High Altitude Electromagnetic Pulse (HEMP) E3 Impacts on Large-Scale Electric Grids

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Acknowledgments

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- Slides also include contributions from many of my students, postdocs, staff and colleagues at TAMU, UIUC, other PSERC schools, and PowerWorld

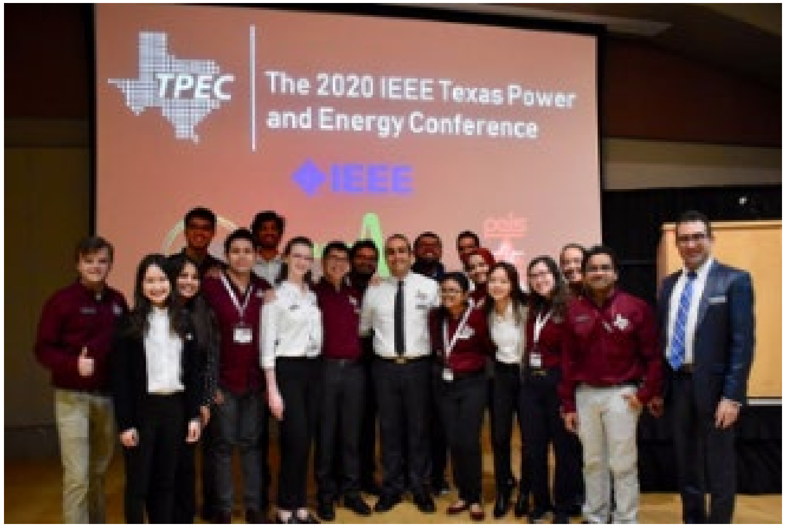
- Simulation results presented here are based on synthetic electric grids, and contain no Critical Electricity/Energy Infrastructure Information (CEII)
  - Simulations done using PowerWorld Simulator ver. 22

Quick Aside: North American Power Symposium Nov 14-16, 2021 at TAMU

- Two weeks ago TAMU hosted an in person NAPS, with about 200 attendees and more than 150 papers presented; thanks to all who participated!

Quick Aside: 2022 Texas Power and Energy Conference (TPEC)

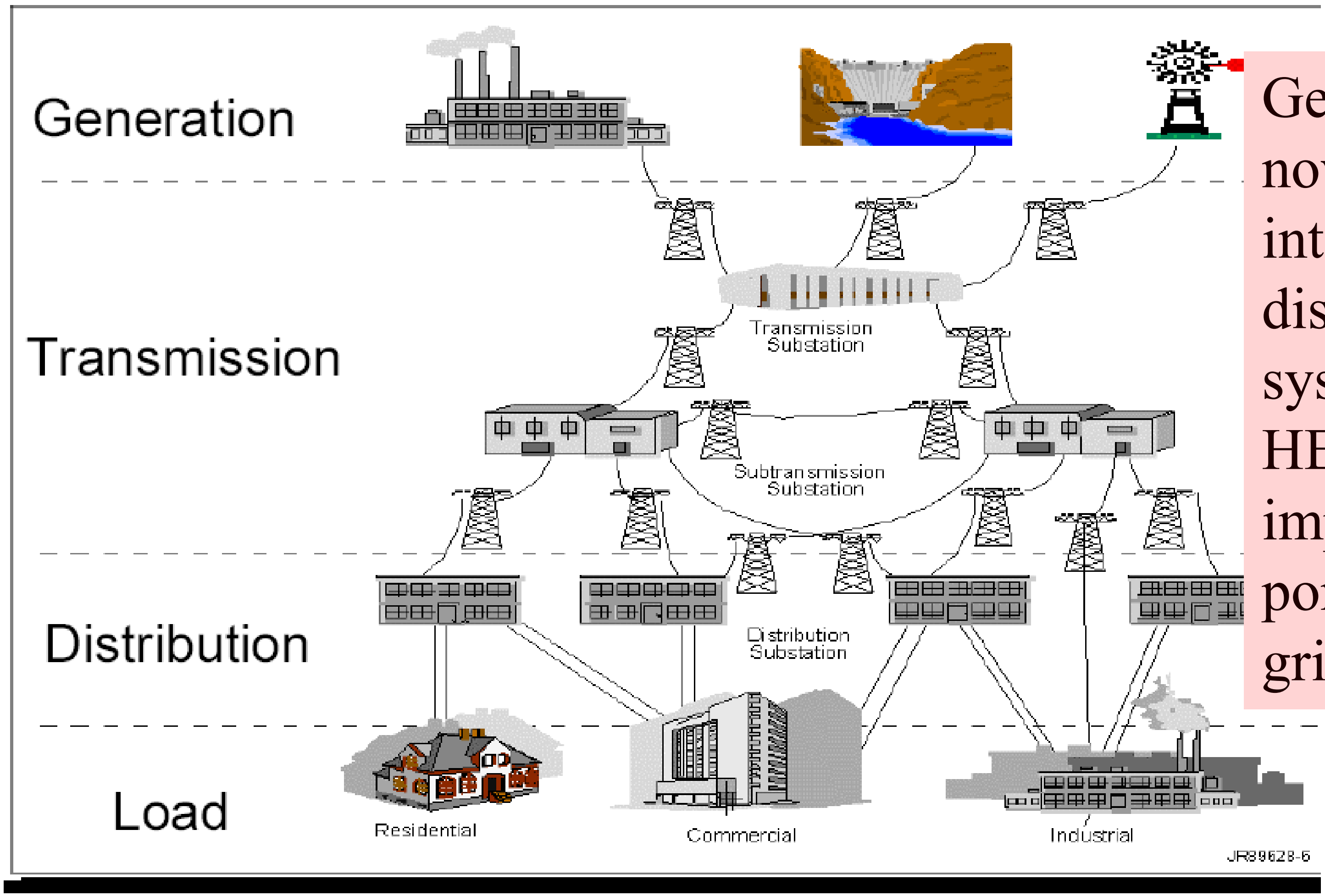
- Starting in 2017 TAMU has been hosting the Texas Power and Energy Conference (TPEC) at the TAMU Memorial Student Center
  - TPEC 2021 was virtual
- TPEC 2022 will be held in person on Feb 28 to March 1, 2022 (tpec.engr.tamu.edu)
  - Papers are due on 12/10/21 (there is a tradition of a two week delay, so 12/24/21 might be more likely); notice of paper acceptance by Jan 20, 2022



Our Energy Future Could be Bright!

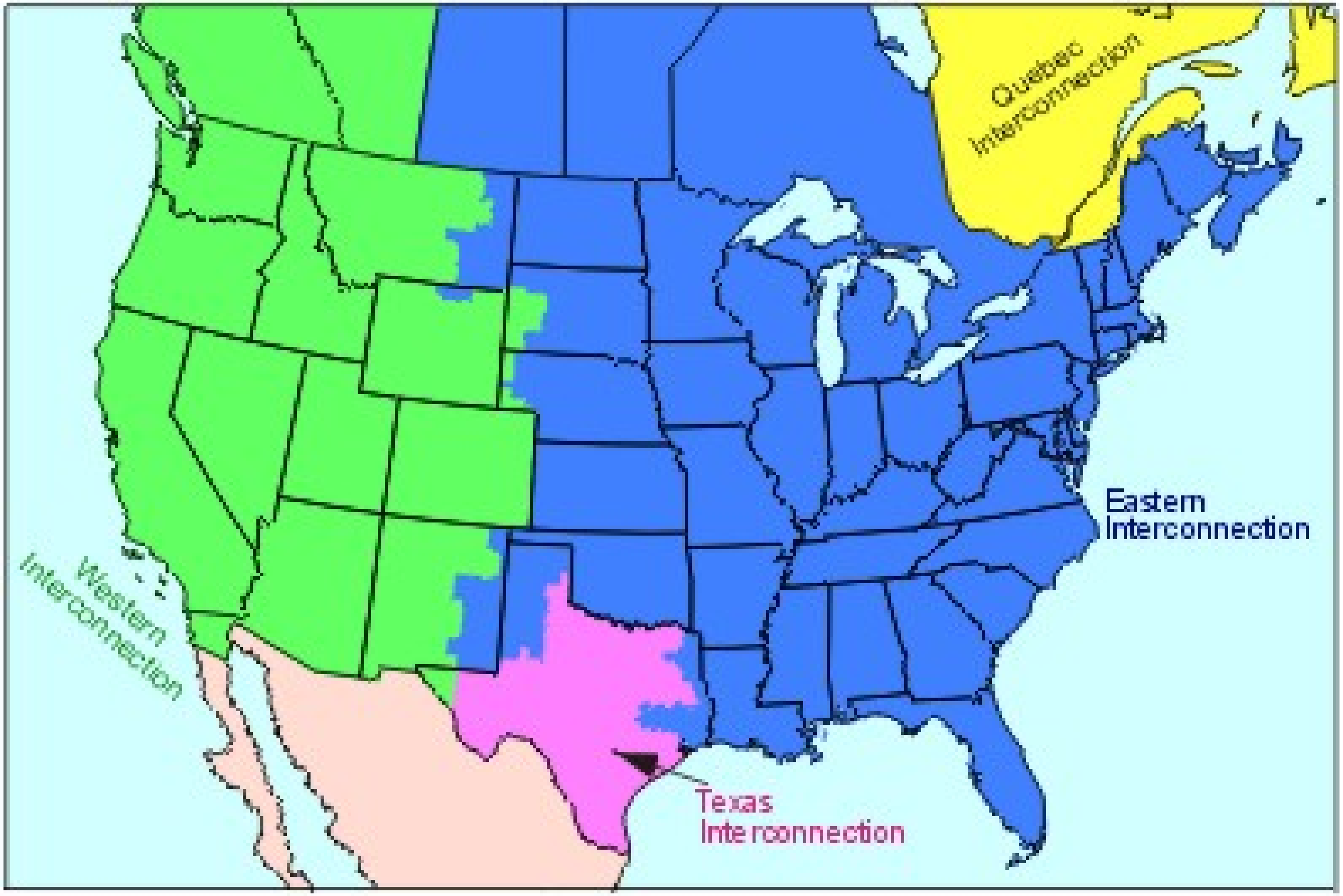
- My professional goal is to help in the development of a sustainable and resilient electric infrastructure for the entire world.
- Electric grids are in a time of rapid transition, with lots of positive developments.
- I think our electric energy future could be quite bright! But there are lots of challenges with this transition, including dealing with severe events, with this presentation covering one of them: the potential impacts of High Altitude Electromagnetic Pulses (HEMPs).

Quick Background: Electric Grid Basics



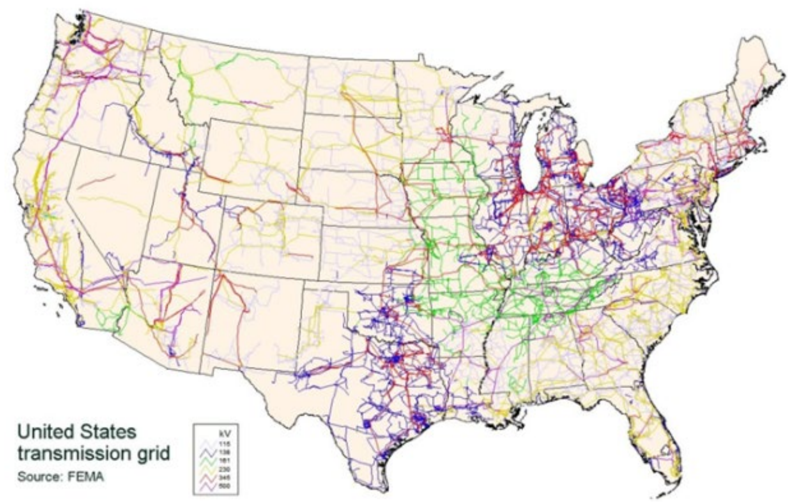
Generation now moving into the distribution system; HEMPs could impact all portions of the grid

North America Grid Interconnections



Important Electric Grid Considerations

- Electricity cannot be economically stored
  - Generation must be continually adjusted to match changes in electric load and losses
- Electric power flows on high voltage transmission lines cannot usually be directly controlled
  - Control is mostly indirect, by changing generation



- Customers have been in control of their load
- Transmission systems have finite limits and are often operated close to its limit for economic reasons

Electric Grid Time Frames

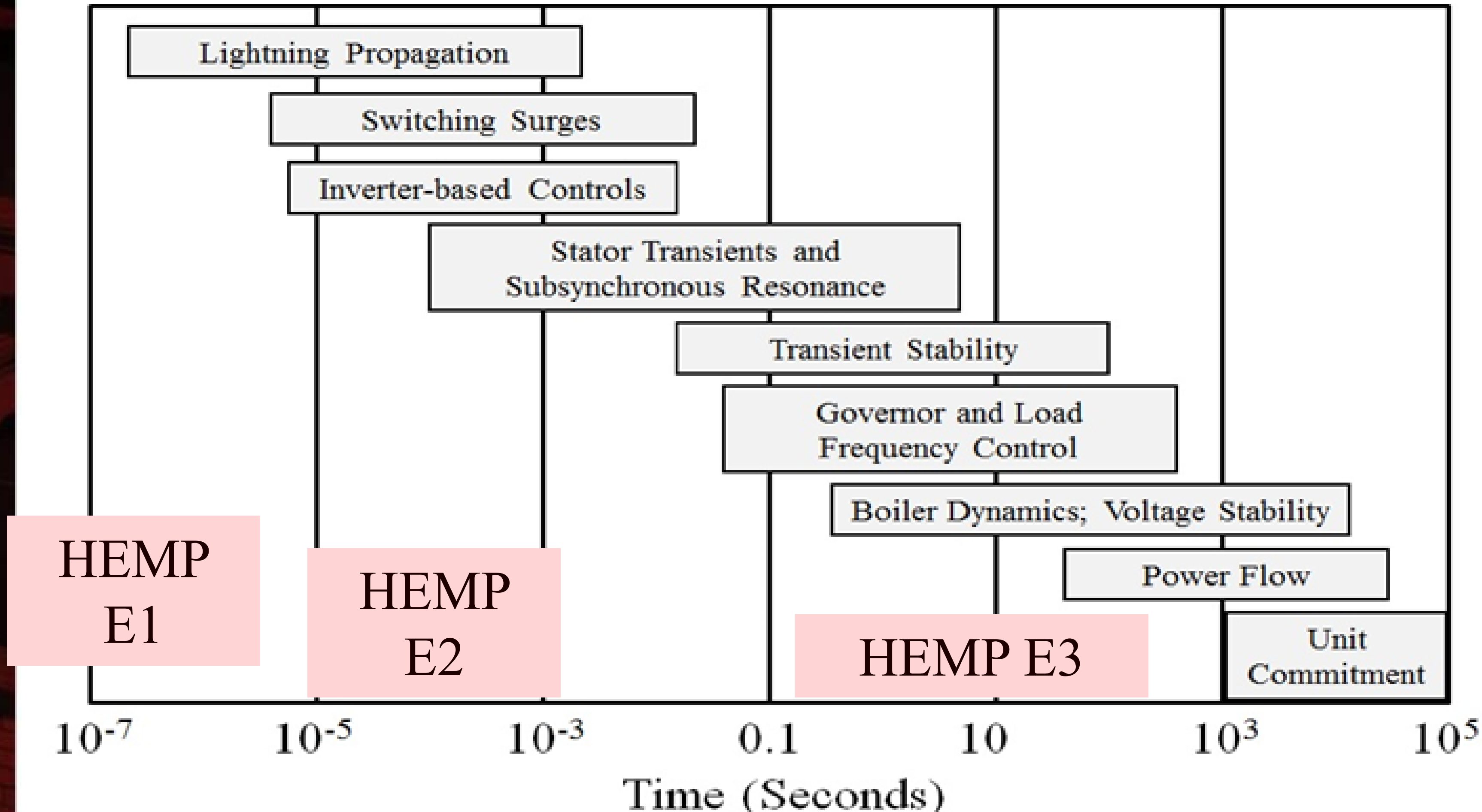
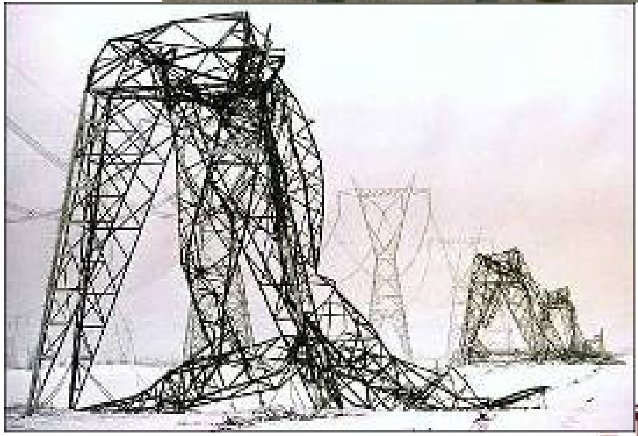


Image: Sauer, P.W., M. A. Pai, *Power System Dynamics and Stability*, Stripes Publishing, 2007

The Grid Needs to Be Resilient to Lots of Disturbances on Different Time Frames

- Events short and long-term
  - Lightning strikes can usually be cleared within seconds
  - But ice, tornados and hurricanes can bring large-scale damage over long time periods
- Need to consider all operating conditions



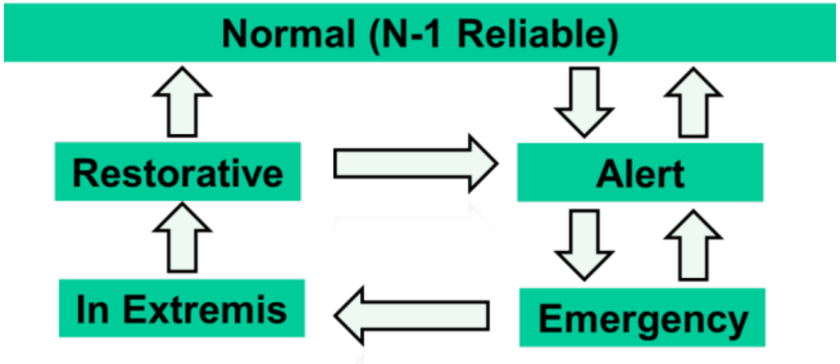
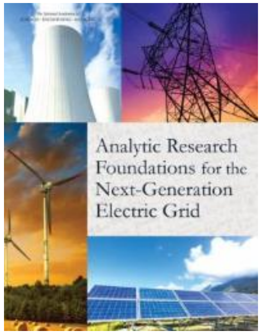


Image Derived From L.H. Fink and K. Carlsen, Operating under stress and strain, *IEEE Spectrum*, March 1978, pp. 48-53

National Academies Reports and DOE Innovation Symposium

- *Analytic Research Foundations for the Next-Generation Electric Grid*, 2016

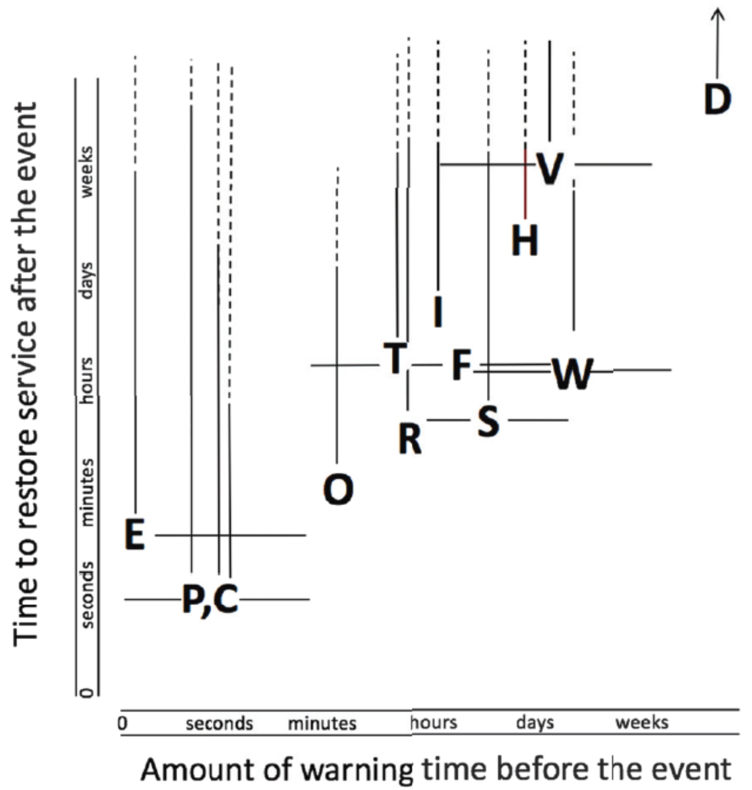


- *Enhancing the Resilience of the Nation's Electricity System*, 2017
  - "While minimizing the likelihood of large-area, long-duration outages is important, a resilient system is one that acknowledges that such outages can occur, prepares to deal with them, minimizes their impact when they occur, is able to restore service quickly, and draws lessons from the experience to improve performance in the future"

- DOE Transmission Innovation Symposium, 06/21
  - www.energy.gov/oe/transmission-innovation-symposium

Some Electric Grid Risks

Figure is from the National Academy's 2017 Grid Resilience Report



C = cyber attack (ranging from state/pro on left to good hacker on right)
D = drought and associated water shortage
E = earthquake (in some cases with warning systems)
F = flood/storm surge
H = hurricane
I = ice storm
O= major operations error
P = physical attack
R = regional storms and tornados
S = space weather
T = tsunami
V = volcanic events
W= wild fire

FIGURE 3.1 Mapping of events that can cause disruption of power systems. The horizontal placement provides some indication of how much warning time there may be before the event. The vertical axis provides some indication of how long it may take to recover after the event. Lines provide a representation

High-Impact, Low-Frequency Events

- In order to enhance electric grid resiliency we need to consider the almost unthinkable events
- These include what the North American Electric Reliability Corporation (NERC) calls High-Impact, Low-Frequency Events (HILFs); others call them black sky days
  - Large-scale, potentially long duration blackouts
  - HILFs identified by NERC were 1) a coordinated cyber, physical or blended attacks, 2) pandemics, 3) geomagnetic disturbances (GMDs), and 4) HEMPs

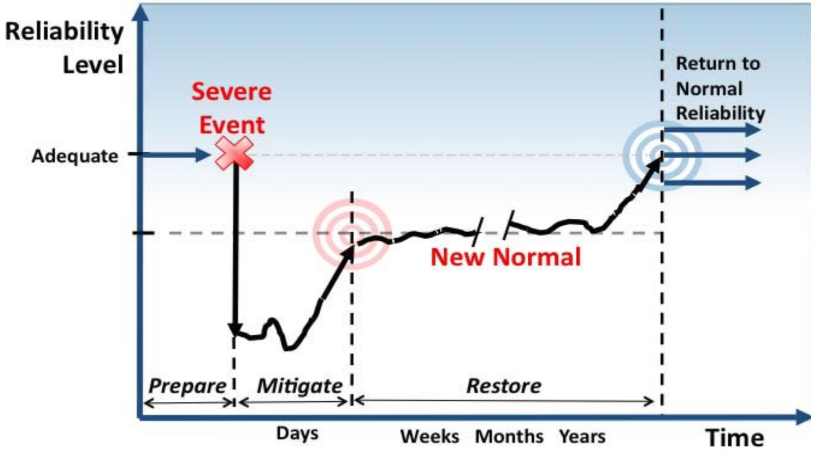


Image Source: NERC, 2012

What is Grid Resilience?

- Merriam Webster Dictionary (resilience in general)
  - "An ability to recover from or adjust easily to misfortune or change"
- FERC
  - "The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event"

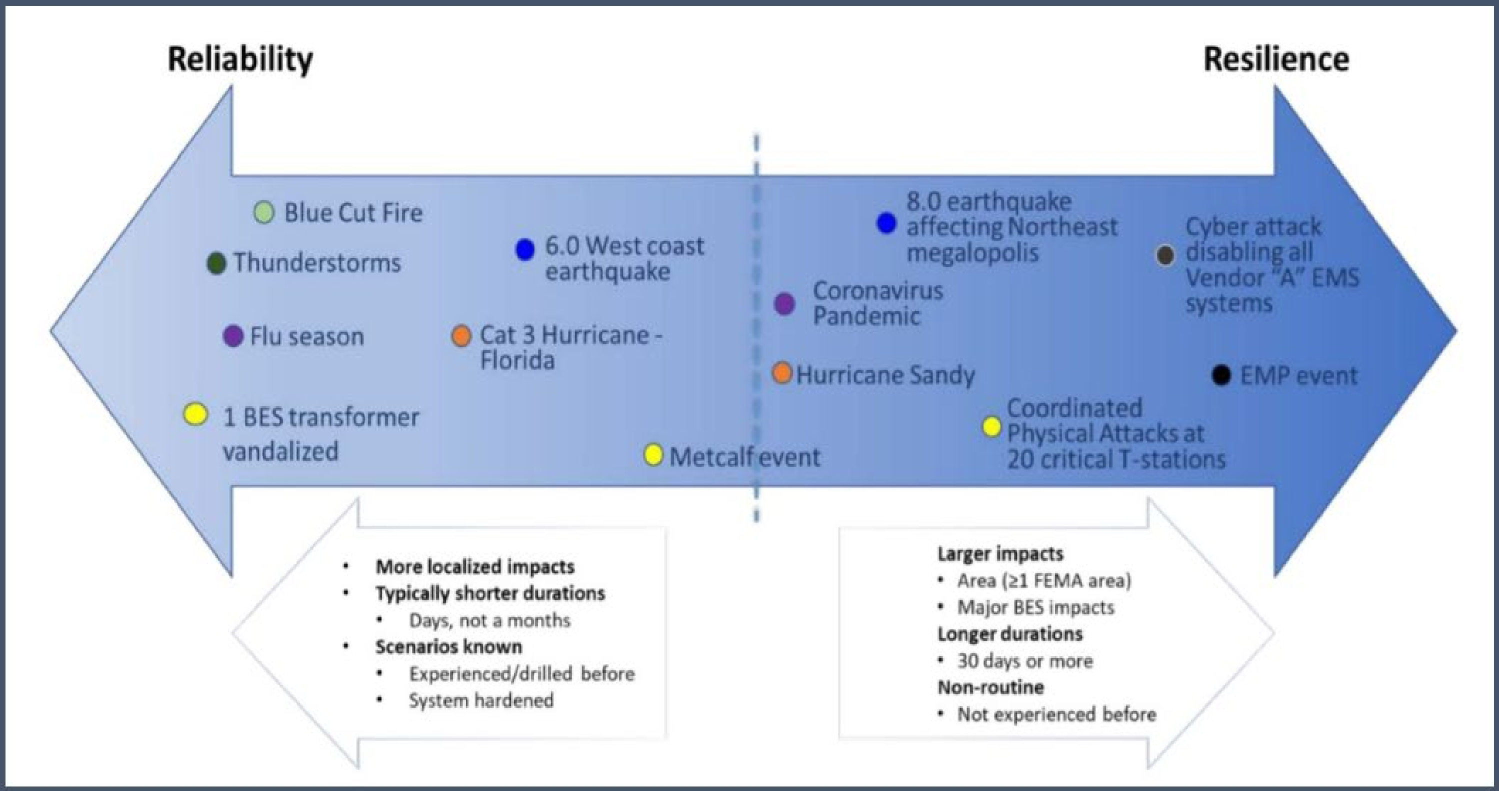
These definitions are from the 53rd North American Power Symposium keynote address by Dan Smith of Lower Colorado River Authority, November 2021

What is Grid Resilience? Cont.

- National Association of Regulatory Utility Commissioners (NARUC)
  - "Robustness and recovery characteristics of utility infrastructure and operations, which avoid or minimize interruptions of service during an extraordinary and hazardous event"
- EPRI & North American Transmission Forum (NATF)
  - The ability of the system and its components (… equipment and human …) to minimize damage and improve recovery from non-routine disruptions, including High Impact, Low Frequency (HILF) events, in a reasonable amount of time"

These definitions are from the 53rd North American Power Symposium keynote address by Dan Smith of Lower Colorado River Authority, November 2021

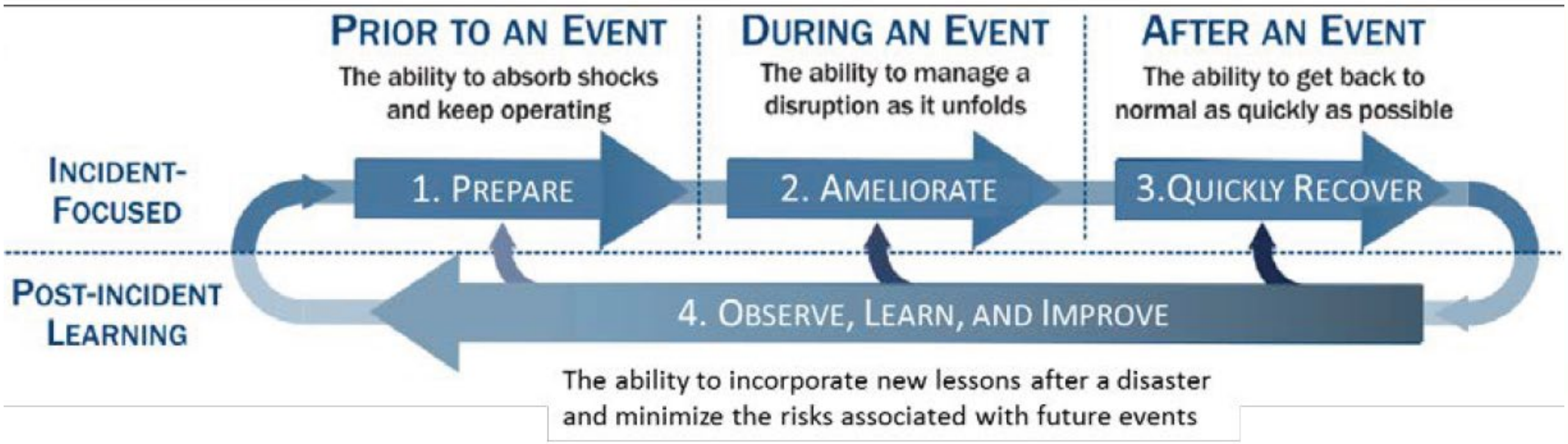
Reliability – Resilience Continuum



Credit: NATF TRMM Users Guide

Slide is from the 53rd North American Power Symposium keynote address by Dan Smith of Lower Colorado River Authority, November 2021; credit NATF

Four Stage Resilience Process



This is presented as Figure 1.2a in the National Academies' *Enhancing the Resilience of the Nation's Electricity System* report (2017), and is originally from S.E. Flynn, "America the resilient: Defying terrorism and mitigating natural disasters." *Foreign Affairs,* vol. 87: 2–8 (2008) and as illustrated by the National Infrastructure Advisory Council (NIAC) in 2010.

How to Approach HILF Events

- The goal in studying HILFs is seldom to replicate a specific event
  - Many have not occurred, and within each class there can be great variability (e.g., a physical attack)
- Nor is it to ensure there is no loss of service
- Rather, it is to be broadly prepared, and to be able to do at least a reasonable cost/benefit analysis
- HILF simulations can help in preparing for the unexpected
- Several techniques, such as improved control room rare event situational awareness and better black start procedures, are generally applicable

Electromagnetic Pulses (EMPs)

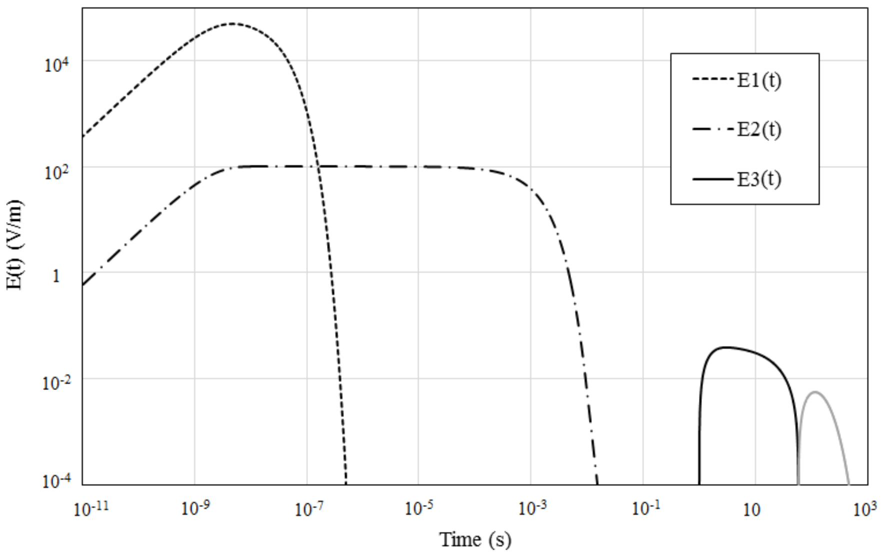
- Broadly defined, an electromagnetic pulse is any transient burst of electromagnet energy
- Characterized by their magnitude, frequencies, footprint, and type of energy
- There are many different types, such as static electricity sparks, interference from gasoline engine sparks, lightning, electric switching, geomagnetic disturbances (GMDs) cause by solar corona mass ejections (CMEs), nuclear electromagnetic pulses, and non-nuclear EMP weapons
- Talk focuses primarily on the impact of nuclear EMPs on the grid, mostly caused by high altitude explosions

Nuclear EMPs

- Naturally some information on nuclear EMPS is not public, but various public documents exist,
- The primary concern about nuclear EMPS is the impacts caused by high altitude EMPs (HEMPs)
  - From 30 to 100's of km in altitude
  - For a high altitude explosion the other common nuclear impacts (blast, thermal, radiation) do not occur at the ground
  - Scope of a single HEMP impact could be large, perhaps 1000 km, but the magnitude of the event would vary widely in the footprint
- Multiple, near simultaneous events could occur

HEMP Time Frames

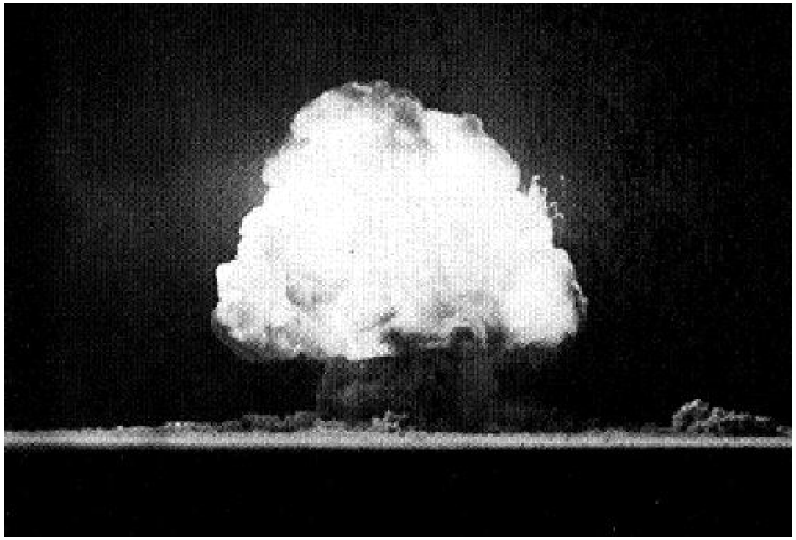
- The impacts of an HEMP are typically divided into three time frames: E1, E2 and E3
- The quickest, E1 with maximum electric fields of 10's of kV per meter, can impact unshielded electronics



- E2, with electric fields of up to 100 volts per meter, is similar to lightning
- Much of talk is on E3, which has impacts somewhat akin to geomagnetic disturbances (GMDs)

Nuclear EMP History

- The presence of EMPs was theorized by Enrico Fermi prior to the first explosion in July 1945
  - Many wires were shielded, but still some data was lost due to EMP
- British called it “radioflash” in their tests in early 1950’s due to the presence of “clicks” heard on radios
- Operation Hardtack tests in 1958 (up to 80 km in altitude) further demonstrated HEMP impacts



Trinity Explosion, July 16, 1945, 20 kilotons of TNT
source: Los Alamos Lab

Nuclear EMP History: Starfish Prime

- Starfish Prime was an explosion of a 1.44 megaton nuclear weapon at an altitude of 400 km over the Pacific Ocean in July 1962
  - Part of series of tests known as Operation Fishbowl
  - The EMPs were much larger than expected, driving instruments off scale
  - Impacts seen in Honolulu (1445 km away), including knocking out about 300 street lights, setting off alarms, and damaging a microwave link
  - Some low earth orbit satellites were also damaged

Starfish Prime observed on Maui in 1962, Source US EMP Commission Report from July 2017

Nuclear EMP History

- Soviet HEMP tests in the early 1960's were reported to have damaged power equipment
- Nuclear tests in the atmosphere, space and under water were banned in 1963
  - There has been a United Nations underground test ban from 1996, though not all countries have agreed to it

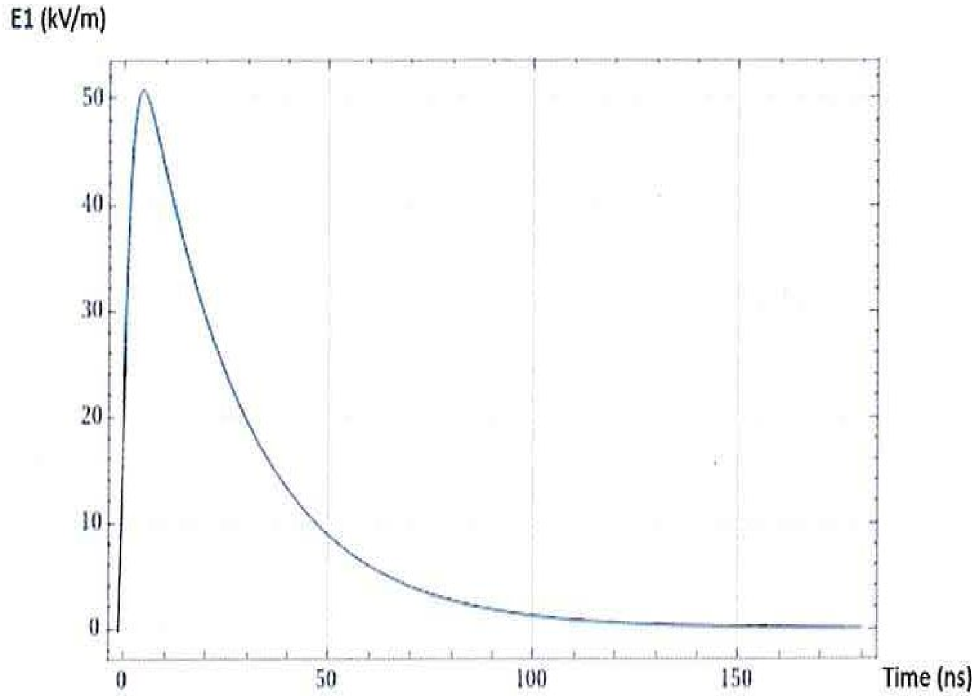
Example E1, E2, and E3 Waveforms

- There are several sources for example or recommended waveforms
  - www.energy.gov/sites/default/files/2021/01/f82/FINAL%20 HEMP%20MEMO_1.12.21_508.pdf (DOE)
  - www.firstempcommission.org/uploads/1/1/9/5/119571849/recommended_e3_waveform_for_critical_infrastructures_-_final_april2018.pdf (EMP Commission, E3)
  - apps.dtic.mil/sti/pdfs/AD1067769.pdf US Defense Threat Reduction Agency, E1)
  - apps.dtic.mil/sti/pdfs/AD1082958.pdf (US Defense Threat Reduction Agency, E3)
  - https://www.cisa.gov/sites/default/files/publications/19_0307_CISA_EMP-Protection-Resilience-Guidelines.pdf

Overview of HEMP Threats to Electric Grids

- E1: Partial loss of load and generation, possible damage to protection system (< one microsecond)
- E2: Voltage impulses on transmission lines and possible insulator flashover (< 0.1 second)
- E3: GIC → half-cycle transformer core saturation →
  - harmonics → excess reactive power losses → possible voltage or transient instability → immediate loss of critical loads; harmonics could damage equipment
  - excess transformer heat → possible damage or long-term degradation to individual components → long-term power supply constraints for critical loads
- Longer-term: potential cascading grid collapse and/or equipment damage

DOE Recommended E1 Waveform DTRA Spatial Variation



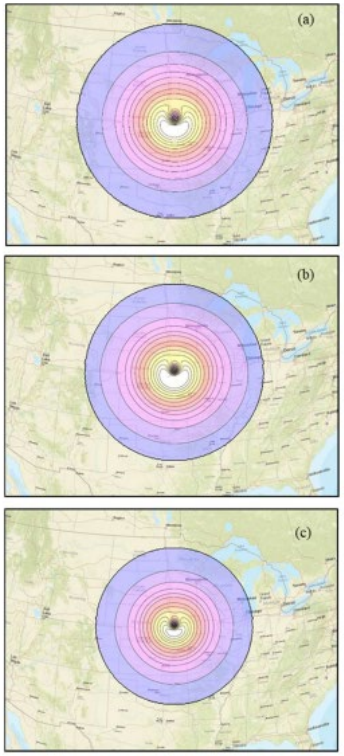


Figure 5. The incident electric field E, in units of kilovolts per meter (kV/m), for a 100 kt nuclear detonation over a location near the geographic center of Continental United States at altitudes of 80 km (a), 65 km (b), and 50 km (c). The rings are in intervals of 2 kV/m, with the outermost ring at 4 kV/m in all three instances. The peak incident field values for all time are 34 kV/m (a), 36 kV/m (b), and 32 kV/m (c), respectively.

Source: January 11, 2021 DOE HEMP Document; pps.dtic.mil/sti/pdfs/AD1067769.pdf (DTRA), Figure 5

E1 Impacts On Bulk Electric Grid

- The focus here is on E3, not E1, but the impact of E1 on the electric grid needs to be considered when doing E3 studies
- The impacted E1 footprint grows with height of burst, but the impact falls off with distance away from the burst
- There are direct electric grid infrastructure impacts (such as relays, communication systems, and SCADA), but this can be reduced with shielding
- There could be indirect impacts, such as from lost load, potentially causing frequency issues

EMP E3 Electric Grid Modeling

- The EMP E3 impacts are caused by the burst perturbing the earth’s magnetic field
  - This is similar to the naturally occurring geomagnetic disturbances (caused by solar corona mass ejections)
  - The dB/dt change is usually expressed in nT/minute
- The dB/dt induces a non-uniform, time-varying electric field (E-field) at the Earth’s surface
  - The magnitude of the induced E-field depends upon the conductivity of Earth's crust going down 100s of km; this conductivity can vary widely!
  - On a 60-Hz timescale, the induced E-fields seen by high voltage transmission lines are essentially dc

Earth’s Magnetic Field (nT)

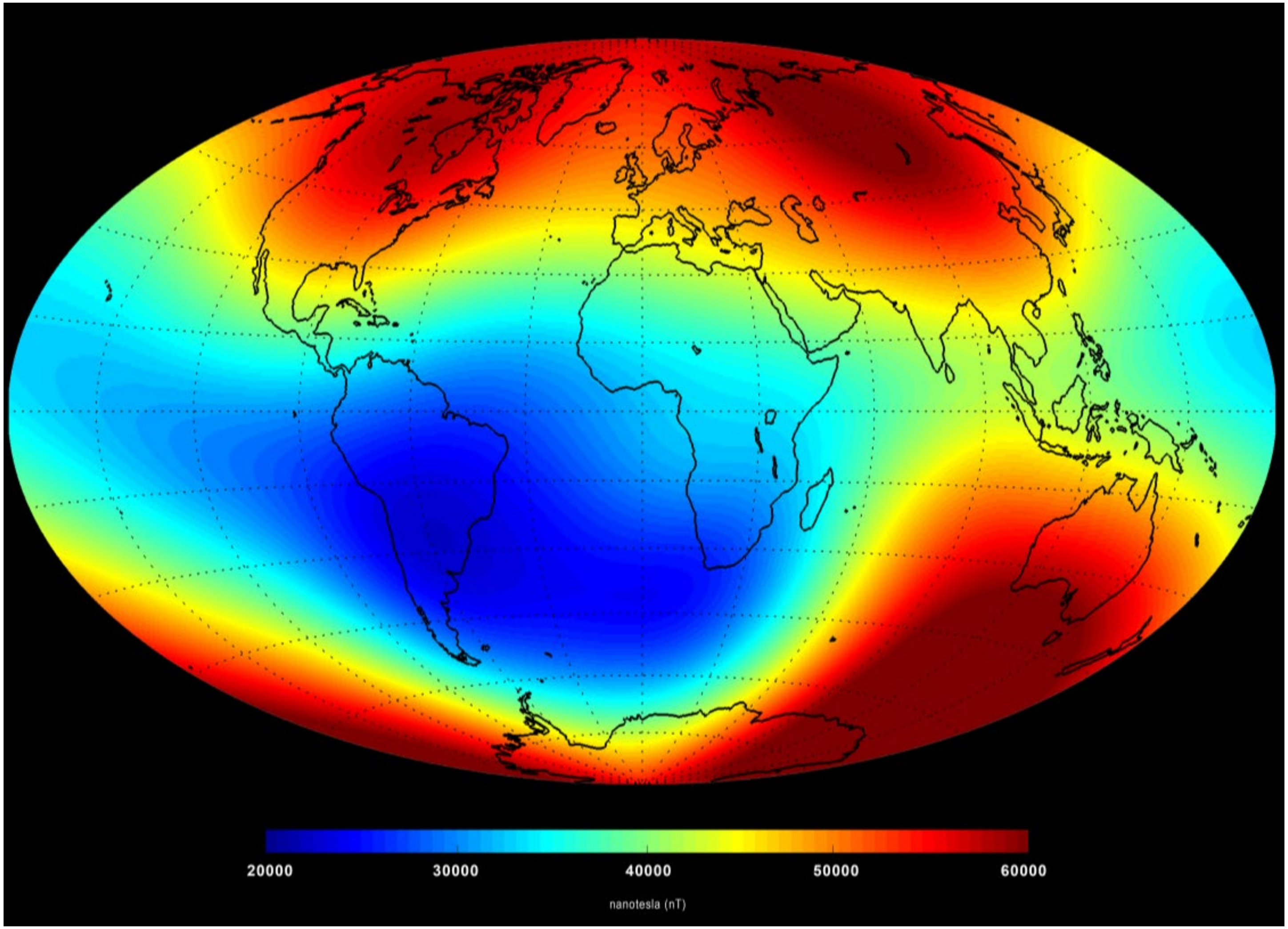
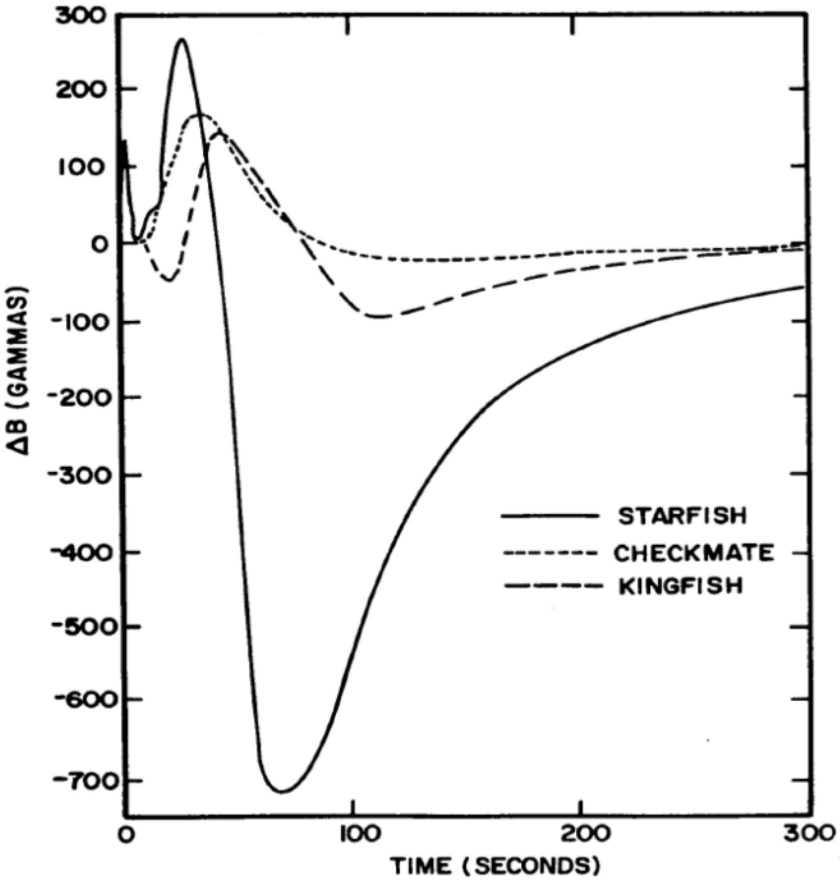


Image Source: https://climate.nasa.gov/internal_resources/2414/

Measured Change in the Earth's Magnetic Field During Fishbowl Tests

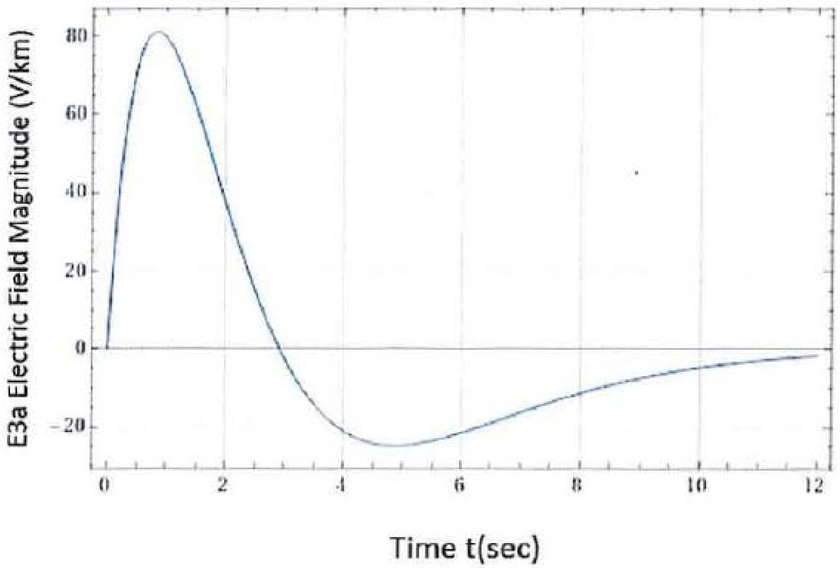


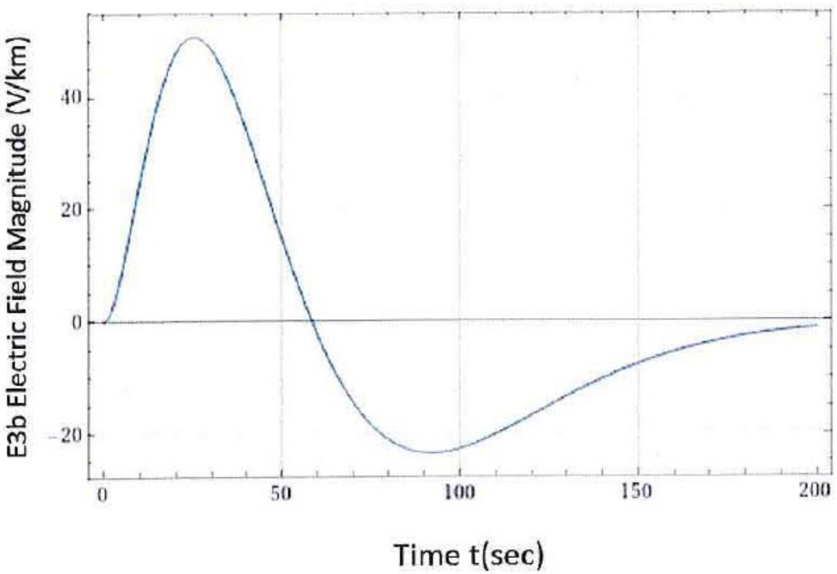
Checkmate and Kingfish were nuclear tests that were part of Operation Fishbowl. A gamma is one nT. For reference the Quebec GMD had 500 nT/minute and the 1859 Carrington GMD event is estimated have have had a variation of perhaps 2500 nT/minute

Image: 1985 ORNL "Study to Assess the Effects of Magnetohydrodynamic Electromagnetic Pulse on Electric Power Systems Phase I Final Report," May 1985, Figure 1

DOE Recommended E3 Waveform

- The E3 waveform is considered as two separate waveforms that are summed together
  - E3a (blast waveform), E3b (heave waveform)





The electric field is impacted by the ground conductivity (10^{-3} S/m here); with a smaller value (less conductive) giving higher electric fields; note the time scale difference for E3a (12 seconds) versus E3b (200 seconds)

A Little Detail on the Ground Calculation

- If the earth is assumed to have a single onductance, σ, then

$$Z(\omega)=\frac{j\omega\mu_0}{\sqrt{j\omega\mu_0\sigma}}=\sqrt{\frac{j\omega\mu_0}{\sigma}}$$

- The magnitude relationship is then

With $B(\omega)=-\mu_0 H(\omega)$

$$|E(\omega)|=|Z(w)\,\mathrm{H}(\omega)|$$

$$=\left|\sqrt{\frac{j\omega\mu_0}{\sigma}}\,\frac{B(\omega)}{\mu_0}\right|$$

For example, assume σ of 0.001 S/m and a 500nT/minute maximum variation at 0.002 Hz. Then

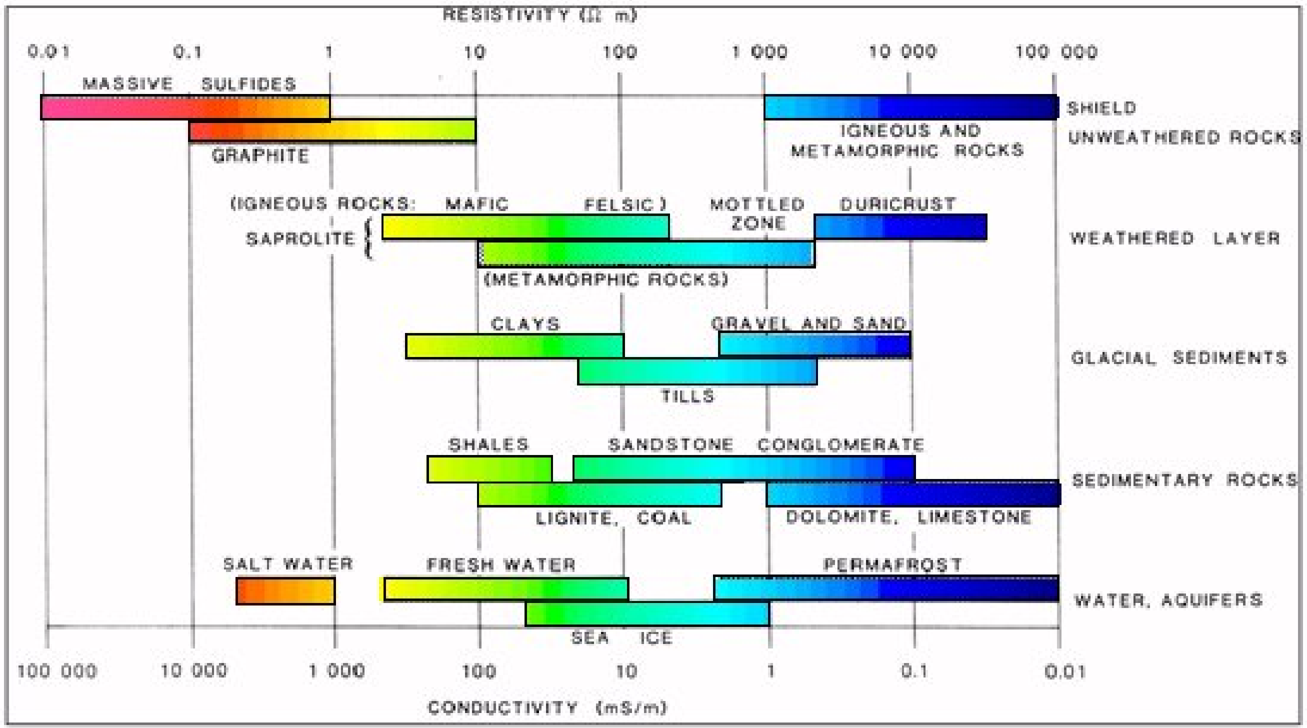
$\mathrm{B}(\omega)=660\times10^{-9}$ T and

$$E(\omega)=\sqrt{\frac{2\pi\times0.002\times\mu_0}{0.001}}\,\frac{660\times10^{-9}\ \mathrm{T}}{\mu_0}$$

$$E(\omega)=0.00397\times0.525=2.1\ \mathrm{V/km}$$

Typical Ground Conductance and Resistivity Values

- Soil conductance is often expressed in its inverse of resistivity in Ω-m; values can vary widely



The bottom scale is in mS/m, so the DOE assumed value of 1 mS/m is right in the middle

Image source: https://www.eoas.ubc.ca/courses/eosc350/content/foundations/properties/resistivity.htm

Time-Varying Spatial Footprint

- The spatial footprint depends on several factors (see DTRA document), and could be time-varying
  - The highest electric field is indicated by red

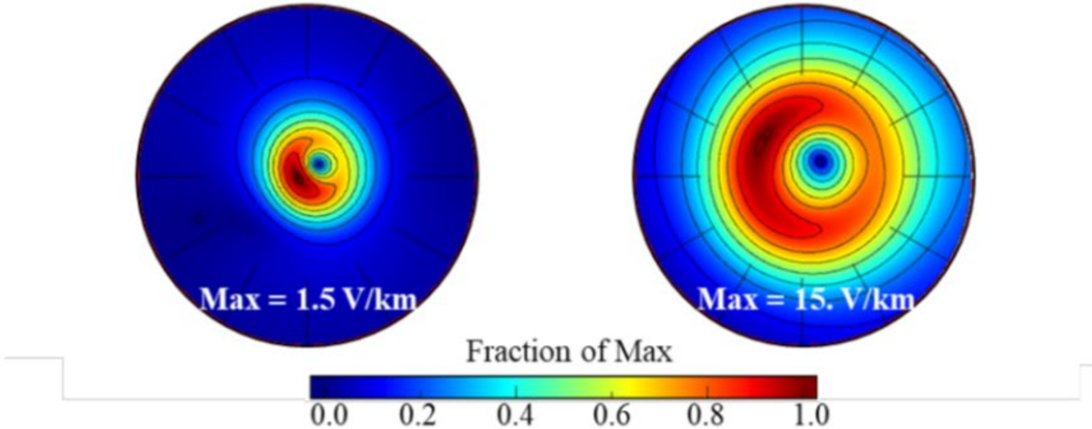
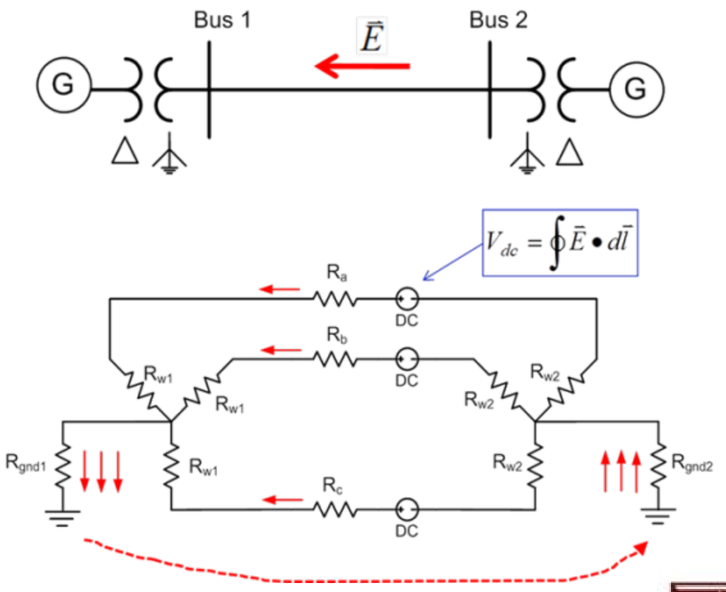


Figure 18. Ground electric field maps from 20 kT case (left) and 1 MT case (right) illustrate differences in maximum field strength and spatial extent. East-West and North-South extents of each plot are 1,110 km.

Each circle diameter is 1110 km (688 miles), about the distance from St. Louis to Washington, DC

Geomagnetically Induced Currents (GICs)

- Along length of a high voltage transmission line, electric fields can be modeled as a dc voltage source superimposed on the lines
- The dc voltage is calculated by integrating the electric field along the line's right-of-way
  - If electric field is uniform (over the line) the integration is path independent
- The GICs are superimposed on the ac (60 Hz) flows



GIC Calculations for Large Systems

- With knowledge of the pertinent transmission system parameters and the GMD-induced line voltages, the dc bus voltages and flows are found by solving a linear equation **I** = **G V** (or **J = G U**)
  - **J** and **U** may be used to emphasize these are dc values, not the power flow ac values
  - The **G** matrix is similar to the $\mathbf{Y_{bus}}$ except 1) it is augmented to include substation neutrals, and 2) it is just resistive values (conductances)
  - Being a linear equation, superposition holds
  - The current vector contains the Norton injections associated with the GMD-induced line voltages

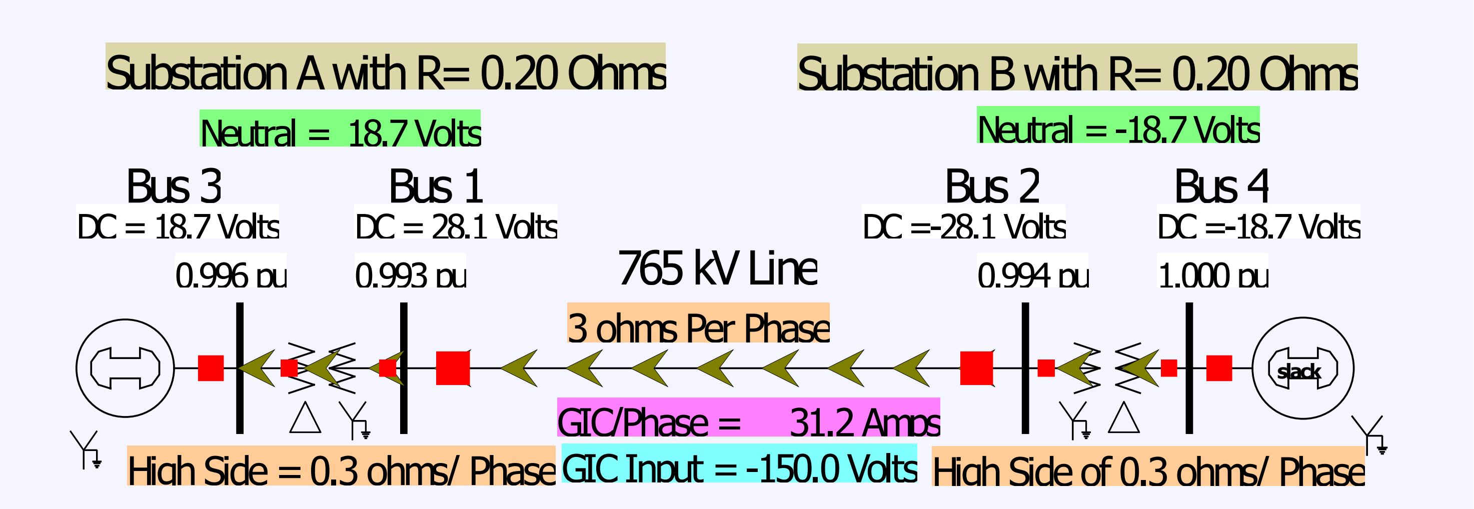
GIC Calculations for Large Systems

- In determining the **G** matrix for the dc GICs, knowing the transformer grouding configurations is crucial
  - Delta windings have no path to ground, and hence look like an open circuit
  - Transmission to distribution transformers look like an open circuit (if delta on the high side)
  - Autotransformers are modeled differently than regular transformer
  - For three-winding transformers, the tertiary winding has no impact (if delta)
- Series capacitors look like an open circuit
- In the US utilities now have this information because of doing the NERC TPL-007 GMD studies

Example (Electric Field Parallel to Line)

Assumed input is a 1 V/km field parallel to a 150 mile long 765 kV line

$$I_{GIC,3Phase} = \frac{150\text{ volts}}{(1+0.1+0.1+0.2+0.2)\Omega} = 93.75\text{ amps or }31.25\text{ amps/phase}$$



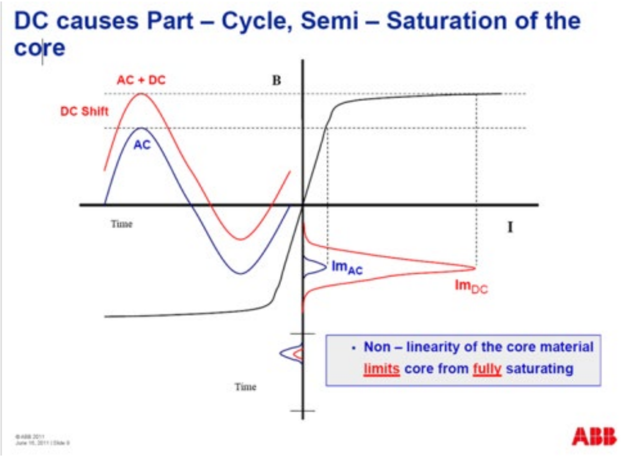
The line and transformer resistance and current values are per phase so the total current is three times this value. Substation grounding values are total resistance. Brown arrows show GIC flow.

GIC Calculations for Large Systems

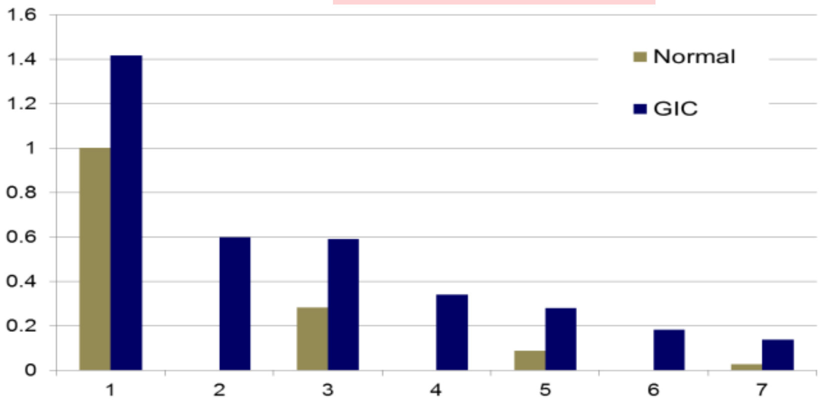
- Factoring the sparse **G** matrix and doing the forward/backward substitution takes about 1 second for a large electric grid model
- The current vector (**I**) depends upon the assumed electric field along each transmission line
  - This requires that substations have correct geo-coordinates
- With the nonuniform electric fields from an HEMP an exact calculation would be path dependent, but just assuming a straight line path is sufficient (given all the other uncertainties!)

GIC Transformer Impacts

- The superimposed dc GICs can push transformers into saturation for part of the ac cycle
- This can cause large harmonics; sequence (e.g., power flow and dynamics) these harmonics can be represented by increased reactive power losses in the transformers



Harmonics



Images: Craig Stiegemeier and Ed Schweitzer, JASON Presentations, June 2011

GICs to Grid Impacts

- Transformer positive sequence reactive power losses vary as a function of both the GICs in the transformer coils and the ac voltage
- A common approach is to use a linear model

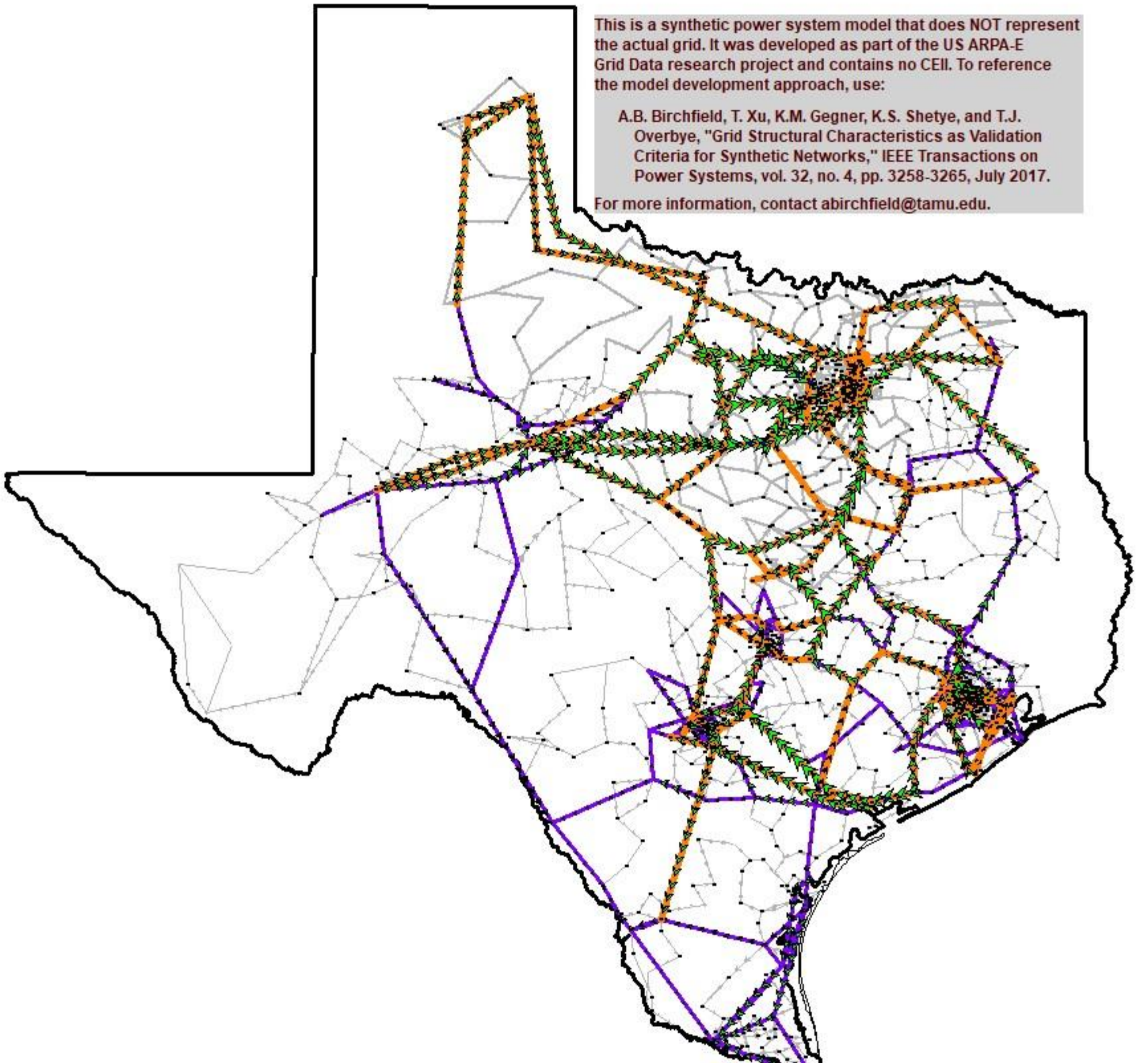
$$Q_{loss} = KV_{pu} I_{GIC,Eff}$$

A non-linear model could also be used

- The $I_{GIC,Eff}$ is an effective current that is a function of the GICs in both coils; whether auto or regular the equation is

$$I_{GIC,Eff} = \left| \frac{a_t I_{GIC,H} + I_{GIC,L}}{a_t} \right| \quad \text{where } a_t \text{ is the turns ratio}$$

Example: 2000-Bus Synthetic Grid



This is a 2000-Bus synthetic grid covering the Texas footprint using a 500 kV, 230 kV, 161 kV, 115 kV transmission system

Example EMP GIC Visualization for a 2000 Bus Synthetic Grid

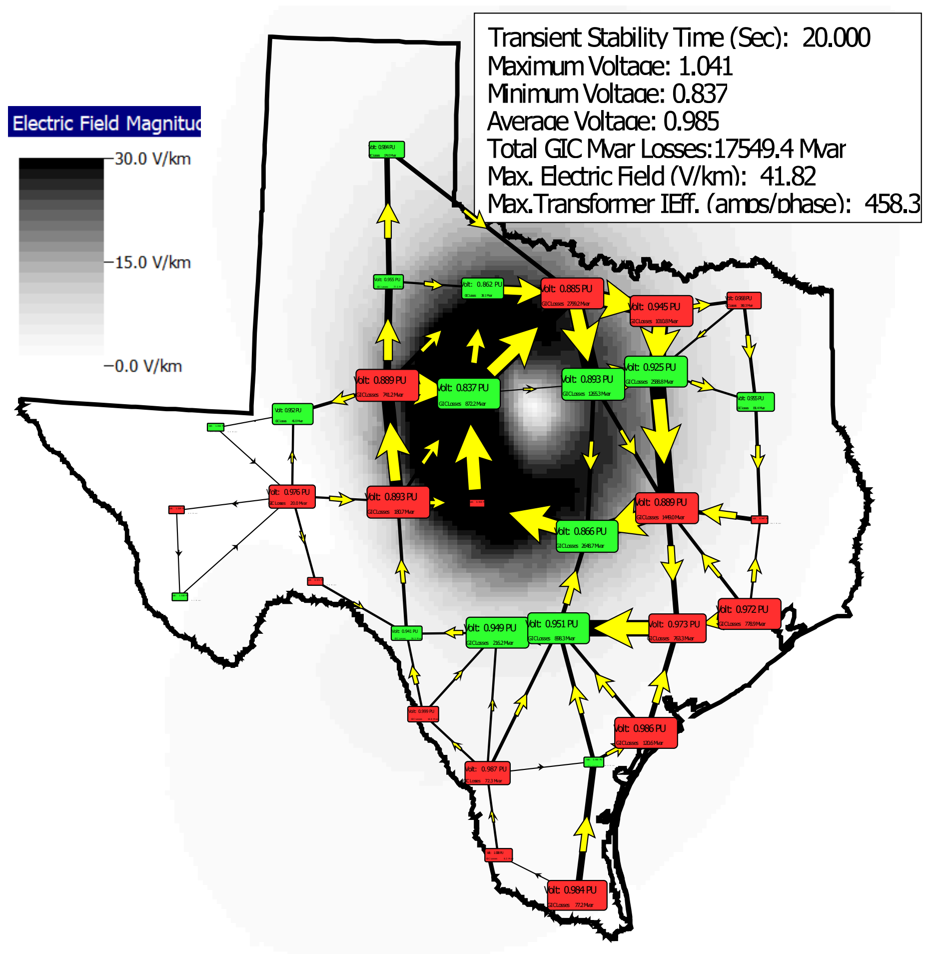
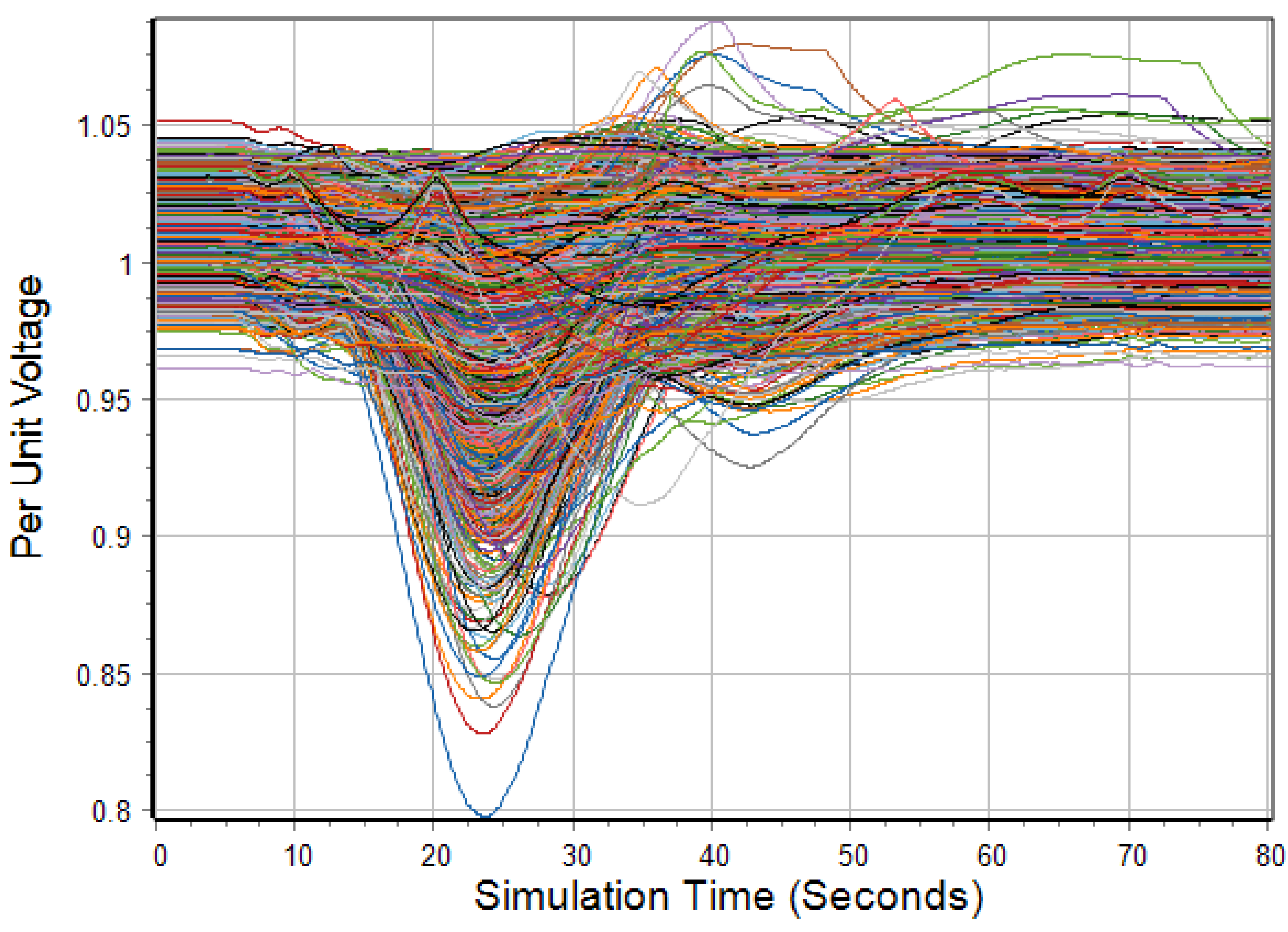


Image shows the GICs during an EMP event. The black/white contour shows the spatial variation in the electric field, the yellow arrows the aggregated GIC flows (using the technique of [a]), and the green/red boxes the GICs flowing out of and into the ground.

[a] T.J. Overbye, J. Wert, K. Shetye, F. Safdarian, and A. Birchfield, "Delaunay Triangulation Based Wide-Area Visualization of Electric Transmission Grids," Kansas Power and Energy Conference (KPEC), Apr. 2021; available oneline at overbye.engr.tamu.edu/publications/

2000 Bus Voltage Variation



An HEMP Assessment Process

- **In practice much of the following procedure is automated**
- Start with a model of the study electric grid, including the extra GIC-related values, the geographic coordinates, the stability models, and a reasonable protection system representation
- Definite a time and spatially-varying electric field input
  - PowerWorld can load several formats, including the *.b3d format, in which the electric fields are specified at an arbitrary set of points
- From the electric field input, calculate the time-varying dc voltages on the transmission lines

An HEMP Assessment Process, Cont.

- Solve the power flow, and initialize the dynamics (transient stability) simulation
- Include the impact of the E1 event as initial conditions (e.g., lost load, disabled relays, etc.)
  - This could result in a large initial frequency deviation
- Run the dynamics, with the impact of the E3 applied at each time step
- Ideally the simulation should run to completion (minutes), with the impact of the event quantified with various metrics (e.g., lost load, etc.)
- **Repeat as needed for sensitivity analysis**

HEMP Impact Example, 10,000 Bus Synthetic Grid

- The below two figures are from [a], showing the impact of an older HEMP waveform on a 10K grid

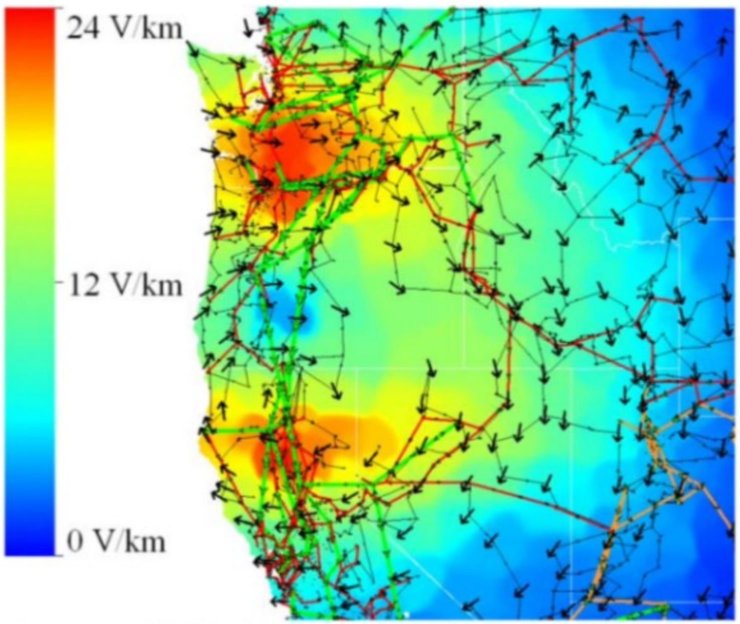


Fig. 9. Contour of ORNL electric field magnitude under a uniform conductivity model shown with the synthetic 10,000 bus system [24][25]. HEMP is centered on 45°N, −122°W. The arrows describe the electric field direction.

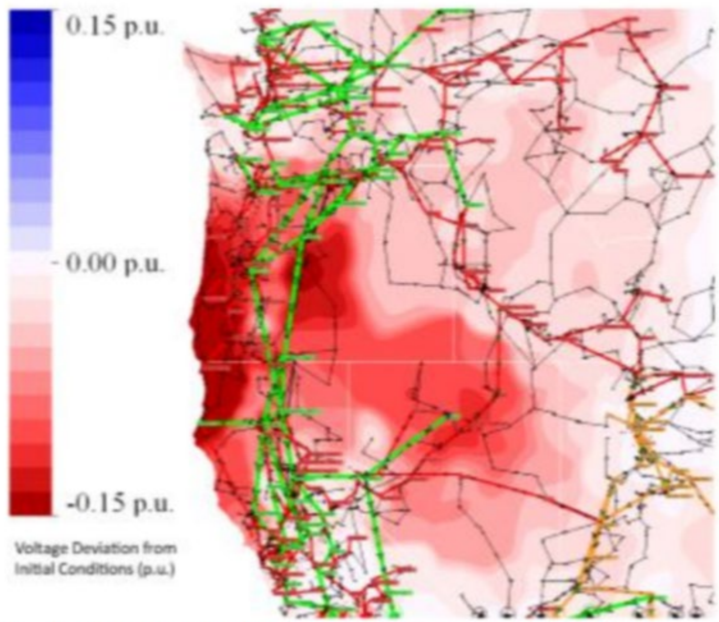


Fig. 14. Contour map showing per unit voltage deviation 63.25 seconds into the simulation (at peak intensity) with EMP under the uniform model.

[a] R.H. Lee, K.S. Shetye, A.B. Birchfield, and T.J. Overbye, "Using Detailed Ground Modeling to Evaluate Electric Grid | Impacts of Late-Time High-Altitude Electromagnetic Pulses (E3 HEMP)," IEEE Transaction on Power Systems, vol. 34(2), pp. 1549-1557, Mar. 2019 (available online at https://overbye.engr.tamu.edu/publications/ [8th paper in 2019])

What Could Occur During an HEMP

- There might be little or no warning (in contrast to a GMD in which there would have at least a day warning that something might be about to occur)
- The time, location and number of events would likely not be arbitrary (again, in contrast to a GMD)
- The system state could change quite abruptly, with little time for initial operator or engineer intervention
- However, the extent of a subsequent cascade and/or equipment damage could depend upon heavily on whether there is effective operator intervention

How to Improve the Electric Grid's Resiliency to HEMPs

- With E1 the hardening of components and their associated communication and controls is ongoing
- There is a need to develop better event simulators so that the power community (engineers, operators, researchers) can experience HEMP and other HILF scenarios
  - This work is ongoing at the Smart Grid Center
- Setup alarms to determine is an HEMP has likely occurred (even harmonics, GICs in transformers, etc.)

How to Improve the Electric Grid's Resiliency to HEMPs, cont.

- Better electric grid visualization to help with situational awareness during HILF events
  - A potential subsequent cascade, which could damage equipment and result in much larger outages, could be preventable
- The use of tools to allow bulk electric system owners and operators to better broadly simulate the event impacts, and develop (at least to some degree) mitigation techniques
- Possible selective use of GIC blocking devices
- More research into HILFs, including more robust analysis tools and wide-area situational awareness

Questions?

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