Atlog to be corroborated in Xyce





Simulation Comparison Parameters

$\varepsilon_{r,ground} = 20$

$\sigma_{ground} = 0.01\ S/m$

$\theta_0 = \dfrac{\pi}{33}\ radians$

$a = 1\ cm$

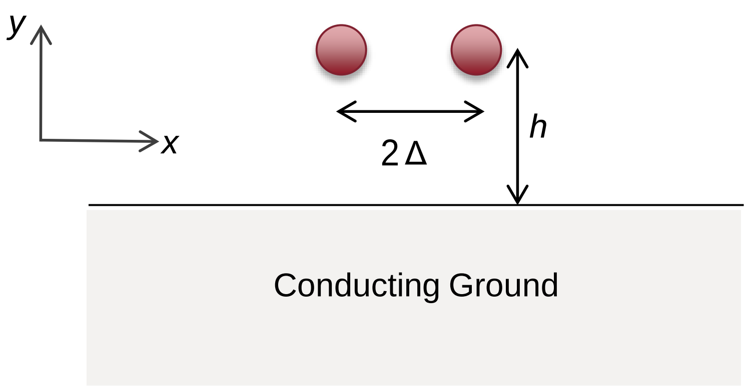
$\sigma_{wire} = 2.9281e7\ S/m$

$h = 10\ m$

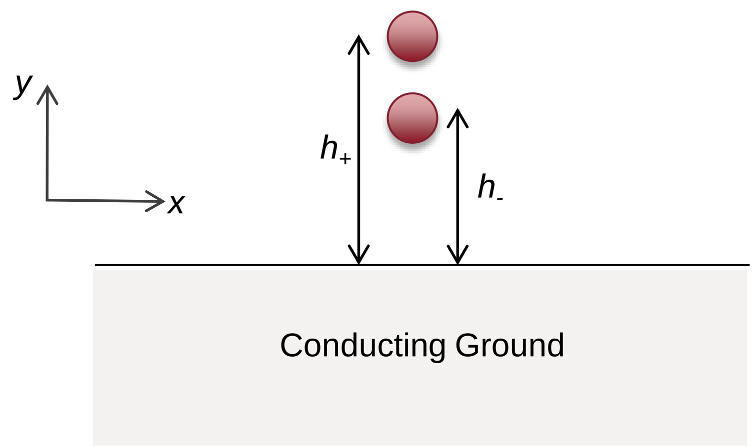
$L = 1\ km$

Coupling Analysis for Multi-Line Systems

- 2-wire example cases
- Currents decoupled for balanced geometry, coupled for unbalanced geometry
- Model decay lengths of interest



Balanced Geometry



Unbalanced Geometry

Differential Mode

$$\underline{I}_1 = \left(c_+ e^{z\sqrt{\Lambda_1}} + c_- e^{-z\sqrt{\Lambda_1}}\right)\begin{pmatrix}1\\-1\end{pmatrix}$$

$$\mathrm{Re}\sqrt{\Lambda_1} = \mathrm{Re}\sqrt{(Y - Y_m)(Z - Z_m)}$$

Common Mode

$$\underline{I}_2 = \left(c_+ e^{z\sqrt{\Lambda_2}} + c_- e^{-z\sqrt{\Lambda_2}}\right)\begin{pmatrix}1\\1\end{pmatrix}$$

$$\mathrm{Re}\sqrt{\Lambda_2} = \mathrm{Re}\sqrt{(Y + Y_m)(Z + Z_m)}$$

Task 1: Important takeaways

Conducted Environments as a Function of Incidence Angle

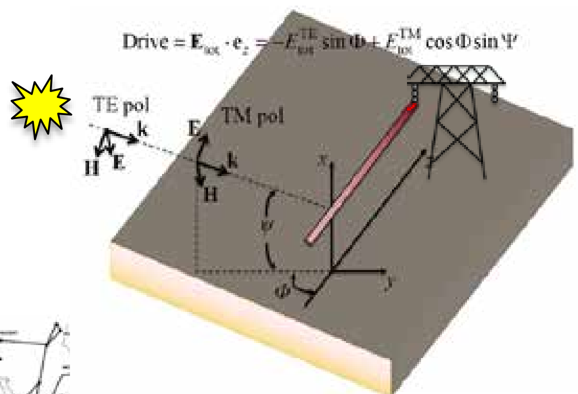
Focus: coupling to power lines and effects

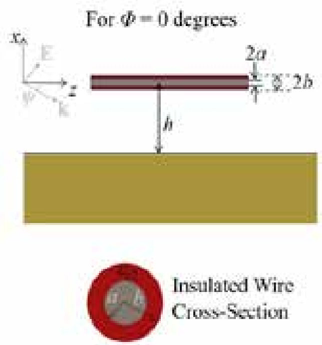
Challenges

Large scale electromagnetic calculations; Many boundary conditions unknown

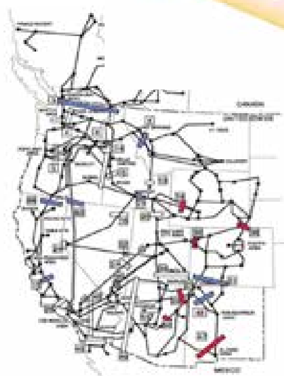
Analysis approach

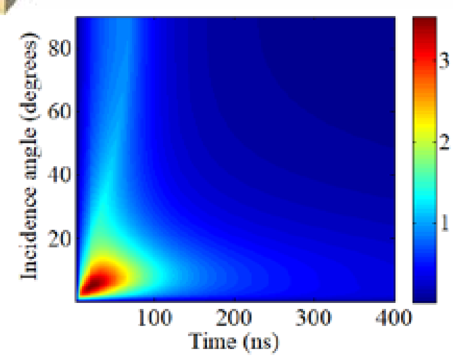
Simplified grid representations; Formulating coupling estimates and bounds ; Solutions leveraging analytic analysis, full wave simulations, ATLOG, and Xyce

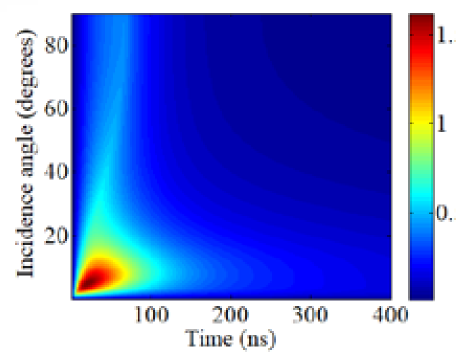


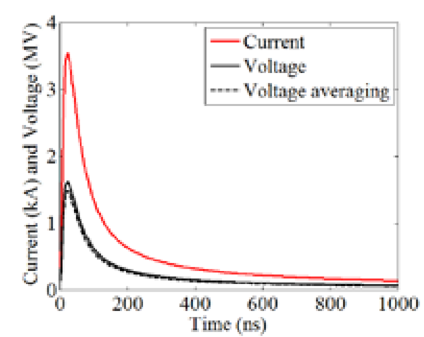


- Analysis on a single, infinite length wire
- MIL-STD-464C EMP waveform
- Maximum coupling near grazing incidence (π/33 rad)





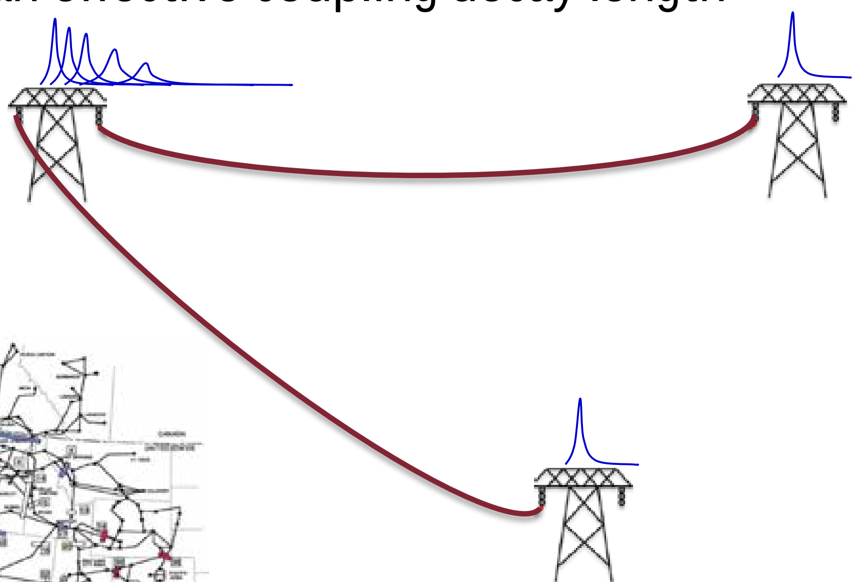


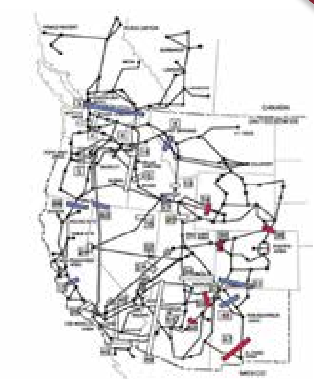


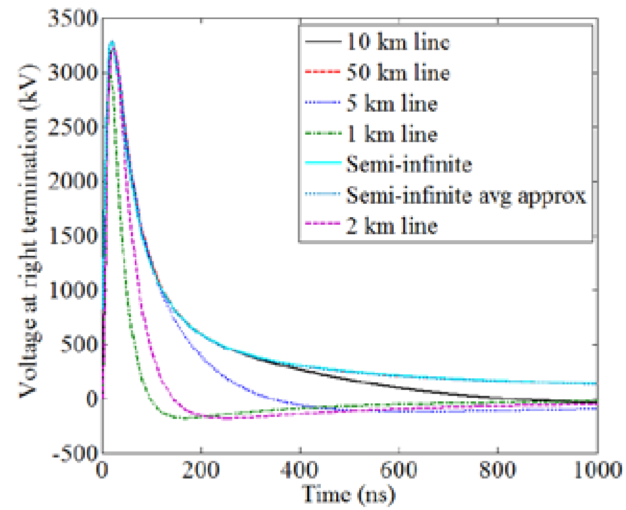
First order calculations show peak environments of order MV and kA for E1

Task 1: Important takeaways: Impact of Single Line Decay Length

- Calculate termination voltage for varying line lengths
- Convergence to infinite results indicates an effective coupling decay length







Line length (km)	Energy (J)	Δ (%)
Semi-infinite	1520.93	0
50	1478.30	2.80
10	1437.21	5.50
5	1338.00	12.03
2	960.46	36.85
1	526.04	65.41

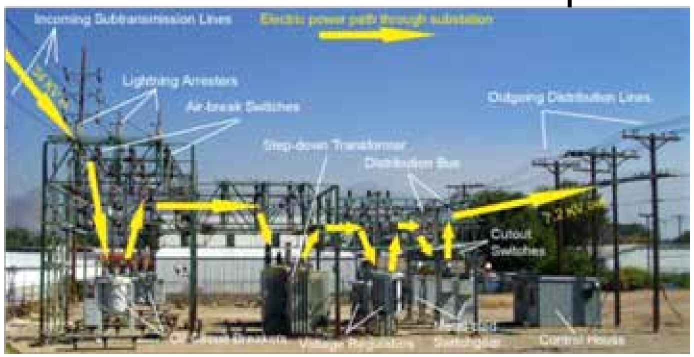
- V_{peak} convergence for lines ≥ 2 km
- Energy convergence for lines ≥ 5 km

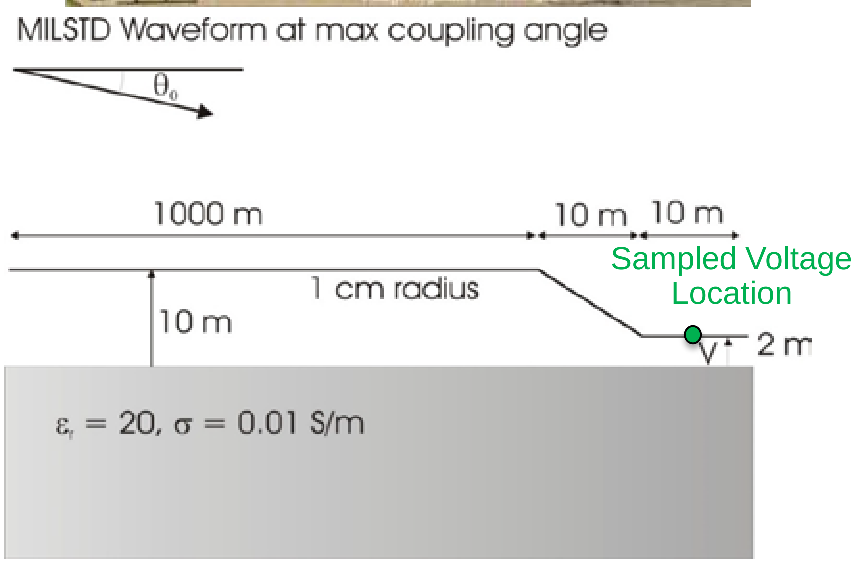
$$E = \int_0^T V^2 dt / z_{peak}$$

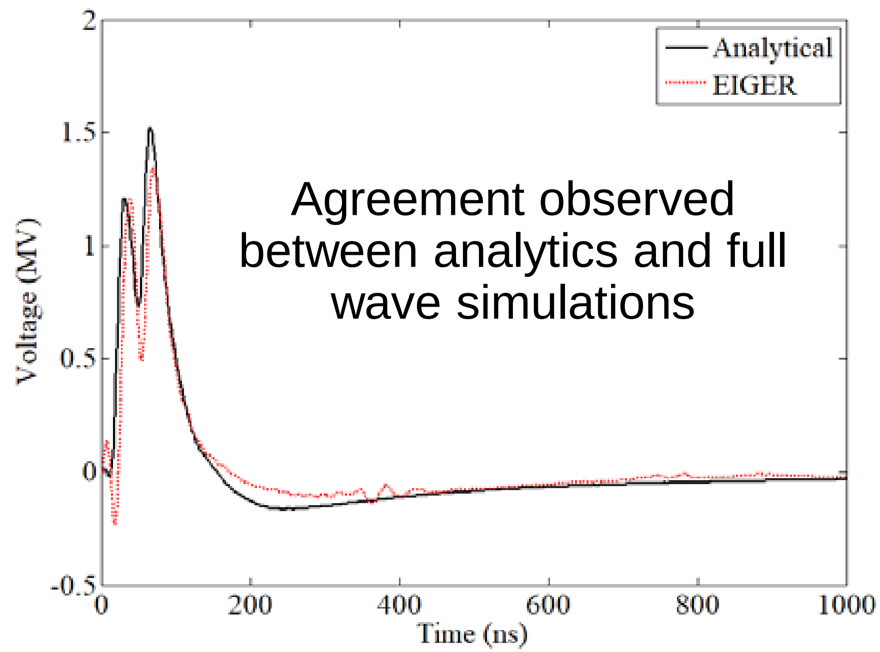
Local voltages and currents are a function of distributed sources within a few km for single line coupling analyses

Substation Line Transition Coupling Impacts

- Modeling arbitrary line height transition for comparison with full-wave simulation
- Additional case studies to be performed with representative substation layouts







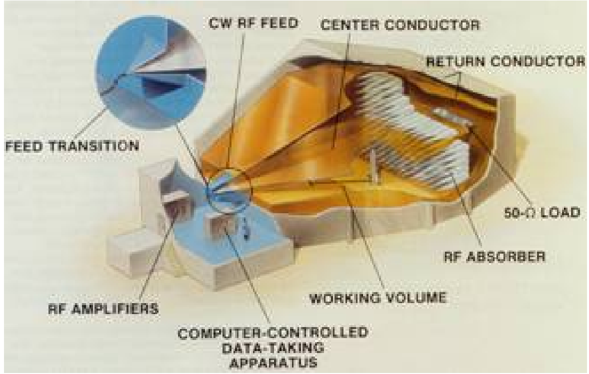
Agreement observed between analytics and full wave simulations

Sandia's Electromagnetic Pulse (EMP) Facilities

Unique EM Test/Experiment Capabilities are Required for our Mission Space

Mode-Stir Chamber

- CW (220 MHz – 40 GHz)

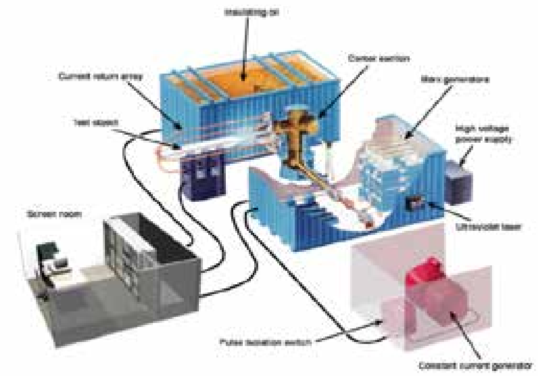


EMES Facility

- CW (100 kHz – 250 MHz)
  125 V/m
- EMP (1 ns risetime)
  250 kV/m

Gigahertz Transverse ElectroMagnetic (GTEM)

- CW (DC – 1GHz) >130 V/m
- EMP (1 ns risetime) > 130 kV/m, HPM

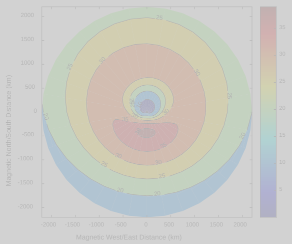


Extreme Lightning Simulator

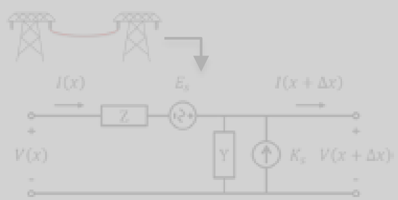
- 200 kA peak
- Two pulse w/ continuing current (600 A)

Our Approach: Three Integrated Tasks

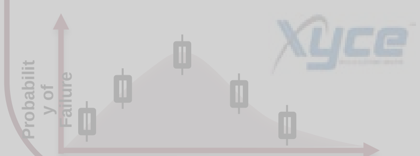
Task 1
Vulnerability Assessment



Environments



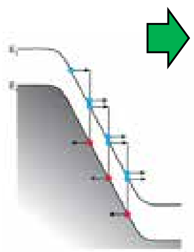
Coupling



Failure Analysis

Task 2
Material & Device Innovation

EMP hardened assets



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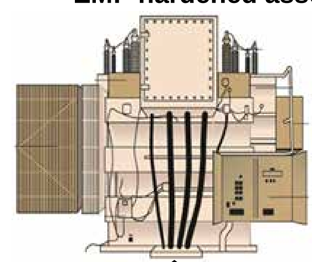
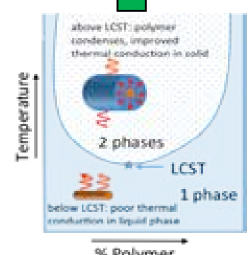
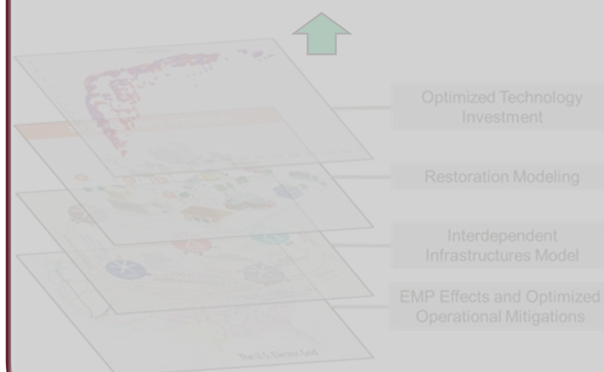




Design New Component Materials to Withstand EMP Effects

Task 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

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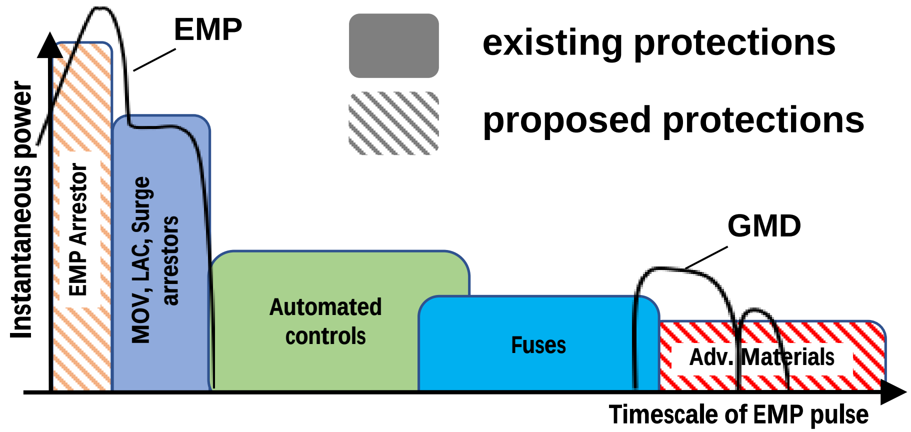
- Baseline assessment of EMP Effects w/ Large Scale Stochastic, AC Dynamic Optimization
- Risk mitigation by Tech Deployment, Operational Mitigation & Optimal Restoration

Thrust 2: Materials and Device Development

Goal: Develop breakthrough materials and devices to enable new EMP-resilient grid hardware, focusing on protection of large EHV transformers.

Motivation: Conventional grid protections are effective at "medium" timescales.

New technologies are needed to protect at the very short and very long timescales of EMP

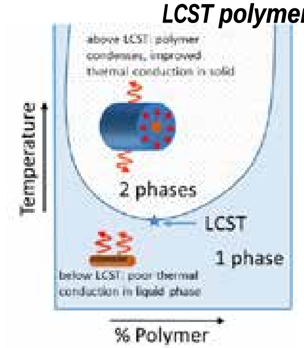


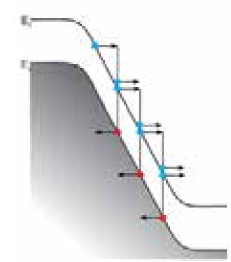
Conventional protections are effective at medium timescales. New technologies will protect against waveforms at the very short and very long timescales of EMP.

Approach:

- **Development of EMP arrestors that can respond to extremely voltage transients on time scales as short as ≤1 ns.**
- **Develop advanced materials for transformers that will mitigate thermal stresses, reducing probability of failure during "slow" GMD events**

LCST polymer



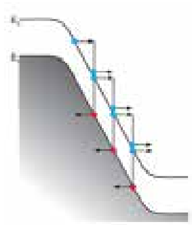


Avalanche breakdown in EMP arrestor

EMP Arrestor

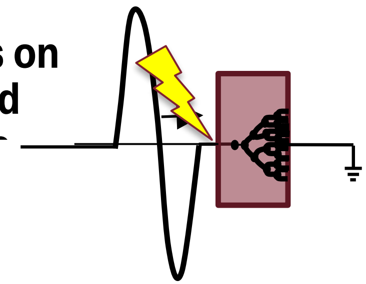
Breakthrough Understanding, Materials, Design Required for E1 Protection

Development of transformational grid protection technology requires a staged approach...

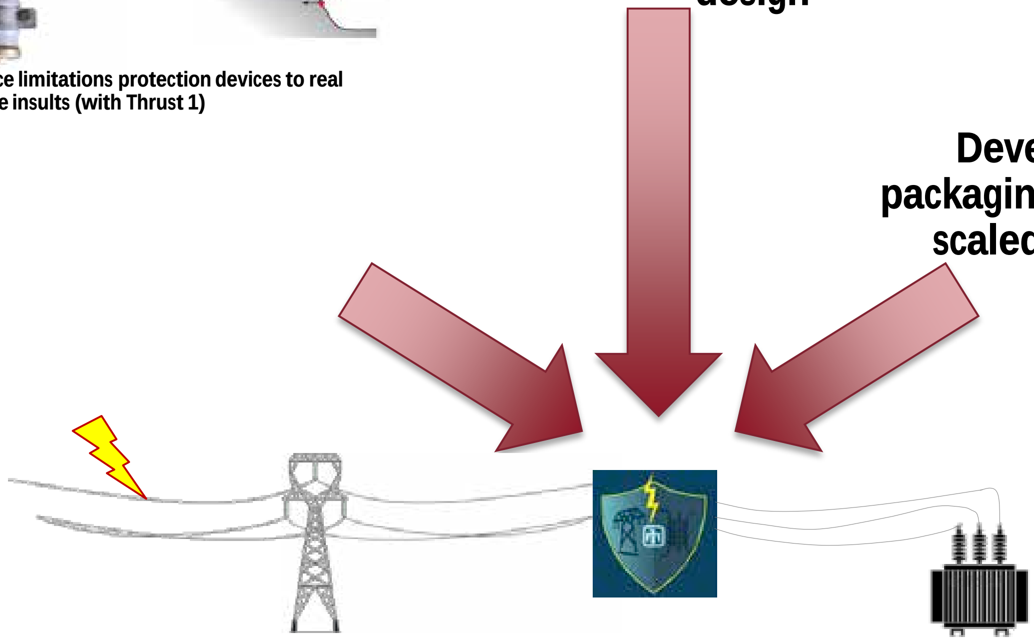


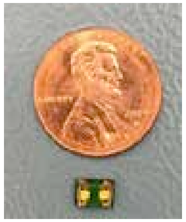
Characterize performance limitations protection devices to real EMP-type insults (with Thrust 1)

Understand fundamental limitations on energy relaxation times in GaN and other materials for optimal devic design

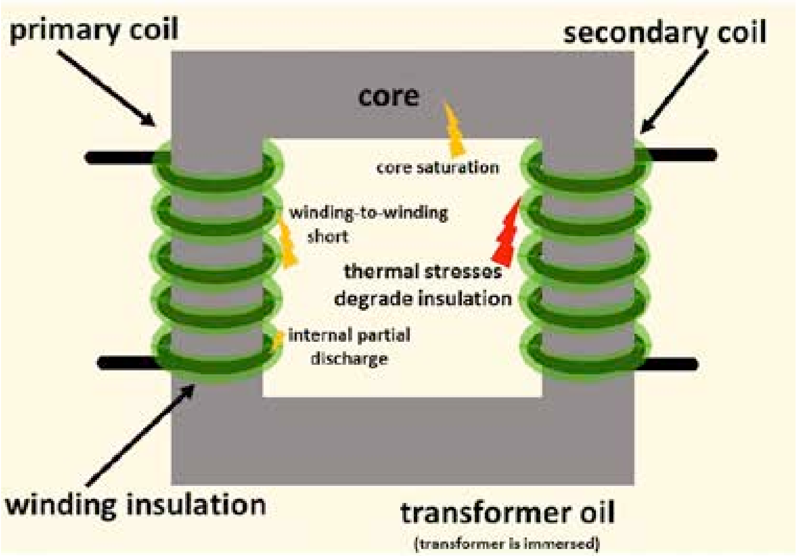


Develop low-cost, low-inductance packaging technologies that can be readily scaled for high voltages and currents





GMD Thermal Mitigation



Core saturation leads to long periods of high thermal stress

Cellulose hydrolytic degradation rate doubles for every 6˚C increase in temperature

Degraded insulation on copper windings

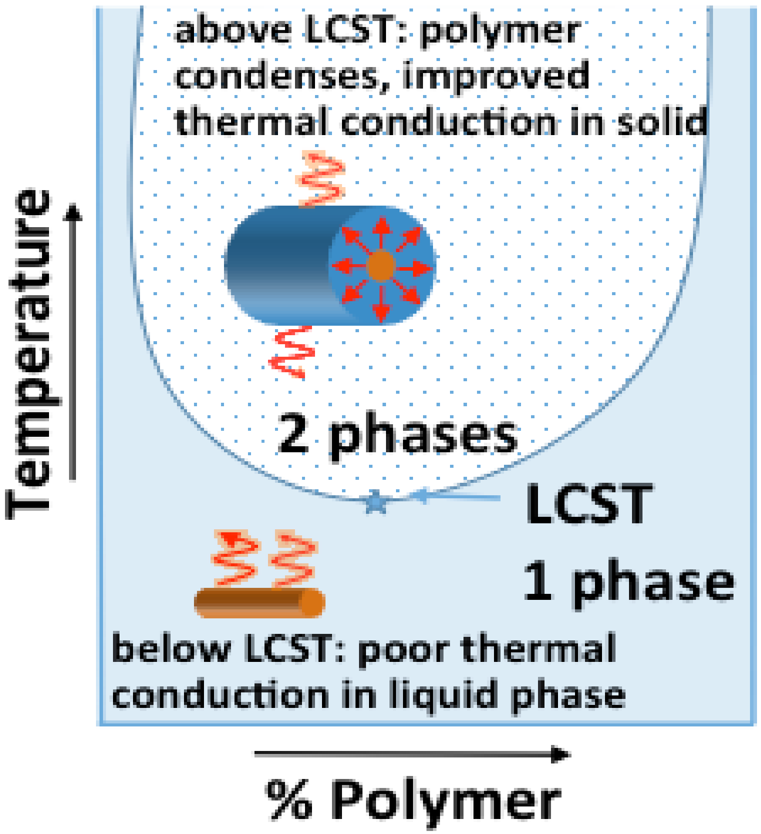
This work will develop LCST polymer technologies for mitigation of GMD thermal stresses.

These technologies will dramatically reduce the sensitivity of EHV power transformers to long duration thermal exposures during GMD events.

Task 2: important takeaways: LCST Polymers for Transformer Protection

*"Keeping the operating temperature as low as possible is the best means of prolonging the life of transformers… **life can be decreased to half for every 6-7˚C rise in [hotspot] temperature**…." (1)*

- Goal is to prevent GMD event from damaging transformers through heating of windings.
- Transformers use liquid dielectric oils to provide constantly refreshing surface to prevent long term dielectric breakdown seen in solid dielectric coatings
- Solids have higher thermal conductivities though and would be beneficial during temperature excursions.
- LCST polymer solutions could give the best of both worlds.



(1) Oommen, T.V.; Prevost, T.A.; *IEEE Electrical Insulation Magazine,* Mar/Apr. 2006, 22(2), p. 5-13

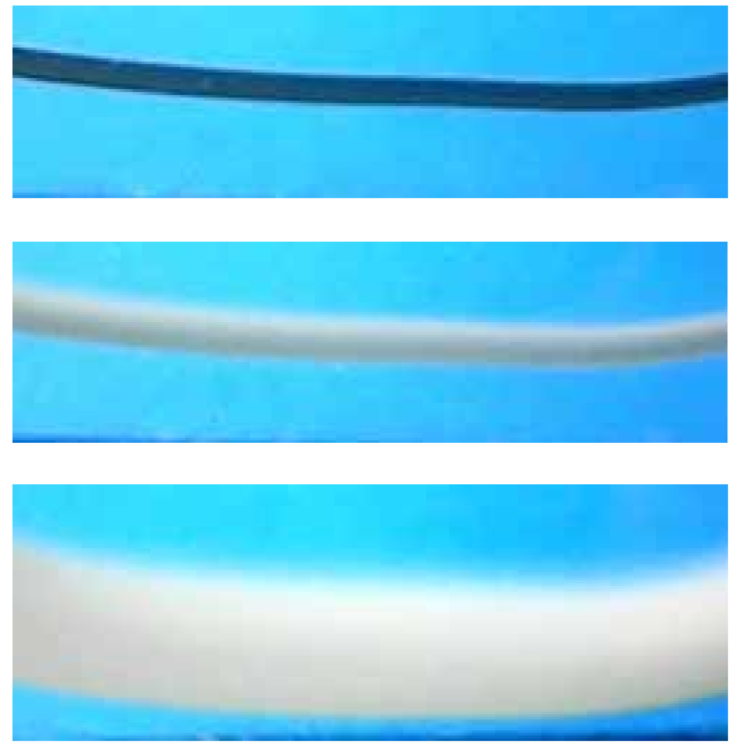
Task 2 takeaways: LCST Polymer Dynamics

- Using a Ni-chrome wire, we can heat quickly and capture polymer precipitation dynamics.
- Precipitation is nearly instantaneous and by 1 second, the volume of polymer precipitated is about the same as the wire volume
- By 15 seconds, the polymer precipitated is about 15 times the volume of the wire.

T = 0 sec

T = 1 sec

T = 15 sec

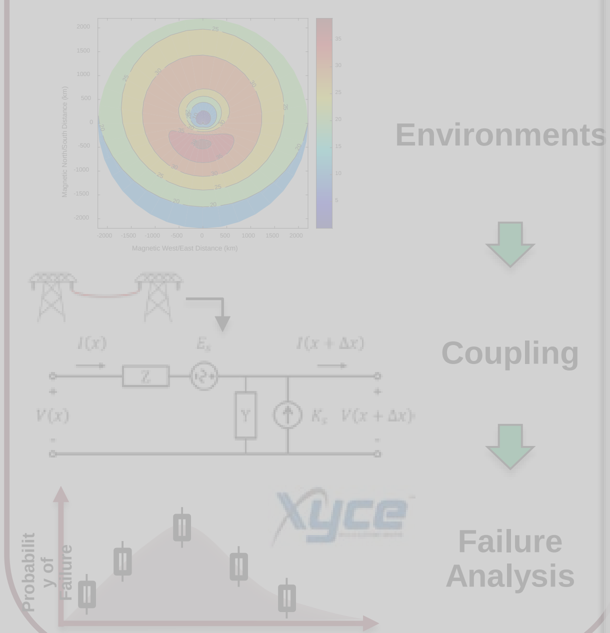


Reward:

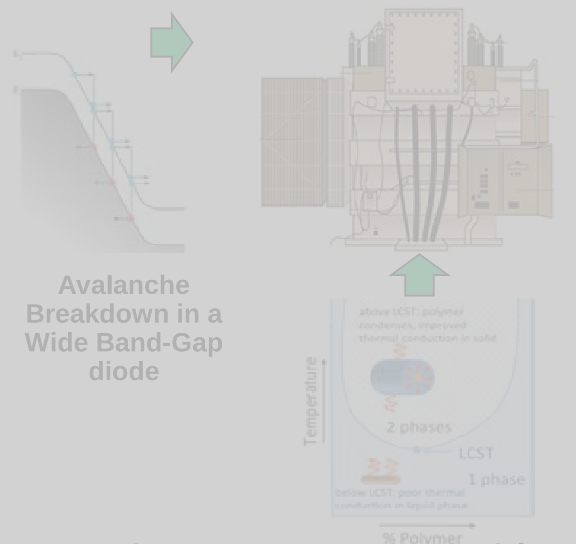
Any heat dissipation extends transformer life.

Our Approach: Three Integrated Tasks

Task 1 Vulnerability Assessment

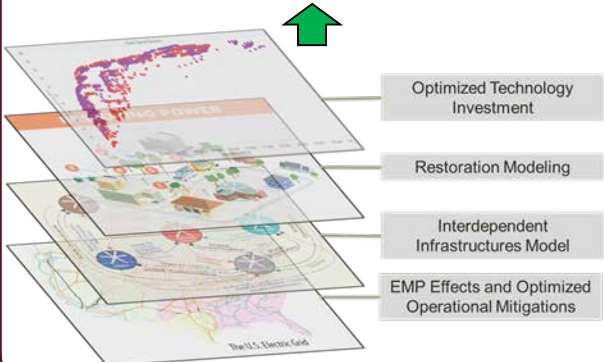


Task 2 Material & Device Innovation



Design New Component Materials to Withstand EMP Effects

Task 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

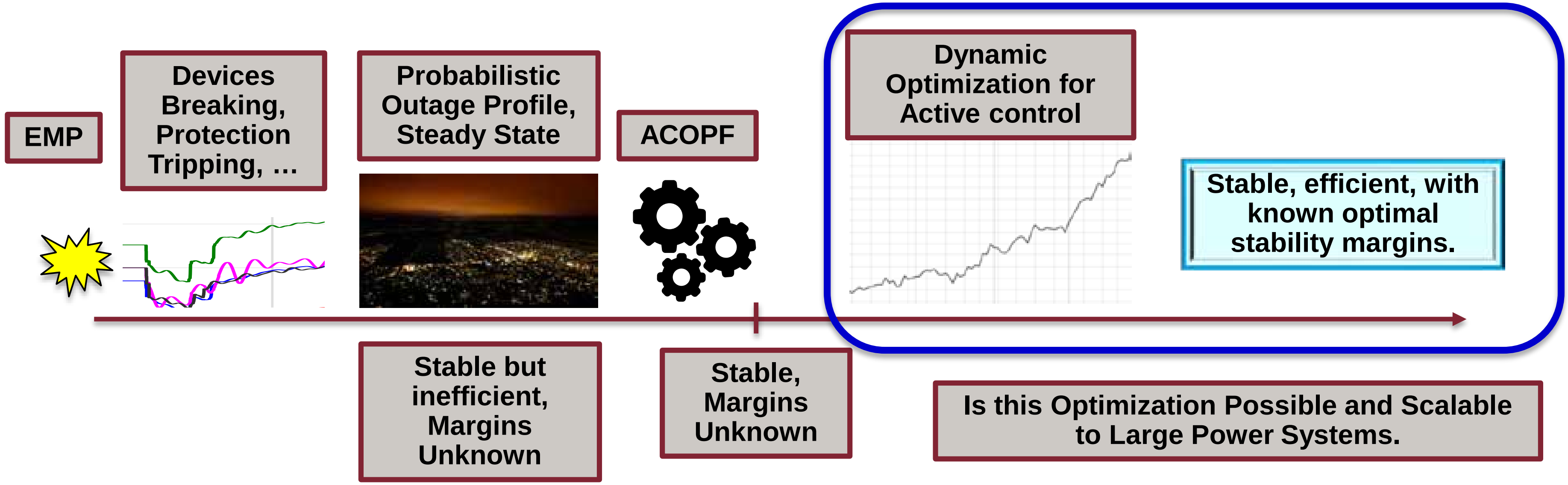
- Develop Wide Band-Gap EMP arrestor
- LCST Polymers for thermal management during E3/GMD

R&D

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

Task 3: Operation Planning and Optimization

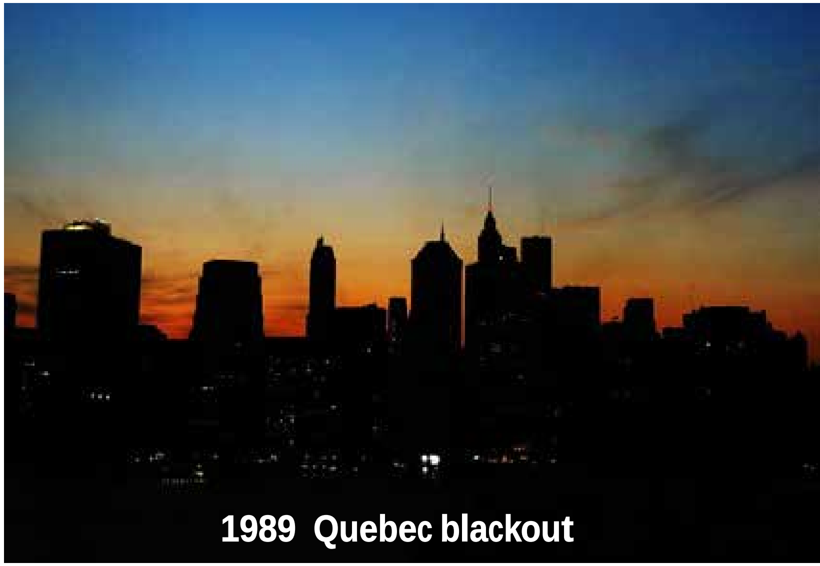
- Task 3.1: dynamic simulation to understand grid-level effects of component failure
  - Augment/implement models in existing simulation frameworks, e.g. PSLF
- Task 3.2: study optimization scalability for active control of power system dynamics
  - Uses same underlying physics/equations in an optimization framework



Task 3 – Verification and Validation

Verification

- *Leverage verification* of optimization solvers and modeling software
- *Internal review* of software implementations
- *Regularly test model and solver behavior*
    - Unit tests of individual components, system integration tests, sanity tests
- *Compare variance and confidence interval* of uncertainty modeling and assess solution quality



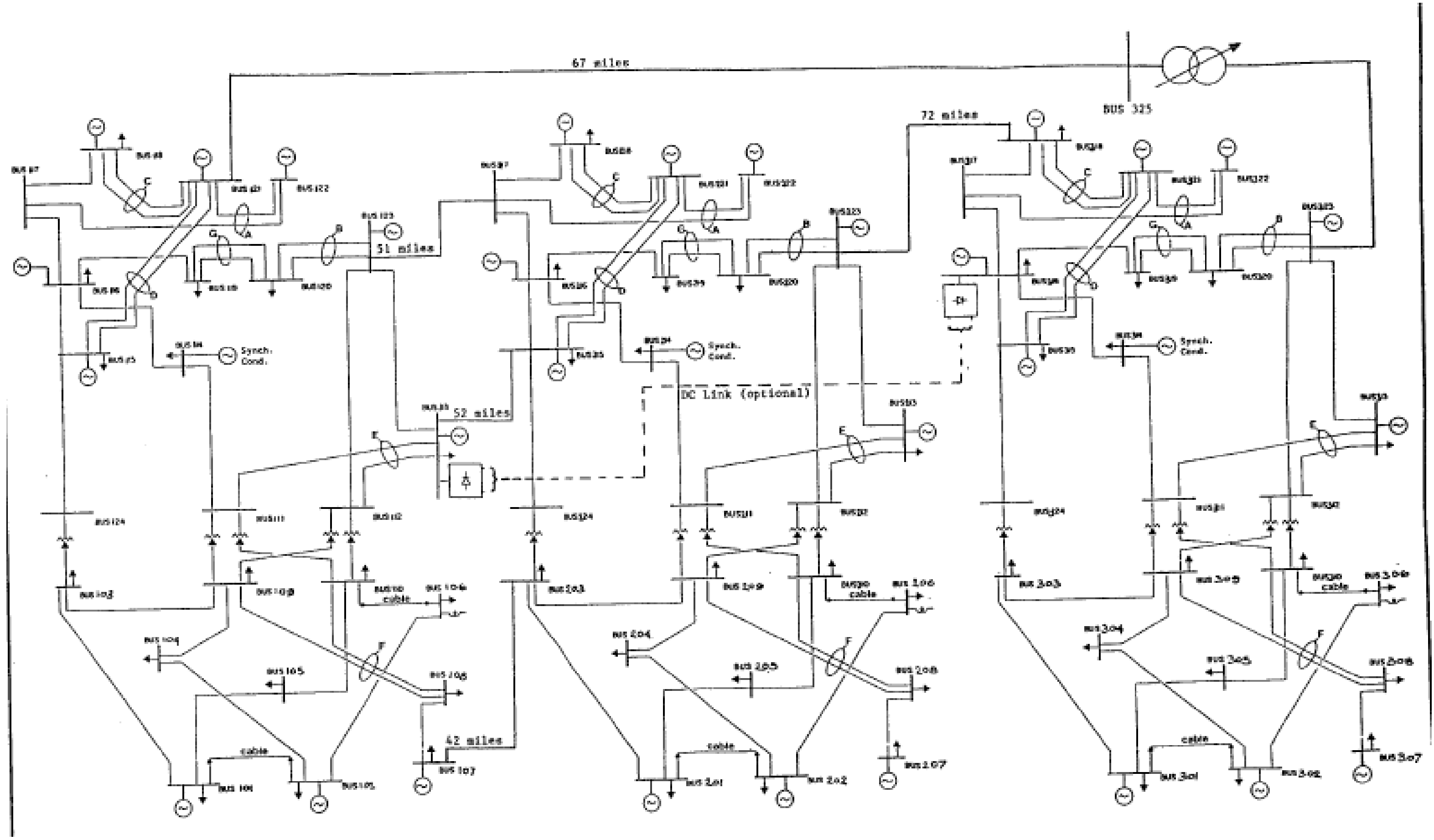
1989 Quebec blackout

Validation

- ***Leverage peer-review of equations*** **describing power grid physics**
    - **Steady-state equations and equations describing dynamic response**
- **Assessment of both *synthetic* and *historical scenarios* (e.g. 1989 Hydro Quebec blackout)**
    - **Evaluate robustness of solutions to scenario generation variability**
- ***Comparison with trusted power grid models***
    - **Evaluation of differences to detect errors and understand dynamic behaviors**
- ***Review by domain experts***
    - **Assessment of solution behavior and optimization trade space**

IEEE RTS-96 System

- IEEE reliability test system
- Developed in 1996 with 74 buses
- Used in multiple publications focused on reliability of electric grids.
- Power flow system published, but no dynamic model



Cascading Outage Model

- Power flow model – developed based on IEEE paper

- Dynamic model – newly developed to allow for a very stable base model. Model parameters are based on WECC standards and average WECC model settings

Dynamic model includes:

- Custom data recording model
- Generator models
- Exciter models
- Governor models
- Synchronous condenser models
- Generator under/over frequency

models

- Generator over/under voltage relays models
- Under frequency load shed relays models
- Line and transformer over current protection relay models
- Frequency meter models for

plotting

- Bus voltage meter models for plotting
- Current meter models for transmission lines and transformers for plotting
- Power meter models for all buses for plotting

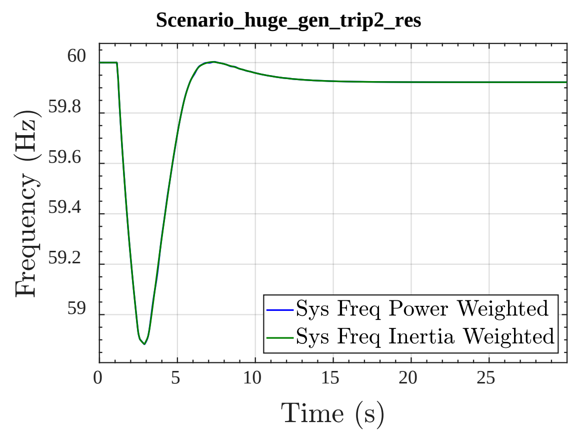
Example scenario

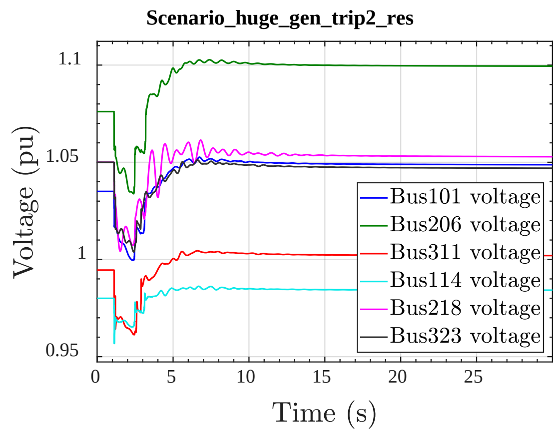
Example scenario has generator protection relays fail which cause 8 generators to trip offline.

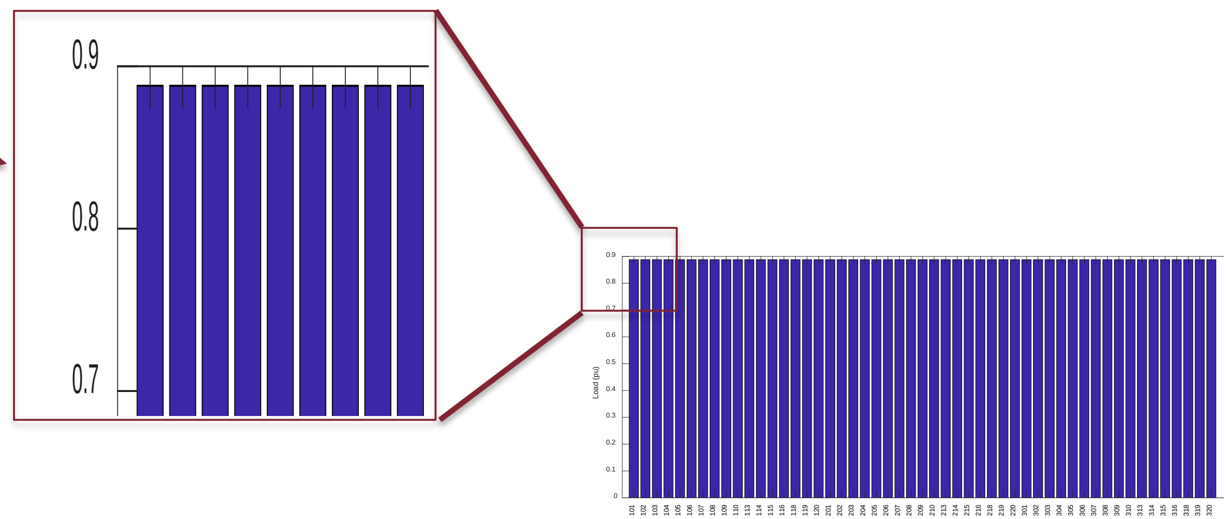
The generator loss causes a large under-frequency event.

This is rectified by an ~11% load shed throughout all 3 areas of the RTS-96 test system.

Each load is 1.0 per unit in normal operation, after the scenario only ~89% of the load is still served.







DAE Model B from “Power System Dynamics and Stability”, Sauer, Pai, Chow

The Optimization Model Under Development Includes:

- Generator Differential Equations
- Algebraic Stator Equations
- Network Power flow Equations

Differential Equations

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s \quad (8.62)$$

$$\frac{d\omega_i}{dt} = \frac{T_{Mi}}{M_i} - \frac{E'_{qi}I_{qi}}{M_i} - \frac{(X_{qi} - X'_{di})}{M_i} I_{di} I_{qi} - \frac{D_i(\omega_i - \omega_s)}{M_i} \quad (8.63)$$

$$\frac{dE'_{qi}}{dt} = -\frac{E'_{qi}}{T'_{doi}} - \frac{(X_{di} - X'_{di})}{T'_{doi}} I_{di} + \frac{E_{fdi}}{T'_{doi}} \quad (8.64)$$

$$\frac{dE_{fdi}}{dt} = -\frac{E_{fdi}}{T_{Ai}} + \frac{K_{Ai}}{T_{Ai}}(V_{\text{ref},i} - V_i) \quad (8.65)$$

for $i = 1, \ldots, m$.

Stator Algebraic Equations

The stator algebraic equations are

$$V_i \sin(\delta_i - \theta_i) + R_{si} I_{di} - X_{qi} I_{qi} = 0 \quad (8.66)$$

$$E'_{qi} - V_i \cos(\delta_i - \theta_i) - R_{si} I_{qi} - X'_{di} I_{di} = 0 \quad (8.67)$$

for $i = 1, \ldots, m$.

Network Equations

The network equations are

$$I_{di} V_i \sin(\delta_i - \theta_i) + I_{qi} V_i \cos(\delta_i - \theta_i) + P_{Li}(V_i) - \sum_{k=1}^{n} V_i V_k Y_{ik} \cos(\theta_i - \theta_k - \alpha_{ik}) = 0 \quad (8.15)$$

$$I_{di} V_i \cos(\delta_i - \theta_i) - I_{qi} V_i \sin(\delta_i - \theta_i) + Q_{Li}(V_i) - \sum_{k=1}^{n} V_i V_k Y_{ik} \sin(\theta_i - \theta_k - \alpha_{ik}) = 0$$

$i = 1, 2, \ldots, m$ (8.16)

$$P_{Li}(V_i) - \sum_{k=1}^{n} V_i V_k Y_{ik} \cos(\theta_i - \theta_k - \alpha_{ik}) = 0 \quad (8.17)$$

$$Q_{Li}(V_i) - \sum_{k=1}^{n} V_i V_k Y_{ik} \sin(\theta_i - \theta_k - \alpha_{ik}) = 0 \quad (8.18)$$

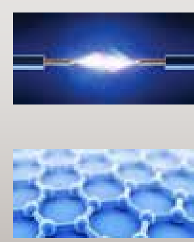
for $i = m + 1, \ldots, n$.

Summary

- Future grid's resiliency is of critical importance to nation's interests.
- The problem is *complex*, *not completely understood*, and will require *integrated work across multiple technical fields.*

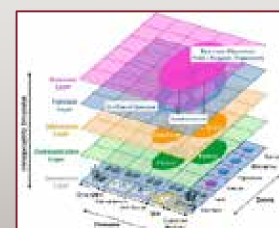
- As the outcome of this project, we will
  - Create deeper detailed understanding of vulnerabilities, failure modes and consequences;
  - Develop technological solutions to harden critical infrastructure of the grid;
  - Develop operational and optimization solutions to improve grid resilience.

Threats



New Materials and Device

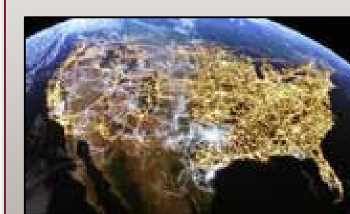
Development



System of Systems

Simulation

Resilient Grid



Thank you !

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