

Using PowerWorld Simulator for High Altitude Electromagnetic Pulse (HEMP) E3 Modeling and Mitigation Plan Design for Large-Scale Electric Grids

Tom Overbye
O'Donnell Foundation Chair III
Department of Electrical and Computer Eng.
Texas A&M University
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About Tom Overbye



- Since 2017 been a professor in the Electrical and Computer Engineering Department at Texas A&M (TAMU) working in the power systems area
- Also the director of the Texas A&M Smart Grid Center
- From 1991 to 2016 was with University of Illinois (UIUC)
- Got all degrees from University of Wisconsin-Madison, and worked eight years as an engineer with Madison
- Taught many power systems classes over last 30 years and worked on a wide variety of research projects

About Tom Overbye



- Started the development of the code that became PowerWorld during graduate school
- Co-founder of PowerWorld Corporation in 1996
 - Goal is to make power system analysis as easy as possible
- Since both UIUC and TAMU encourage faculty to do consulting and/or have external business relationships, has continued to work with the development of the PowerWorld code including OPF, stability, visualization, geomagnetic disturbance (GMD) and high altitude electromagnetic pulse (HEMP analysis
- As was the case at UIUC, at TAMU my relationship with PowerWorld is covered by a management plan

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 2022 will be held in person on Feb 28 to March 1, 2022 (tpec.engr.tamu.edu)
 - Some of the material from this presentation is contained in a TPEC paper titled, “Towards Developing Implementable High Altitude Electromagnetic Pulse E3 Mitigation Strategies for Large-Scale Electric Grids”
 - This paper and others are available at overbye.engr.tamu.edu/publications/



Our Energy Future Could be Quite 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 including the addition of large amounts of renewable generation, and lots of good engineering challenges
- I think our electric energy future could be quite bright, and it is a great time for students entering the field!!
- There are lots of concerns with this transition, particularly in dealing with electric grid resilience issues like the focus here on HEMP's

Presentation Overview

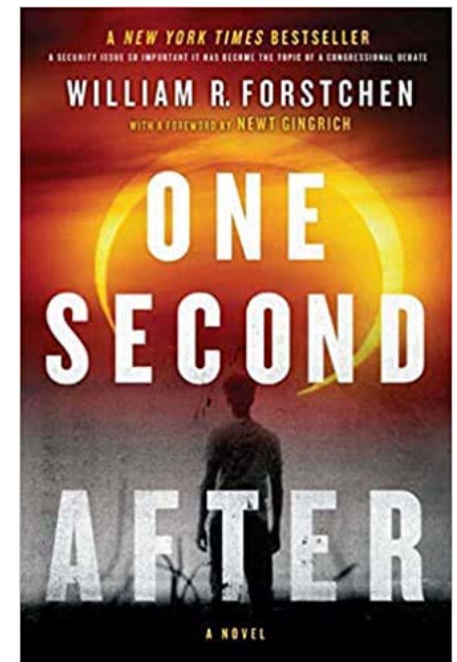


- The presentation covers HEMPs, with a particular focus on how PowerWorld Simulator can be used to model and determine HEMP mitigation strategies
 - On Dec 1, 2021 I gave a more general presentation on HEMP for the Smart Grid Center, with the those slides available at smartgridcenter.tamu.edu/index.php/webinars/
- This presentation is most appropriate for engineers and students with some familiarity with electric power system analysis and PowerWorld Simulator
 - Knowledge of GMD analysis is a plus
 - Still, I tried to make the presentation have as much general appeal as possible

Presentation in a Nutshell



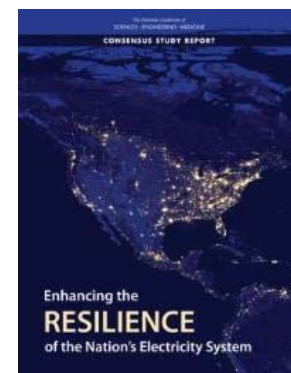
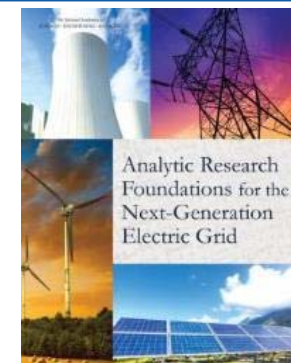
- HEMPs are certainly rare events, and an HEMP could be quite severe; HEMPs have three components (E1, E2, E3) with this presentation mostly focusing on E3
- HEMPs are not so severe that they cannot be mitigated, and their impacts on grids need to be simulated
 - The results are not likely to match the quite severe results presented in the book *One Second After* by Forstchen in 2009
- Presentation does not provide any specific commentary on the HEMP vulnerability of any actual electric grid; all examples are done using synthetic grids with synthetic HEMP waveforms



Recent National Academies Reports and the 2021 DOE Innovation Symposium



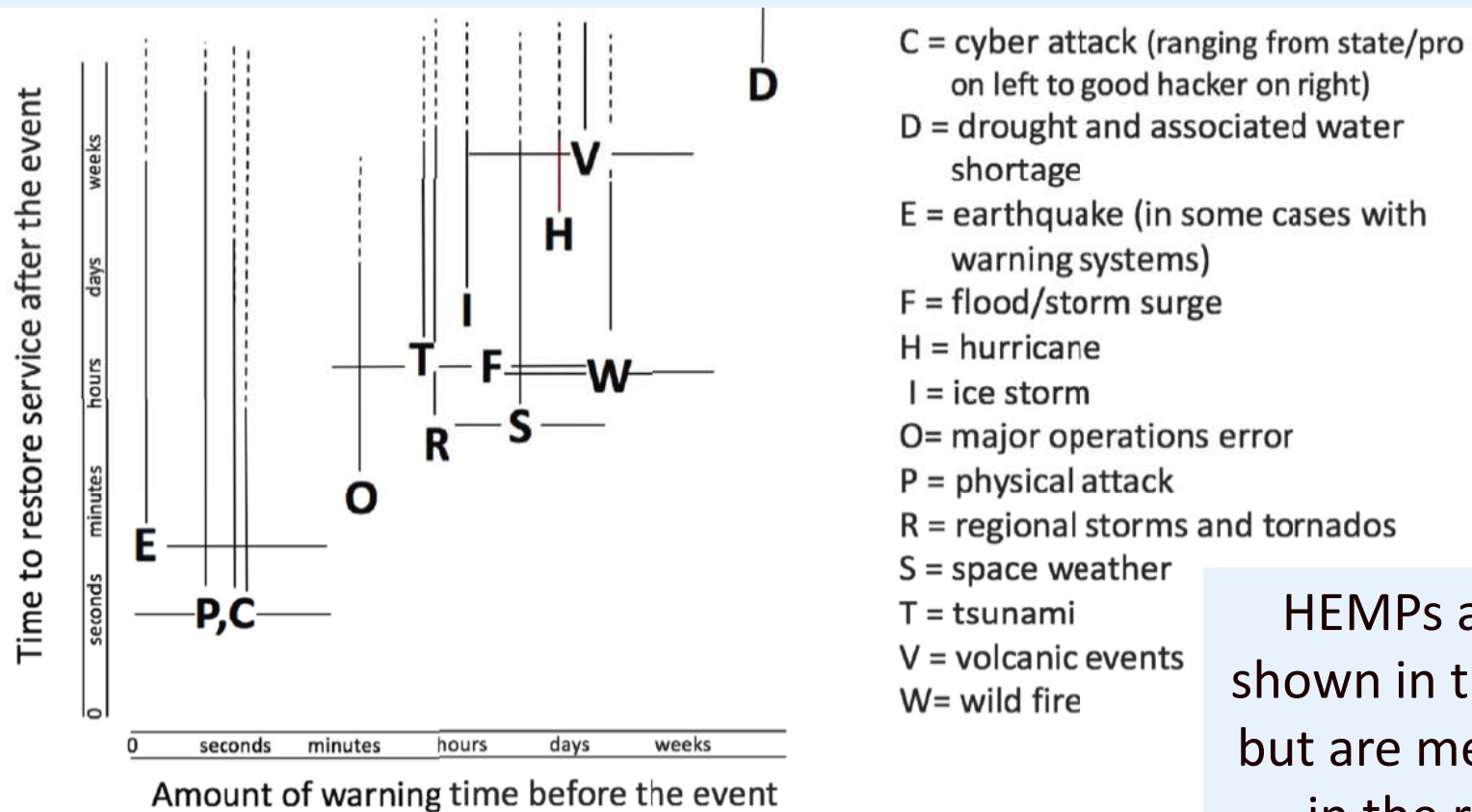
- *Analytic Research Foundations for the Next-Generation Electric Grid, 2016*
- *Enhancing the Resilience of the Nation's Electricity System, 2017*
 - “While minimizing the likelihood of large-area, long-duration outages is important, a resilient system is one that acknowledges that such outages can 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



HEMPs are not shown in the figure but are mentioned in the report

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

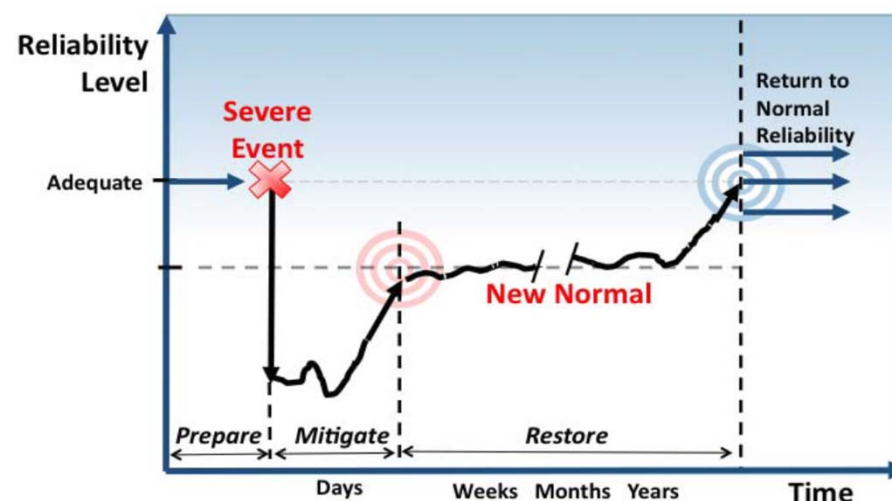
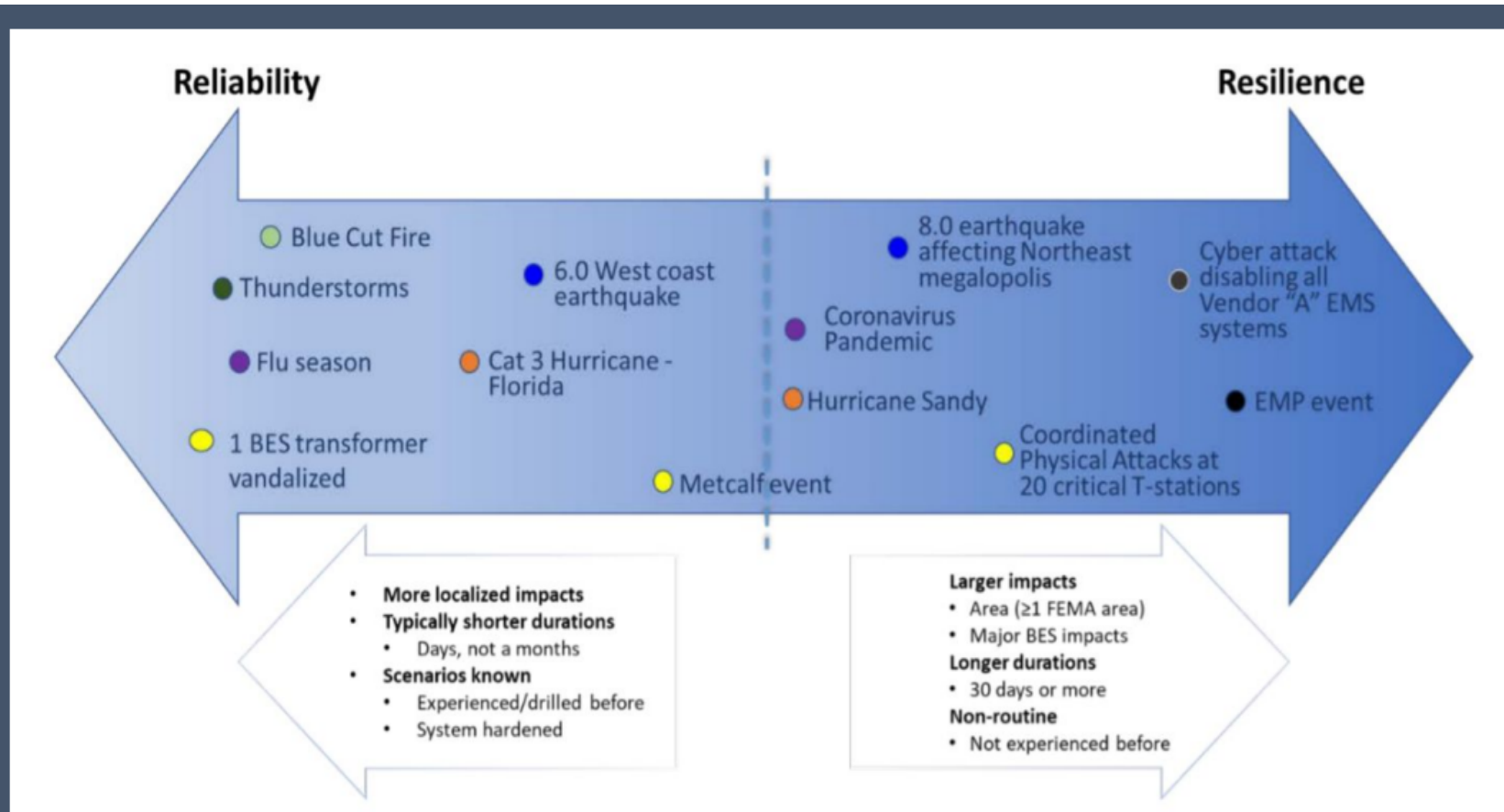


Image Source: NERC, 2012

- 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

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 North American Transmission Forum (NATF)

What is Grid Resilience?



- On the reliability-resilience continuum, NATF treats HEMPs as the event most on the resilience side, so a natural question is what is meant by 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.



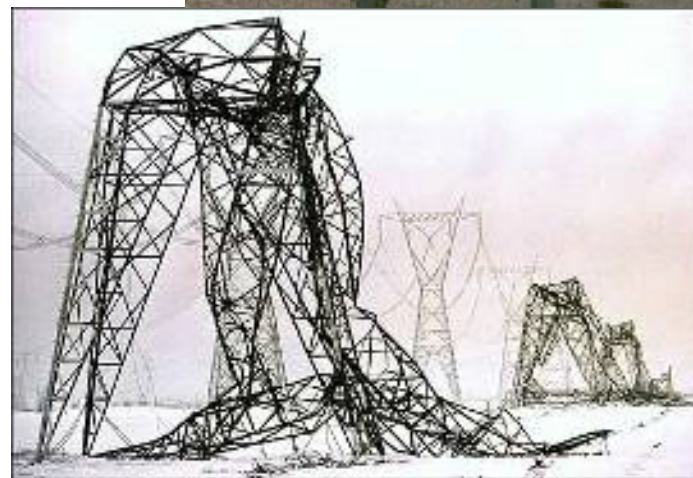
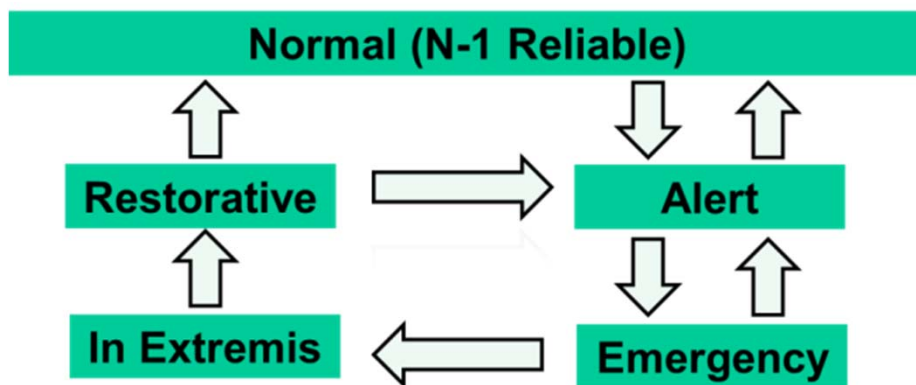
- National Association of Regulatory Utility Commissioners (NARUC)
 - “Robustness and recovery characteristics of utility infrastructure and operations, which avoid or minimize interruptions of service during an extraordinary and hazardous event”
- EPRI & North American Transmission Forum (NATF)
 - The 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

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



Electric Grid Time Frames

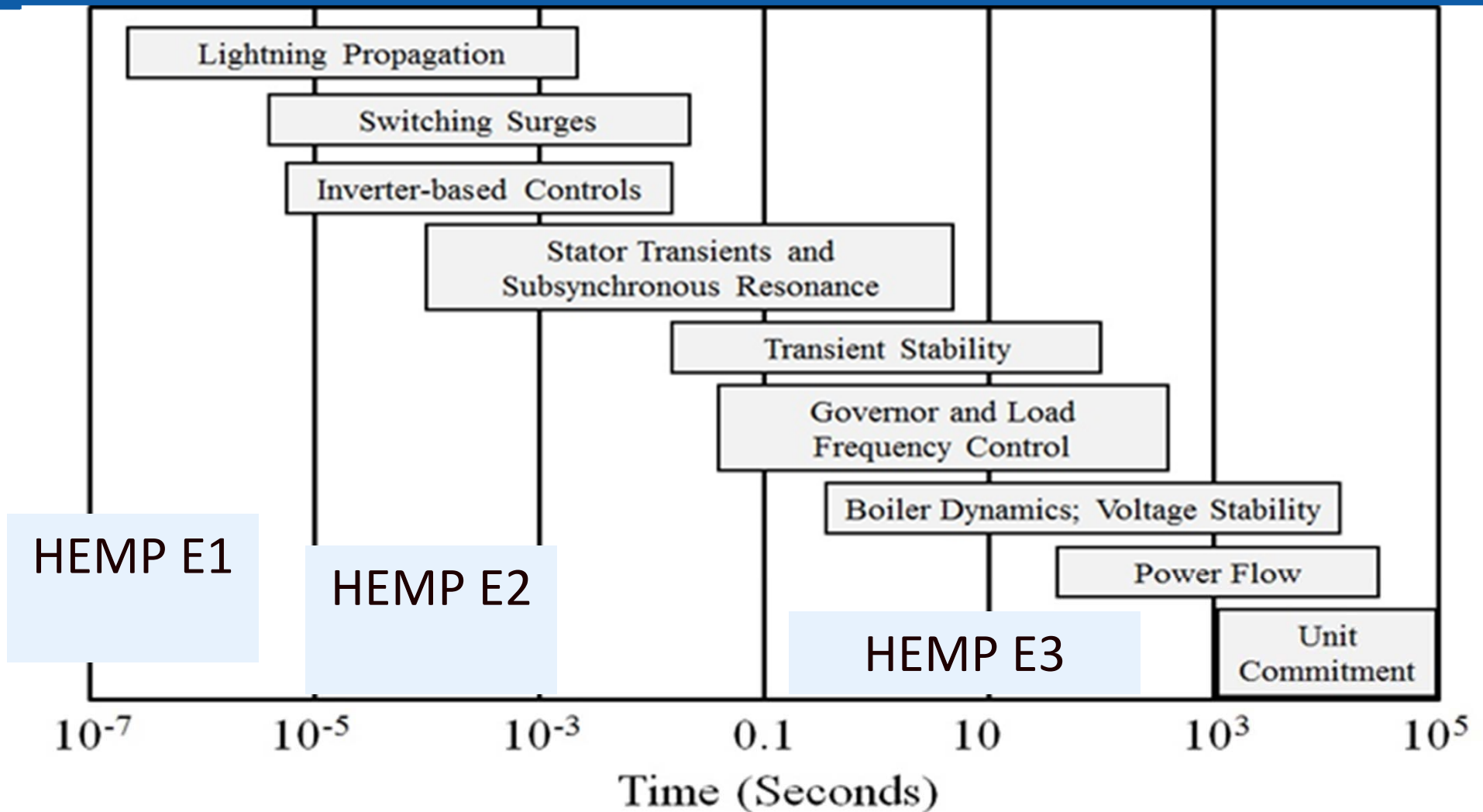
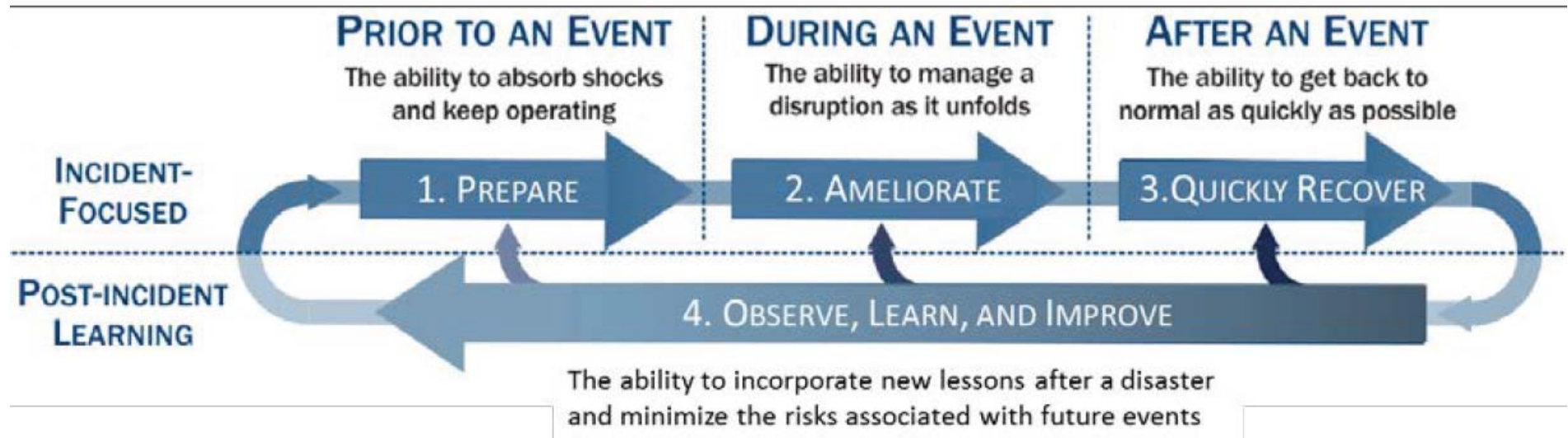


Image: Sauer, P.W., M. A. Pai, *Power System Dynamics and Stability*, Stripes Publishing, 2007

Four Stage Resilience Process



The focus here is mostly on the 1) Prepare and 2) Ameliorate steps

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 electromagnetic 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) caused 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

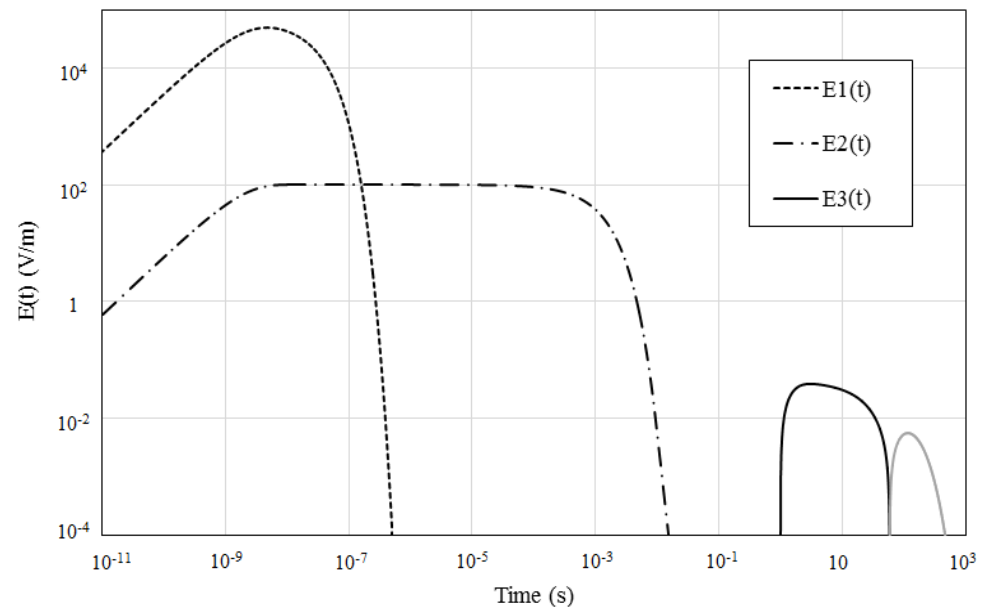


- Naturally some information on nuclear EMPS is not public, but various public documents exist,
- The primary concern about nuclear EMPS is the impacts caused by high altitude EMPs (HEMPs)
 - From 30 to 100's of km in altitude
 - For a high altitude explosion the other common nuclear impacts (blast, 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



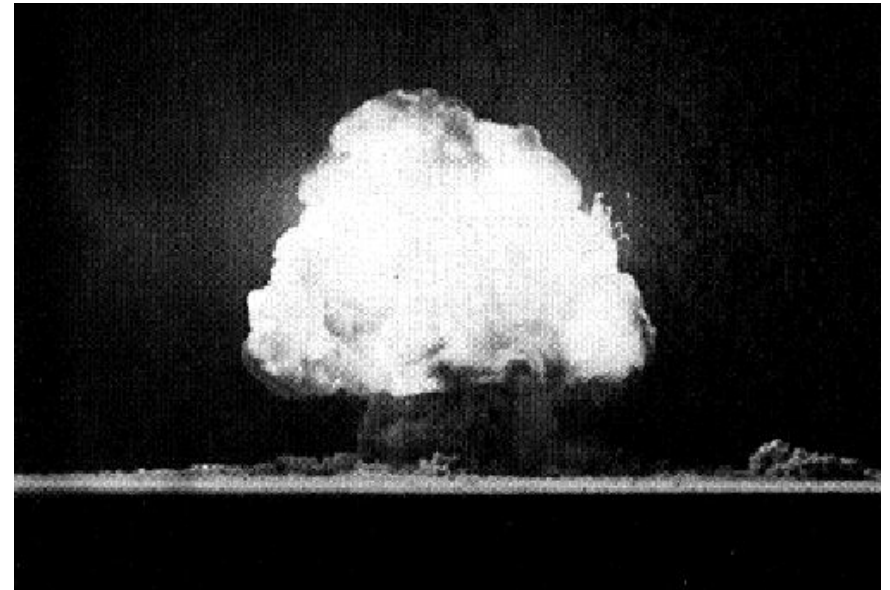
- The impacts of an HEMP are typically divided into three time frames: E1, E2 and E3
- The quickest, E1 with maximum electric fields of 10's of kV per meter, can impact unshielded electronics
- E2, with electric fields of up to 100 volts per meter, is similar to lightning
- Much of talk is on E3, which 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%20HEMP%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

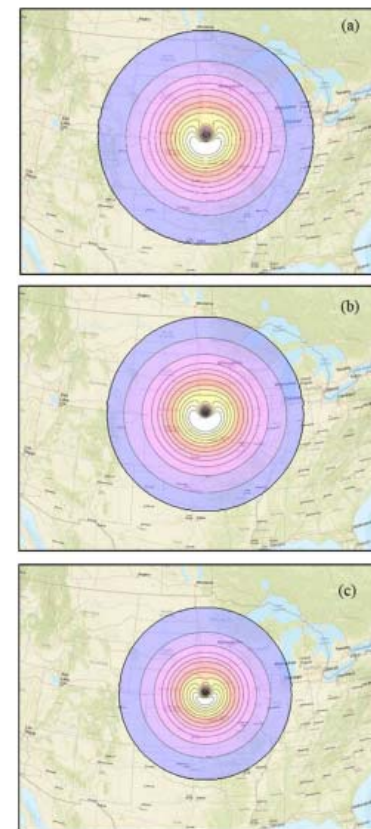
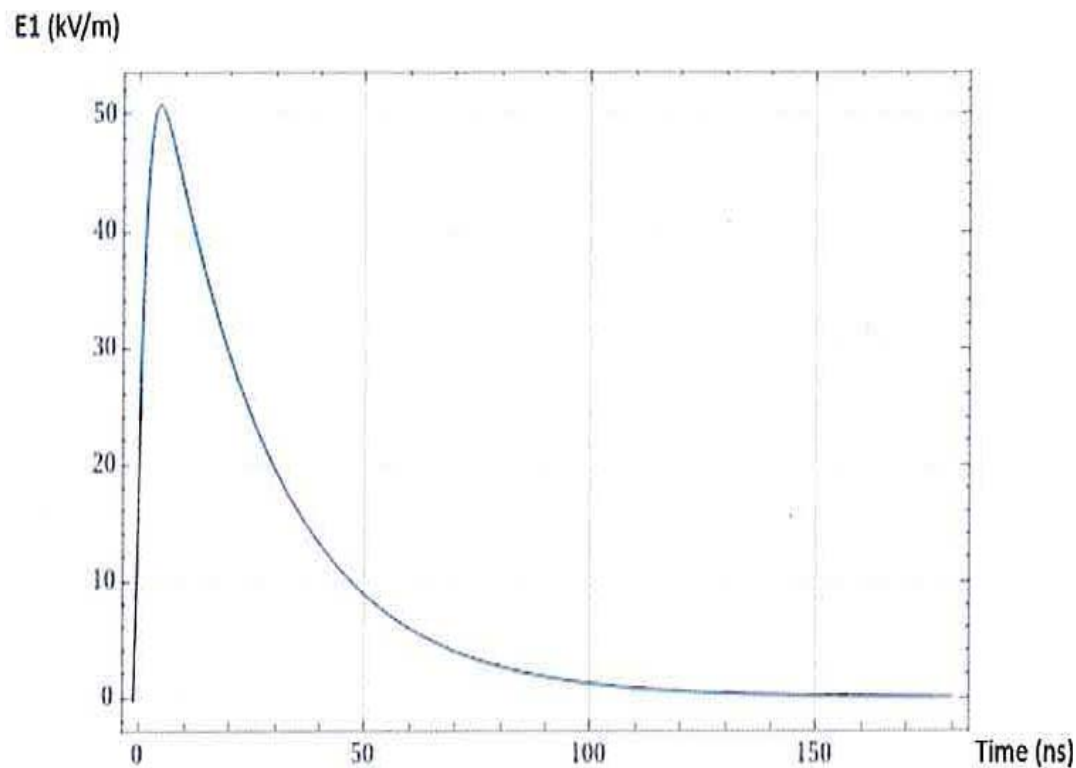


Figure 5. The incident electric field E , in units of kilovolts per meter (kV/m), for a 100 kt nuclear detonation over a location near the geographic center of Continental United States at altitudes of 80 km (a), 65 km (b), and 50 km (c). The rings are in intervals of 2 kV/m, with the outermost ring 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](https://www.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 (GMDs) 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)

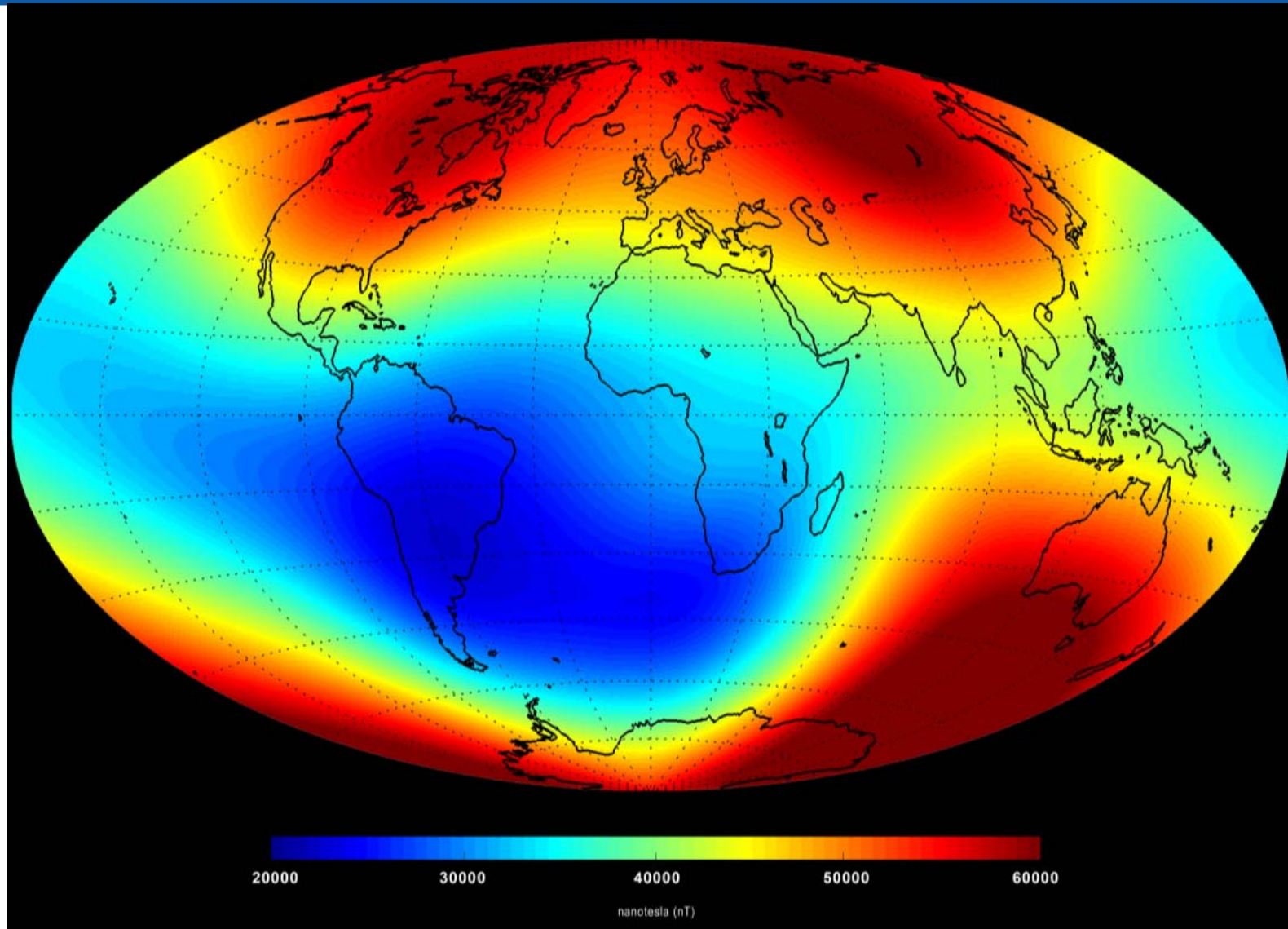
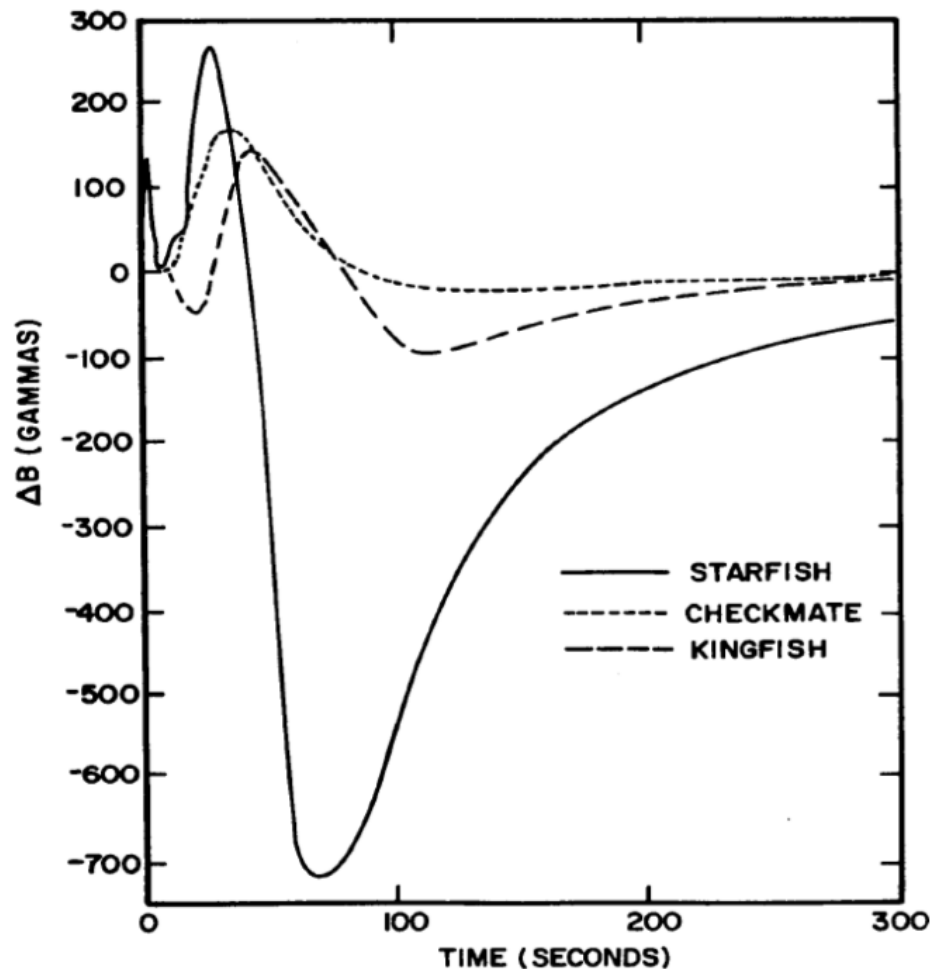


Image Source: https://climate.nasa.gov/internal_resources/2414/

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



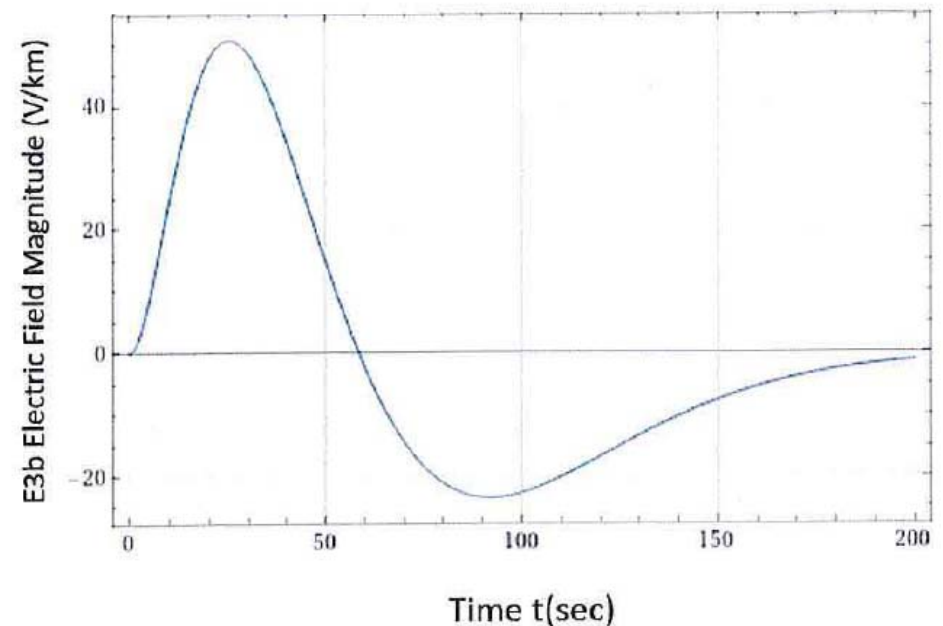
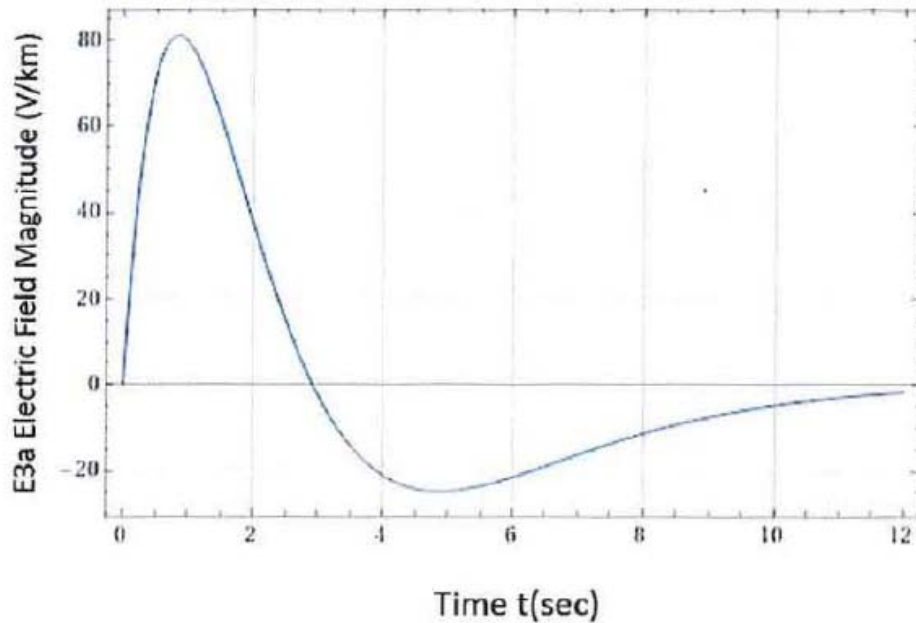
Checkmate and Kingfish were nuclear tests that were part of Operation Fishbowl. A gamma is one nT. For reference the Quebec GMD had 500 nT/minute and the 1859 Carrington GMD event is estimated have had a variation of perhaps 2500 nT/minute

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 conductance, 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 $B(\omega) = -\mu_0 H(\omega)$

$$|E(\omega)| = |Z(\omega) H(\omega)|$$

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

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

$B(\omega) = 660 \times 10^{-9}$ T and

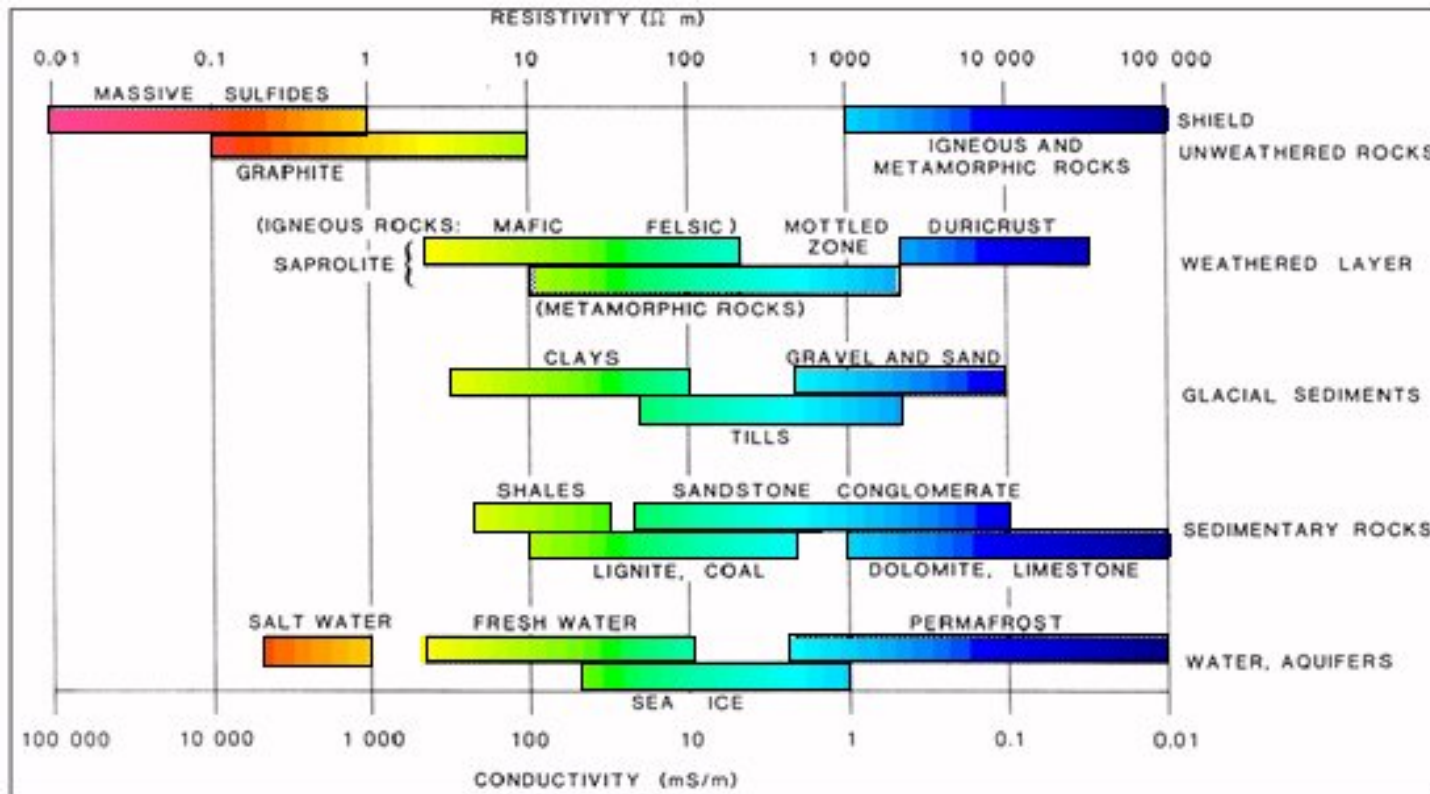
$$E(\omega) = \sqrt{\frac{2\pi \times 0.002 \times \mu_0}{0.001}} \frac{660 \times 10^{-9} \text{ T}}{\mu_0}$$

$$E(\omega) = 0.00397 \times 0.525 = 2.1 \text{ V/km}$$

Typical Ground Conductance and Resistivity Values



- Soil conductance is often expressed in its inverse of resistivity in $\Omega\text{-m}$; 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, Magnitude



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

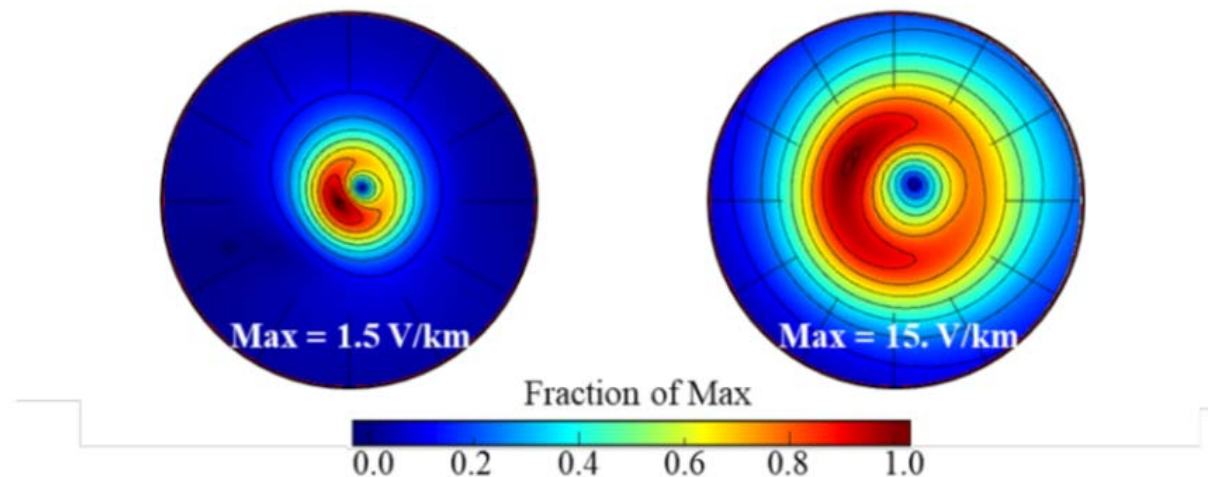


Figure 18. Ground electric field maps from 20 kT case (left) and 1 MT case (right) illustrate differences in maximum field strength and spatial extent. East-West and North-South extents of each plot are 1,110 km.

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

Time-Varying Spatial Footprint, Magnitude

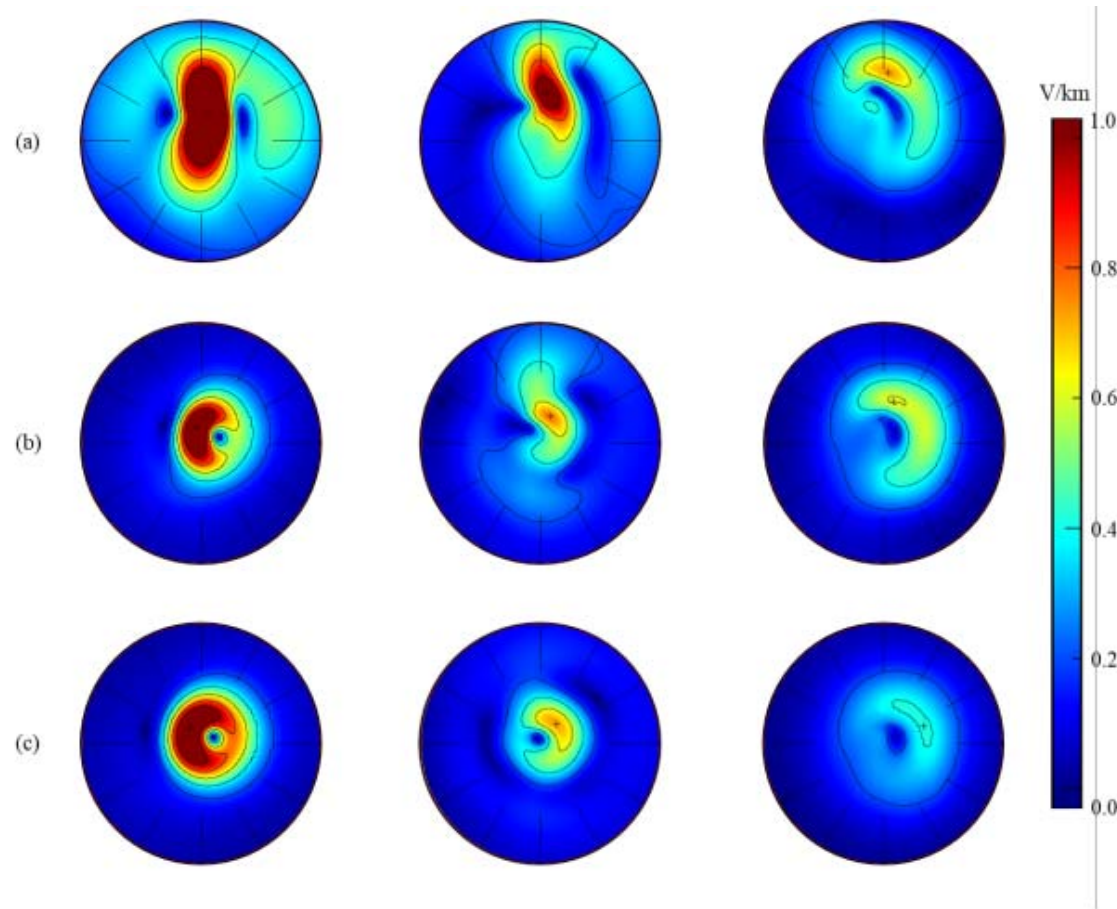
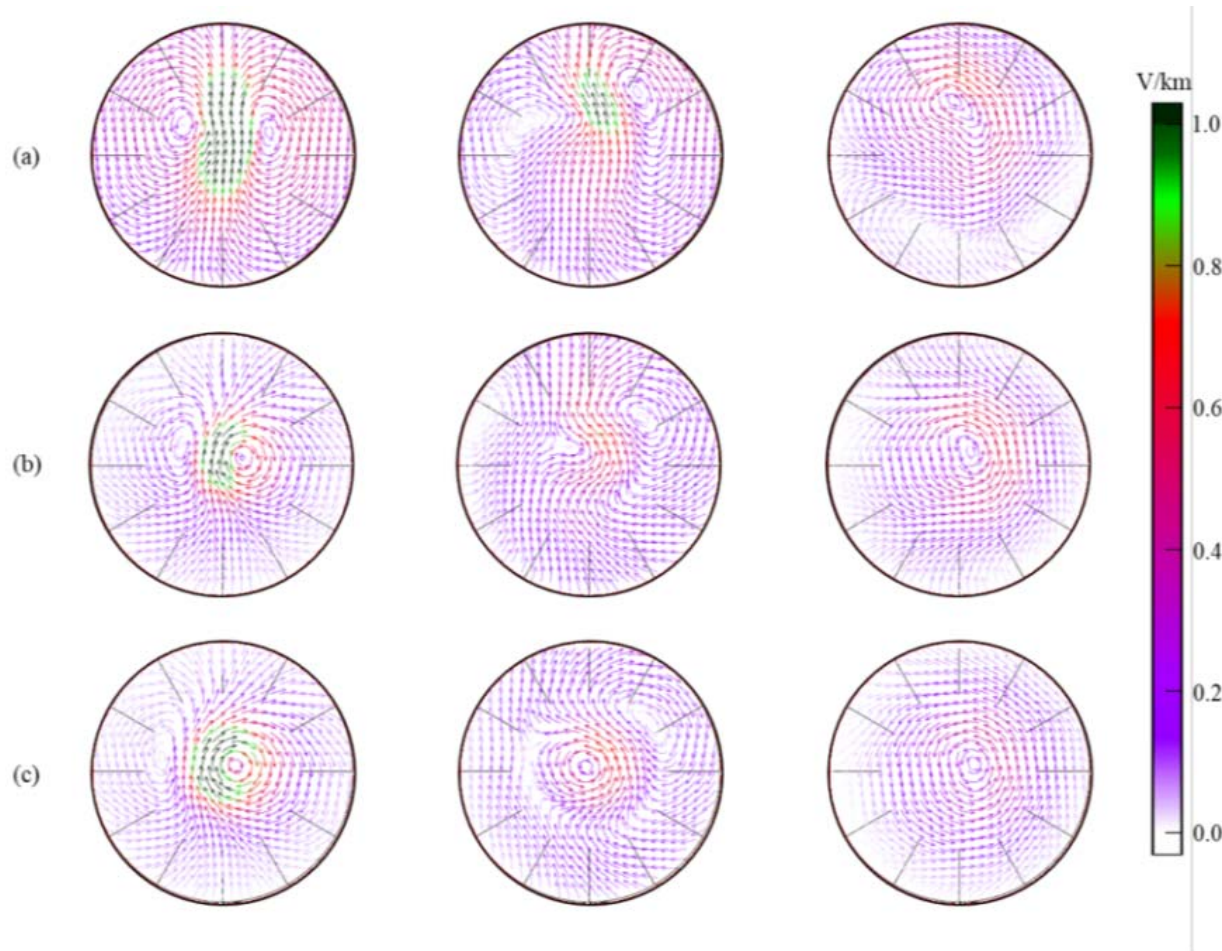


Figure 7. Ground electric field magnitudes from latitude sensitivity study:
(a) burst magnetic latitude = 14.5° at 40, 60, and 90 s (left to right);
(b) burst magnetic latitude = 31.6° at 20, 60, and 90 s (left to right);
(c) burst magnetic latitude = 48.8° at 20, 60, and 90 s (left to right)

A takeaway from the figure is that the field is not uniform, and its shape is time-varying

Source is Figure 7 from <https://apps.dtic.mil/sti/pdfs/AD1082958.pdf>; each circle diameter is again 1110 km (688 miles);

Time-Varying Spatial Footprint, Direction



A takeaway from the figure is that the field is not uniform, with a circular pattern in the area with the highest field

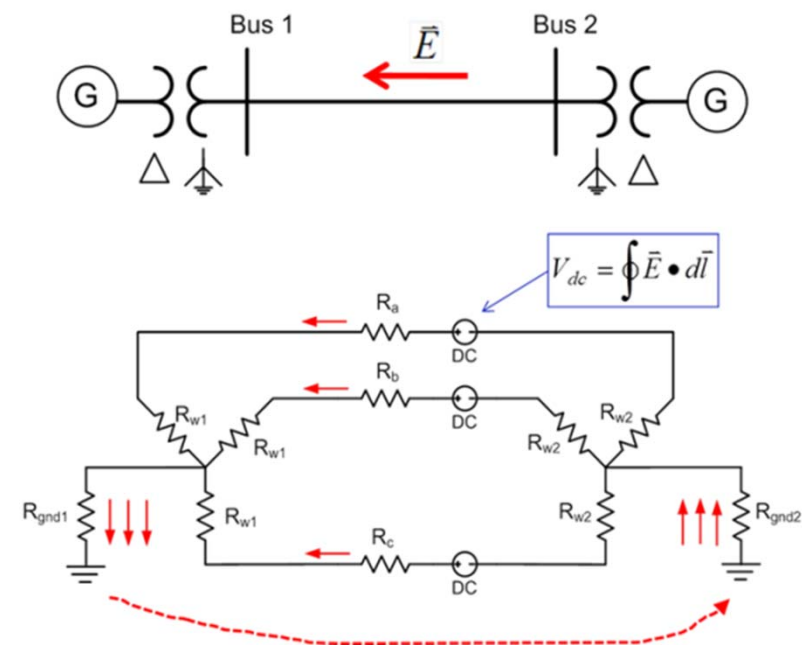
Figure 8. Ground electric field vectors from latitude sensitivity study:
(a) burst magnetic latitude = 14.5° at 40, 60, and 90 s (left to right);
(b) burst magnetic latitude = 31.6° at 20, 60, and 90 s (left to right);
(c) burst magnetic latitude = 48.8° at 20, 60, and 90 s (left to right)

Source is Figure 8 from <https://apps.dtic.mil/sti/pdfs/AD1082958.pdf>; each circle diameter is again 1110 km (688 miles);

Geomagnetically Induced Currents (GICs)



- Whether caused by an HEMP or a GMD, along the length of a high voltage transmission line the 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 $\mathbf{I} = \mathbf{G} \mathbf{V}$ (or $\mathbf{J} = \mathbf{G} \mathbf{U}$)
 - $\mathbf{J}$ and $\mathbf{U}$ may be used to emphasize these are dc values, not the power flow ac values
 - The $\mathbf{G}$ 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



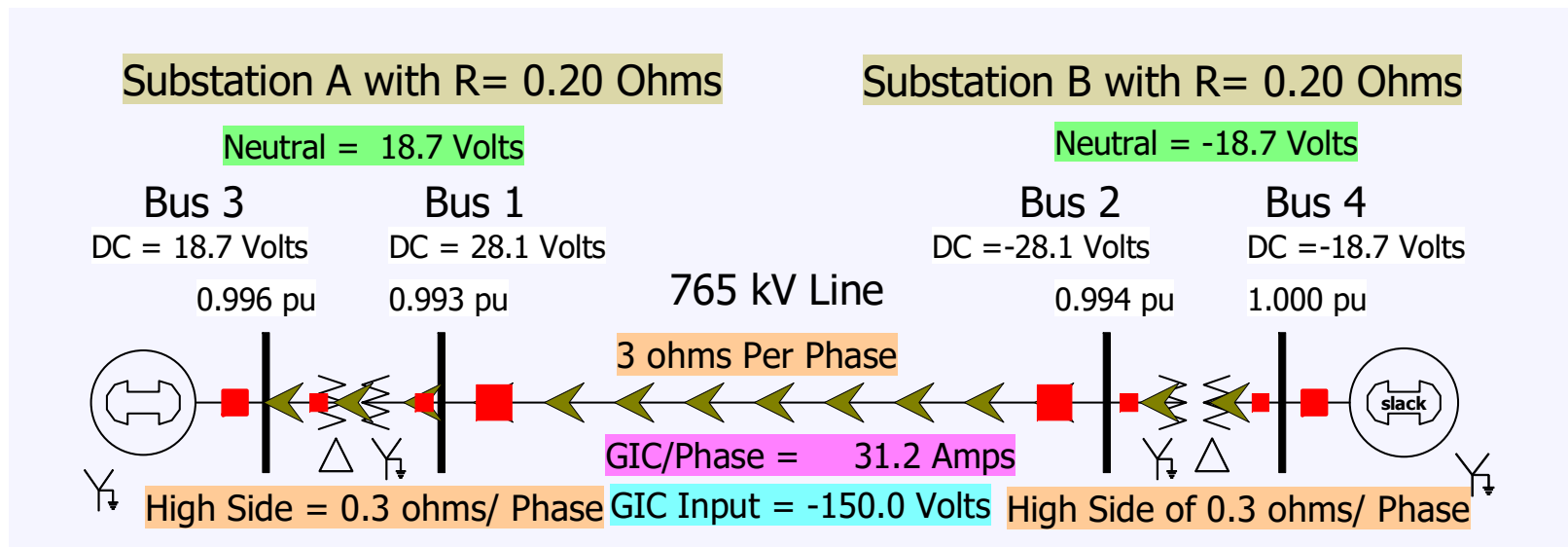
- In determining the **G** matrix for the dc GICs, knowing the transformer grounding configurations is crucial
 - Delta windings have no path to ground, and hence look like an open circuit
 - Transmission to distribution transformers look like an open circuit (if delta on the high side)
 - Autotransformers 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.

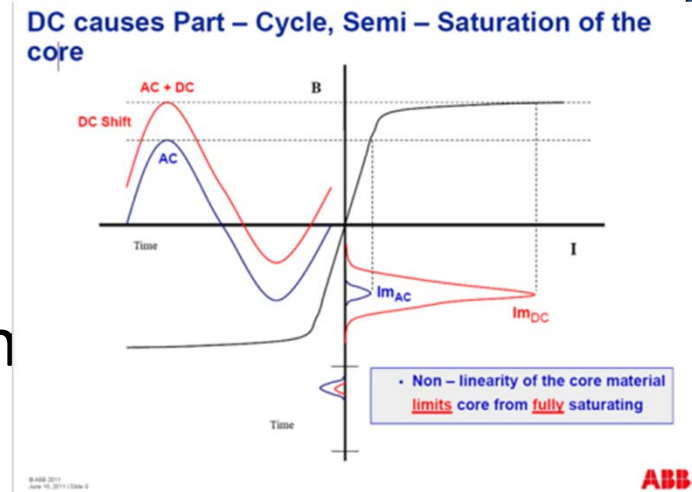
GIC Calculations for Large Systems



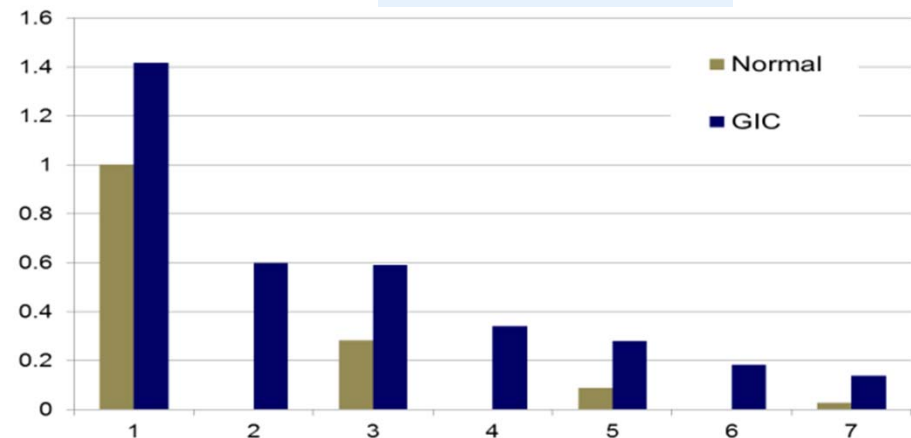
- Factoring the sparse **G** matrix and doing the forward/backward substitution takes about 1 second for a large electric grid model
- The current vector (**I**) depends upon the assumed electric field along each transmission line
 - This requires that substations have correct geo-coordinates
- With 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; in the (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

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

GMDs versus HEMPs E3



- GMD and HEMP electric grid impacts are similar in that they both cause GICs, but there are some key differences
 - Because of the faster rise time and shorter total duration (minutes for an E3 versus hours or days for the GMD), the E3 is typically simulated using time-domain stability simulations
 - Because the E3 is preceded by the E1 and E2, their impacts need to be considered; they would be treated as initial conditions for the time-domain simulation
 - An HEMP could occur with little or no warning, causing the grid to almost instantly go from normal to “in extremis” operation
 - There would be essentially no time for operator intervention, but automatic EMS level mitigation control could occur
 - There is no HEMP operational experience
 - With an HEMP the adversary could select the time and location

HEMP Modeling in PowerWorld

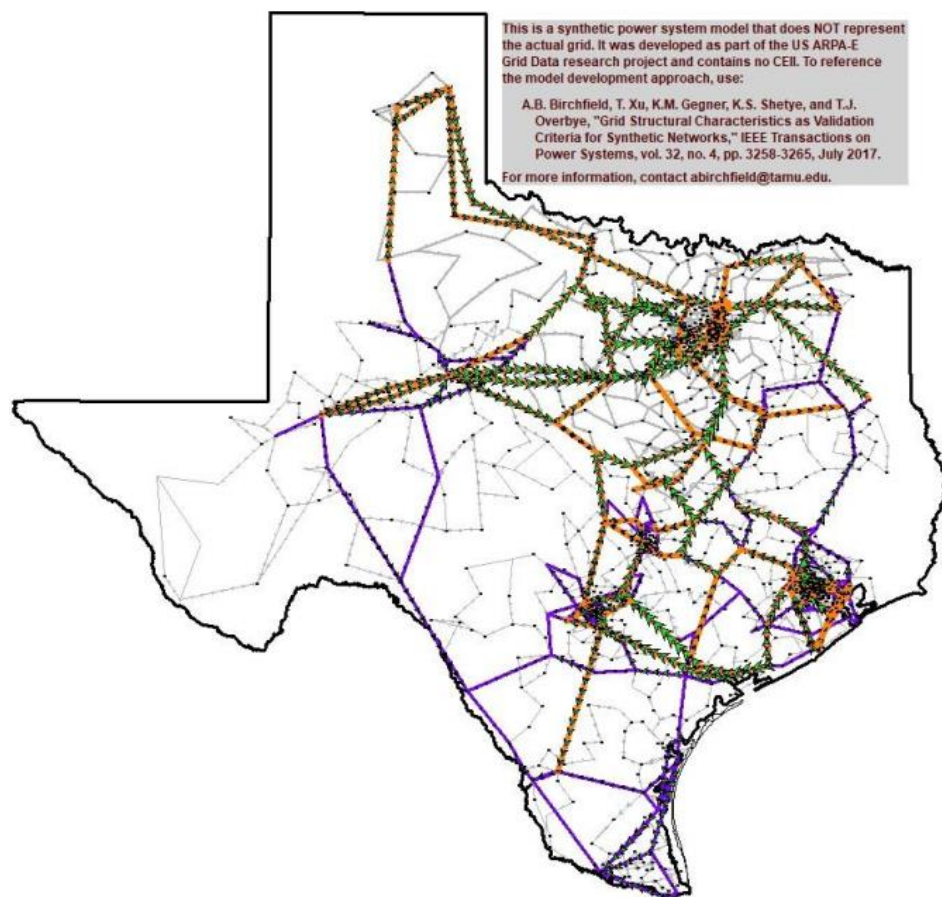


- The setup includes much of what is used for GMD assessment (power flow plus location information and GIC specific parameters)
- The setup is augmented with standard stability models and a time-varying electric field input
 - An important part of the stability models is to include at least some representation of the protection system
- In PowerWorld a common way to express the time and spatially varying electric field input is with a *.b3d file
 - The b3d files are binary files with a public format allowing for easy file interchange

HEMP Modeling Example 2000-Bus (2K) Synthetic Grid



- The modeling of HEMPs in PowerWorld will be demonstrated using a 2000 bus synthetic grid covering a Texas geographic footprint



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

Case Setup



- The initial case setup is identical to what is done for a GMD study. This includes
 - Mapping buses into substations and having geographic coordinates for the substations and grounding resistance
 - Having grounding configuration information for all the transformers
 - Having models relating the transformer GICs to their reactive power losses
- For HEMP studies the case also needs to include stability (dynamics) information, including pertinent parts of the protection system
- All this information can be in a PowerWorld *.pwb file. The example case is in the file **TSGC_HEMP_Start**

Aside: Testing the Stability Input



- The case can be used for all time-domain stability studies
 - The models can be seen at **Stability Case Info, Models in Use**

Model Explorer: Models in Use

Explore

Fields

- Transfer Directions
- Zones
- Solution Details
- Case Information and Aux
- Contingency Analysis
- Optimal Power Flow
- Tools and Add Ons
- Transient Stability
 - DC Models
 - Summary
 - Generator Model Use
 - Load Model Use
 - Model Support Sta
 - Models in Use**
- Area AGC Models
- DS Time Schedules
- Generator Exciters
- Generator Governors
- Generator Machine Mo
- Generator Other Mode
- Generator Stabilizer
- Injection Group Mode
- Line Relay Models
- Line Shunts Models

Models in Use

Records Set Columns

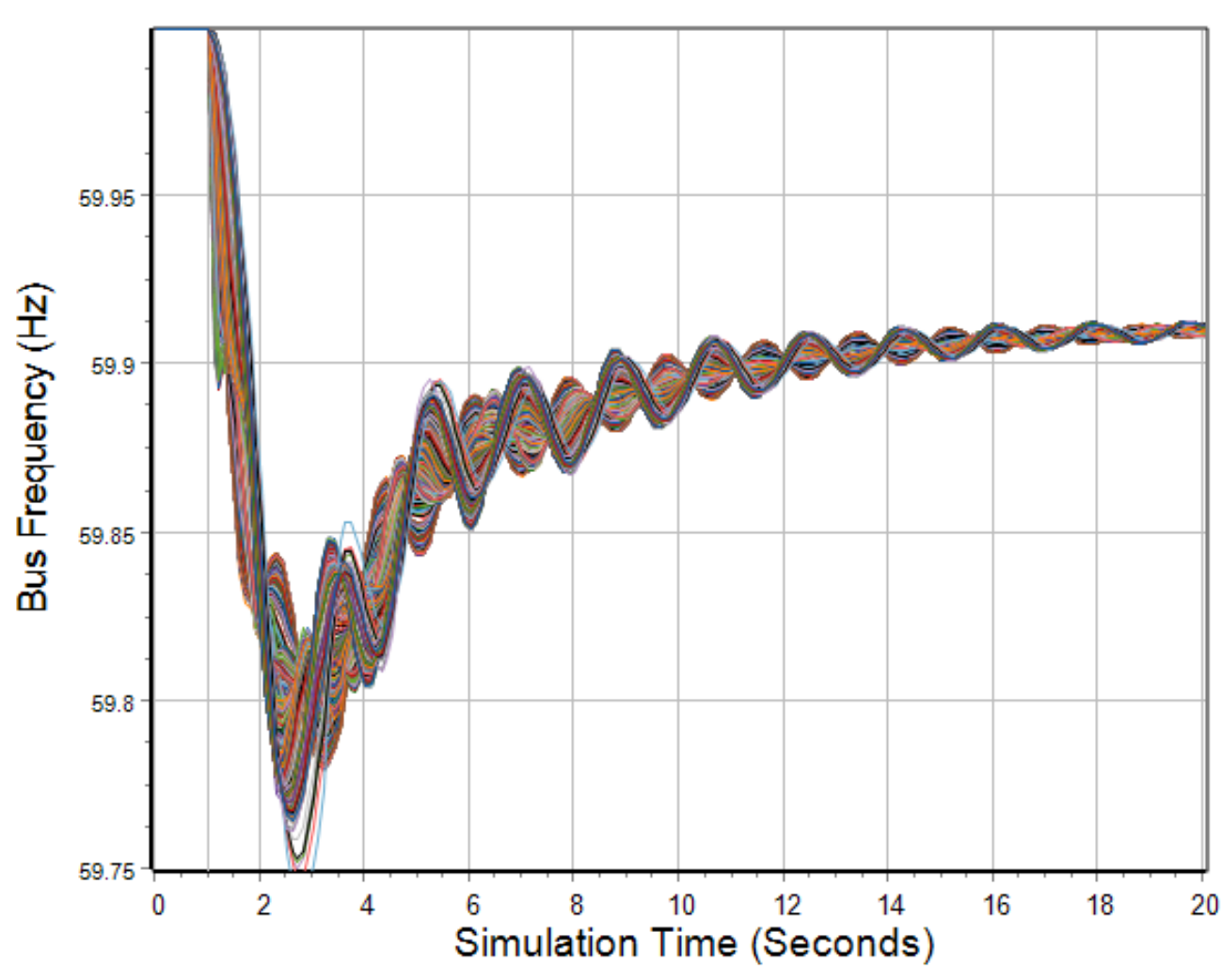
Filter Advanced TSMModelSummaryObject Find... Remove Quick

	Model Class	Object Type	Active and Online Count	Active Count	Inactive Count	Fully Supported
1	_All Models	_All Models	4751	5278	2154	YES
2	Machine Model	GENSAL	20	25	0	YES
3	Machine Model	GENROU	319	413	0	YES
4	Machine Model	WT4G	78	84	0	YES
5	Over Excitation Lim	OEL4C	123	156	282	YES
6	Relay Model	LHVRT	0	0	522	YES
7	Exciter	SCRX	4	5	0	YES
8	Exciter	IEEET1	18	25	0	YES
9	Exciter	EXAC1	4	6	0	YES
10	Exciter	EXAC2	31	38	0	YES
11	Exciter	EXPIC1	52	61	0	YES
12	Exciter	WT4E	78	84	0	YES
13	Exciter	EXST4B	1	1	0	YES
14	Exciter	ESST4B	214	278	0	YES
15	Exciter	ESDC1A	10	12	0	YES
16	Exciter	ESDC2A	1	1	0	YES
17	Exciter	ESAC1A	2	4	0	YES
18	Exciter	ESAC6A	2	7	0	YES
19	Governor	GAST_PTI	3	3	0	YES
20	Governor	GGOV1	290	367	0	YES
21	Governor	HYGOV	20	25	0	YES
22	Governor	IEEEG1	26	43	0	YES
23	Stabilizer	IEEEST	335	434	0	YES
24	Load Relay	LVSH	0	0	1350	YES
25	Line Relay Model	SIMPLEOC1	3120	3206	0	YES

Aside: Testing the Stability Input



- The below graph shows for the 2K grid the frequency response at all the buses for the loss of 2700 MW



Generator GSU Status Fields



- An important, but sometimes overlooked aspect of the case setup is that the GSUs should have correct statuses
 - Usually a GSU is out-of-service when its generator is out-of-service, but there can be exceptions
- PowerWorld now has fields to show and change the generator GSU statuses
 - They are in **Case Information, Generators, Display/Column Options** in the Step-up Transformer Topology folder

Number of Bus	Name of Bus	ID	Status	Gen MW	Gen Mvar	Min MW	Low Side Gen Count Off	Low Side Gen Count On	Step-Up Transformer Flow (MW)	Step-Up Transformer(s) Status	Step-Up Transformer Count
2095	PANHANDLE 5	1	Open	0.00	0.00	23.85	1		0.00	Closed	1
3087	LORAIN 1 2	1	Open	0.00	0.00	22.50	1		0.00	Closed	1
4096	SANTA ROSA	1	Open	0.00	0.00	8.40	1		0.00	Closed	1
6049	SAN ANTONIO	1	Open	0.00	0.00	7.85	1		0.00	Closed	1

Mismatch in status

This is fixed in the case
TSGC_HEMP_GSUStatusSet

Assumed HEMP is Specified in a B3D File



- To load and view the input file, go to the **Add-Ons, GIC** form and select the **Time Varying Electric Field Inputs** page
- To load a b3d file, select the **Browse** button
 - The b3d file specifies the time and spatially varying electric field

GIC Analysis Form

Calculation Mode
☐ Single Snapshot
☐ Time Varying Series Voltage Inputs
☒ Time Varying Electric Field Inputs
☐ Spatially Uniform Time-Varying E-Field

Calculate GIC Values Clear GIC Values ☐ Include GIC in Power Flow and Transient Stability Validate Input Data for GIC

Current Time 0.00 ☐ Calculate GIC on Time Change ☐ Use EMP as Input

Select Step
 Field/Voltage Input

Field/Voltage Input

Non-uniform Electric Field Files (*.b3d, *.dat, *.json) Browse...

Options for Loading Multiple Files of Selected Type
☒ Just selected file
☐ All after last time in Time Points List
☐ All before first time in TimePoints List
☐ All files of selected type

Setup Time Varying Series Voltage Inputs
 Start Time (Seconds) 0.00
 End Time (Seconds) 0.00
 Sampling Rate (Seconds) 0.00
☒ Do All if Start and End Time = 0

Clear Existing Time Points or Merging
☒ Clear Existing
☐ Merge
☒ Setup Time-Varying Series on Load
☒ Save Non-uniform Fields in PWB File

Input Summary
 Starting Time (Seconds) Ending Time (Seconds) Number of Time Points Interpolated Offset Time 0.000
 Starting Latitude Ending Latitude Latitude Increment Starting Longitude Ending Longitude Longitude Increment Starting Date and Time 1/1/1970 (UTC) Second Offset 0.000 ☐ Use Local Time Zone

Save Selected Time Points in B3D Format Clear All Time Points

B3D Save Format Version
☒ Latest (Four) ☐ Three
☐ Two

Scale or Shift All Input Points
 Latitude Shift (Degrees) 0.000 Magnitude Scalar 1.000 Stretch Scalar 1.000
 Longitude Shift (Degrees) 0.000 Shift, Scale and or Stretch all Time Point Grid Values

Time Points (Select Point to Preview)

Time Offset, Seconds	Maximum Electric Field, V/km	Maximum Electric Field Longitude	Maximum Electric Field Angle Latitude	Save in File	Date/Time St

Time Point Grid Preview (First Entry is the Eastward Value, the Second the Northward)

Longitude	Latitude	Distance to Station (km)	Electric Field East, V/km	Electric Field North, V/km	Electric Field Magnitude, V/km	Electric Field Angle, Degrees

Assumed HEMP is Specified in a B3D File



GIC Analysis Form

Calculation Mode
☐ Single Snapshot
☐ Time Varying Series Voltage Inputs
☒ Time Varying Electric Field Inputs
☐ Spatially Uniform Time-Varying E-Field

Calculate GIC Values Clear GIC Values ☒ Include GIC in Power Flow and Transient Stability Validate Input Data for GIC

Current Time 0.00 ☐ Calculate GIC on Time Change

Select Step
 Field/Voltage Input
 Options
 DC Current Calculation
 AC Power Flow Model
 Tables and Results
 Areas
 Buses
 Generators
 DC Lines
 Lines
 Line Shunts
 Loads
 Switched Shunts
 Substations
 Transformers
 Multi-Section Lines
 System Summary
 G-Matrix
 Multi-Terminal DC Lines
 VSC DC Lines
 Sensitivity Analysis
 Non-Uniform Electric Field Scaling
 Geomagnetic Latitude Scaling
 Earth Resistivity Scaling
 Earth Resistivity Scaling

Field/Voltage Input

Non-uniform Electric Field Files (*.b3d, *.dat, *.json)
 C:\Projects_2022\PowerWorld_EMP\Talk_Feb2022\Example_B3D.b3d Browse...

Options for Loading Multiple Files of Selected Type
☒ Just selected file
☐ All after last time in Time Points List
☐ All before first time in TimePoints List
☐ All files of selected type

Setup Time Varying Series Voltage Inputs
 Start Time (Seconds) 0.00 Setup Time Varying Series
 End Time (Seconds) 60.01 ☒ Do All if Start and End Time = 0
 Sampling Rate (Seconds) 0.00

Input Summary
 Starting Time (Seconds) 0.00 Starting Latitude 18.71 Starting Longitude -111.32
 Ending Time (Seconds) 60.01 Ending Latitude 43.86 Ending Longitude -80.51
 Number of Time Points 602 Number Data Points 23409
 Interpolated Offset Time 0.000 View Interpolated Offset Time (Seconds) Starting Date and Time 1/1/1970 12:00:01 AM (UTC) Second Offset 0.648 ☐ Use Local Time Zone

Save Selected Time Points in B3D Format Clear All Time Points
 Change Start Date and Time to Zero Time Offset

B3D Save Format Version
☒ Latest (Four) ☐ Three
☐ Two

Scale or Shift All Input Points
 Latitude Shift (Degrees) 0.000 Magnitude Scalar 1.000 Stretch Scalar 1.000
 Longitude Shift (Degrees) 0.000 Shift, Scale and or Stretch all Time Point Grid Values

Time Points (Select Point to Preview)

	Time Offset, Seconds	Maximum Electric Field, V/km	Maximum Electric Field Longitude	Maximum Electric Field Angle Latitude	Save in File	Date/Time
1	0.000	0.010	-93.6909	27.1638	YES	1/1/1970 12:0
2	0.103	0.010	-107.8630	26.6185	YES	1/1/1970 12:0
3	0.201	0.010	-94.3803	27.5722	YES	1/1/1970 12:0
4	0.303	0.010	-99.9007	36.8894	YES	1/1/1970 12:0
5	0.408	0.013	-97.1812	31.8141	YES	1/1/1970 12:0
6	0.508	0.021	-97.2638	31.8948	YES	1/1/1970 12:0
7	0.608	0.030	-97.1252	32.3135	YES	1/1/1970 12:0
8	0.708	0.040	-97.0105	31.8003	YES	1/1/1970 12:0
9	0.808	0.052	-96.8250	31.8590	YES	1/1/1970 12:0
10	0.908	0.066	-96.7756	32.2848	YES	1/1/1970 12:0
11	1.008	0.082	-96.7756	32.2848	YES	1/1/1970 12:0
12	1.108	0.099	-97.2164	32.3208	YES	1/1/1970 12:0
13	1.208	0.117	-97.3324	32.1454	YES	1/1/1970 12:0
14	1.308	0.137	-96.7014	32.0939	YES	1/1/1970 12:0
15	1.408	0.159	-96.7014	32.0939	YES	1/1/1970 12:0
16	1.508	0.182	-97.0865	31.8805	YES	1/1/1970 12:0
17	1.608	0.207	-96.8554	32.3907	YES	1/1/1970 12:0
18	1.708	0.234	-97.2552	31.9719	YES	1/1/1970 12:0
19	1.808	0.262	-97.2552	31.9719	YES	1/1/1970 12:0
20	1.908	0.292	-97.2054	32.4192	YES	1/1/1970 12:0
21	2.008	0.323	-96.9069	31.9436	YES	1/1/1970 12:0
22	2.108	0.356	-96.8068	32.0170	YES	1/1/1970 12:0
23	2.208	0.389	-96.8068	32.0170	YES	1/1/1970 12:0
24	2.308	0.426	-97.1644	31.9646	YES	1/1/1970 12:0
25	2.408	0.463	-97.0778	31.9576	YES	1/1/1970 12:0
26	2.508	0.503	-97.0153	32.5081	YES	1/1/1970 12:0
27	2.608	0.543	-96.7969	32.1019	YES	1/1/1970 12:0
28	2.708	0.586	-96.9304	32.5012	YES	1/1/1970 12:0
29	2.808	0.629	-97.1938	32.5225	YES	1/1/1970 12:0
30	2.908	0.673	-97.4128	32.3363	YES	1/1/1970 12:0
31	3.008	0.721	-96.7865	32.1911	YES	1/1/1970 12:0
32	3.108	0.770	-97.2463	32.0528	YES	1/1/1970 12:0
33	3.201	0.815	-96.7756	32.2848	YES	1/1/1970 12:0
34	3.303	0.868	-97.2898	32.5301	YES	1/1/1970 12:0
35	3.401	0.920	-97.1553	32.0456	YES	1/1/1970 12:0

Time Point Grid Preview (First Entry is the Eastward Value, the Second the Northward)

	Longitude	Latitude	Distance to Station (km)	Electric Field East, V/km	Electric Field North, V/km	Electric Field Magnitude, V/km	Electric Field Angle, Degrees	Data Quality
369	-110.4745	33.6330	-1.0000	0.0014	0.0099	0.0100	8.1672	0
370	-110.4697	33.4940	-1.0000	0.0013	0.0099	0.0100	7.4771	0
371	-110.4652	33.3616	-1.0000	0.0012	0.0099	0.0100	6.8183	0
372	-110.4609	33.2355	-1.0000	0.0011	0.0099	0.0100	6.1897	0
373	-110.4568	33.1154	-1.0000	0.0010	0.0100	0.0100	5.5902	0
374	-110.4529	33.0011	-1.0000	0.0009	0.0099	0.0100	5.0000	0
375	-110.4492	32.8922	-1.0000	0.0008	0.0099	0.0100	4.4111	0
376	-110.4457	32.7885	-1.0000	0.0007	0.0099	0.0100	3.8222	0
377	-110.4424	32.6897	-1.0000	0.0006	0.0099	0.0100	3.2333	0
378	-110.4392	32.5956	-1.0000	0.0005	0.0099	0.0100	2.6444	0
379	-110.4362	32.5060	-1.0000	0.0004	0.0099	0.0100	2.0555	0
380	-110.4333	32.4207	-1.0000	0.0004	0.0099	0.0100	1.4666	0
381	-110.4306	32.3394	-1.0000	0.0003	0.0099	0.0100	0.8777	0
382	-110.4280	32.2620	-1.0000	0.0002	0.0099	0.0100	0.2888	0
383	-110.4255	32.1883	-1.0000	0.0002	0.0099	0.0100	-0.3000	0
384	-110.4231	32.1164	-1.0000	0.0001	0.0099	0.0100	-0.8888	0
385	-110.4207	32.0427	-1.0000	0.0000	0.0099	0.0100	-1.4777	0
386	-110.4181	31.9653	-1.0000	-0.0000	0.0099	0.0100	-2.0666	0
387	-110.4154	31.8840	-1.0000	-0.0001	0.0099	0.0100	-2.6555	0
388	-110.4126	31.7987	-1.0000	-0.0002	0.0099	0.0100	-3.2444	0
389	-110.4096	31.7091	-1.0000	-0.0003	0.0099	0.0100	-3.8333	0
390	-110.4065	31.6150	-1.0000	-0.0003	0.0099	0.0100	-4.4222	0
391	-110.4033	31.5162	-1.0000	-0.0004	0.0099	0.0100	-5.0111	0
392	-110.3999	31.4125	-1.0000	-0.0005	0.0099	0.0100	-5.6000	0
393	-110.3963	31.3036	-1.0000	-0.0006	0.0099	0.0100	-6.1888	0
394	-110.3926	31.1892	-1.0000	-0.0007	0.0099	0.0100	-6.7777	0
395	-110.3886	31.0692	-1.0000	-0.0008	0.0099	0.0100	-7.3666	0
396	-110.3845	30.9431	-1.0000	-0.0009	0.0099	0.0100	-7.9555	0
397	-110.3802	30.8107	-1.0000	-0.0010	0.0099	0.0100	-8.5444	0
398	-110.3758	30.6717	-1.0000	-0.0011	0.0099	0.0100	-9.1333	0
399	-110.3710	30.5258	-1.0000	-0.0013	0.0099	0.0100	-9.7222	0
400	-110.3661	30.3725	-1.0000	-0.0014	0.0099	0.0100	-10.3111	0
401	-110.3610	30.2116	-1.0000	-0.0015	0.0099	0.0100	-10.9000	0
402	-110.3557	30.0468	-1.0000	-0.0017	0.0099	0.0100	-11.4888	0
403	-110.3504	29.8819	-1.0000	-0.0018	0.0098	0.0100	-12.0777	0
404	-110.3452	29.7171	-1.0000	-0.0019	0.0098	0.0100	-12.6666	0

Save Setting to Aux Load AUX Supplemental File Options Clear All GIC Input Fields

The b3d file used here is entirely fictional; it is used for demonstration purposes and is not meant to be realistic

Assumed HEMP is Specified in a B3D File



- There are a number of options and commands available on the Field/Voltage Input page to interact with the b3d input
 - **Setup Time-Varying Series on Load** which maps the b3d data to the transmission line voltages used in the stability simulation
 - **Save Non-uniform Fields in PWB file** which stores the data in the pwb file, avoiding the need for a separate b3d file
 - **Input Summary** summarizes the file contents
 - **Saved Selected Time Points in B3D Format** allows a subset of the time points to be stored in a new file
 - **Scale or Shift All Input Points** scales and/or shifts the electric field input data
 - **Setup Time Varying Series** can be used to manually setup the transmission line voltages

Assumed HEMP is Specified in a B3D File

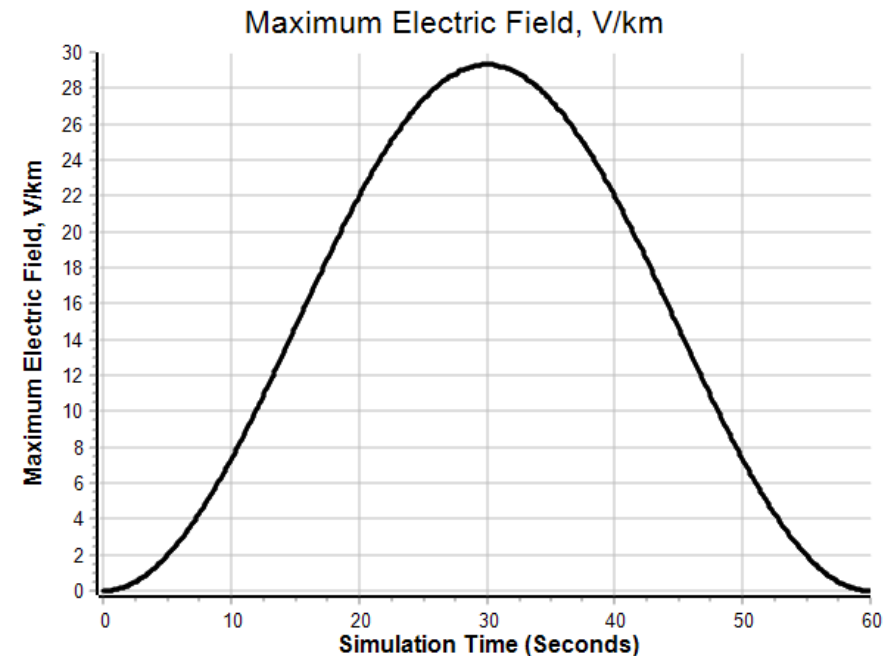
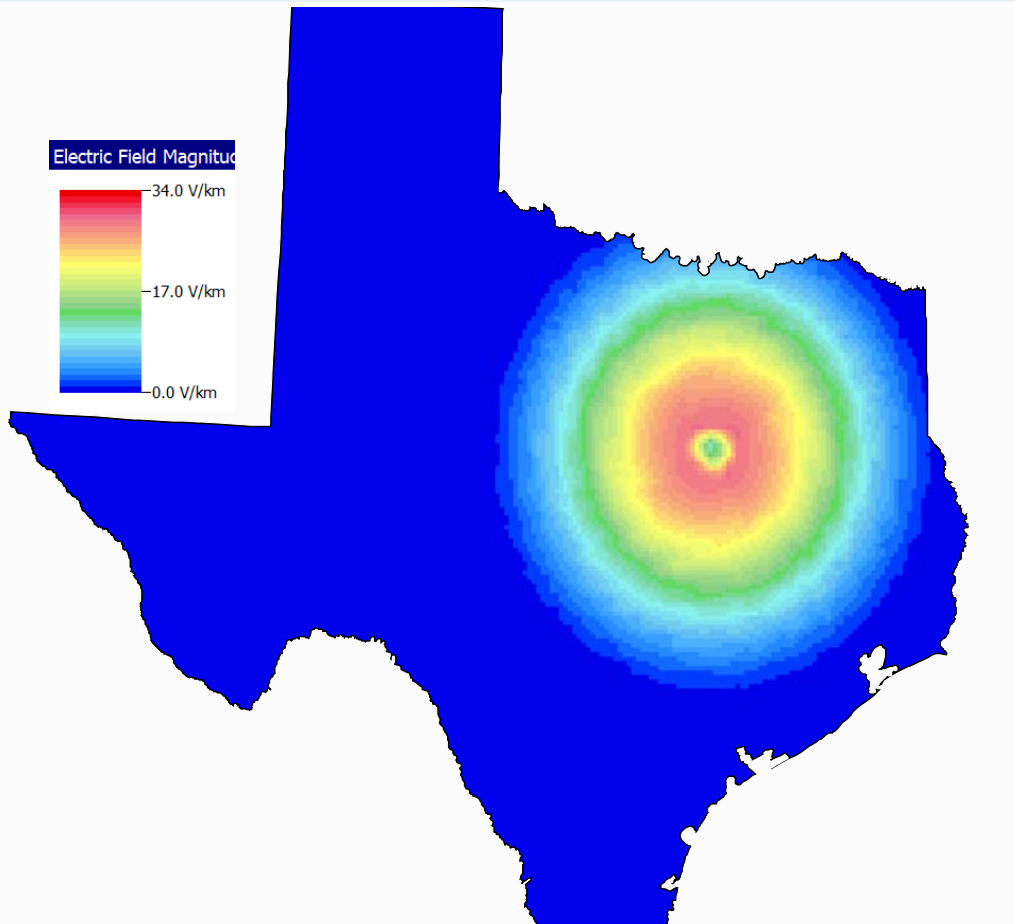


- The **Time Points** and **Time Point Grid Preview** grids can be used to get detailed information about the electric field input
- The **Time Points** grid can be used to easily contour any time point
 - Select the desired time point
 - One the desired oneline right-click and select **Contouring**
 - For the **Contour Type** select **Spatial Data** and then set the field to **Electric Field Magnitude, V/km**
 - Select **OK** or **Recalculate Contour**
 - The contour can be updated by selecting other time points
 - The easy creation of movies is covered later.

Example Electric Field Input



The initial electric field variation has a maximum of 30 V/km. Again, this is an entirely fictional waveform just to demonstrate the approach.



Viewing the Stability Input Electric Fields



- If desired, to see the stability input electric fields, on the GIC Form select the **Time Varying Series Voltage Inputs**
 - If desired this data can be loaded from a csv or aux file but usually it will be created from b3d input
 - Viewing this page is not required to do a study

Field/Voltage Input																	
AC Line Input Voltages Substation EField V/km (Display Only) Substation EField Direction Degrees (Display Only)																	
	Branch ID	From Number	To Number	Circuit	From Latitude	To Latitude	From Longitude	To Longitude	Distance Between Substations (km)	Timepoint_1	Timepoint_2	Timepoint_3	Timepoint_4	Timepoint_5	Timepoint_6	Timepoint_7	Timepoint_8
1	Time in Seconds									0.000	0.103	0.201	0.303	0.408	0.508	0.608	0.708
2	Branch '1001' '1064' '1'	1001	1064	1	31.9067	32.0011	-102.2623	-102.3124	11.49	0.105	0.105	0.105	0.105	0.106	0.106	0.106	0.106
3	Branch '1001' '1064' '2'	1001	1064	2	31.9067	32.0011	-102.2623	-102.3124	11.49	0.105	0.105	0.105	0.105	0.106	0.106	0.106	0.106
4	Branch '1001' '1071' '1'	1001	1071	1	31.9067	31.8403	-102.2623	-102.3264	9.54	-0.072	-0.072	-0.072	-0.072	-0.071	-0.071	-0.071	-0.071
5	Branch '1001' '1071' '2'	1001	1071	2	31.9067	31.8403	-102.2623	-102.3264	9.54	-0.072	-0.072	-0.072	-0.072	-0.071	-0.071	-0.071	-0.071
6	Branch '1002' '1007' '1'	1002	1007	1	29.8880	31.0935	-104.5191	-104.6245	134.02	1.323	1.323	1.322	1.322	1.322	1.321	1.321	1.321
7	Branch '1010' '1002' '1'	1010	1002	1	29.6000	29.8880	-104.3000	-104.5191	38.33	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.373
8	Branch '1004' '1003' '1'	1004	1003	1	32.9264	32.9264	-101.6478	-101.6478	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	Branch '1022' '1003' '1'	1022	1003	1	32.9290	32.9264	-101.5786	-101.6478	6.48	-0.018	-0.018	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017
10	Branch '1055' '1003' '1'	1055	1003	1	32.9270	32.9264	-101.7644	-101.6478	10.91	0.024	0.024	0.024	0.023	0.023	0.023	0.023	0.022
11	Branch '1004' '3133' '1'	1004	3133	1	32.9264	32.7471	-101.6478	-100.9547	67.87	-0.049	-0.051	-0.052	-0.054	-0.056	-0.058	-0.059	-0.061
12	Branch '1006' '1005' '1'	1006	1005	1	32.2075	32.2075	-101.3883	-101.3883	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
13	Branch '1025' '1005' '1'	1025	1005	1	32.0390	32.2075	-101.2200	-101.3883	24.52	0.181	0.182	0.182	0.183	0.183	0.184	0.184	0.185
14	Branch '1005' '1061' '1'	1005	1061	1	32.2075	32.2732	-101.3883	-101.4224	7.96	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071
15	Branch '1067' '1005' '1'	1067	1005	1	32.1029	32.2075	-101.3654	-101.3883	11.80	0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.115
16	Branch '1007' '1015' '1'	1007	1015	1	31.0935	30.2853	-104.6245	-104.0058	107.44	-0.998	-0.998	-0.999	-0.999	-1.000	-1.001	-1.001	-1.002
17	Branch '1031' '1007' '1'	1031	1007	1	31.0050	31.0935	-103.7591	-104.6245	83.19	0.223	0.225	0.226	0.227	0.228	0.230	0.231	0.232
18	Branch '1009' '1008' '1'	1009	1008	1	30.9315	30.9315	-102.2014	-102.2014	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
19	Branch '1008' '1032' '1'	1008	1032	1	30.9315	31.2092	-102.2014	-102.2417	31.03	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309
20	Branch '1008' '1069' '1'	1008	1069	1	30.9315	30.9178	-102.2014	-102.0867	11.07	-0.041	-0.041	-0.041	-0.041	-0.042	-0.042	-0.042	-0.042
21	Branch '1011' '1010' '1'	1011	1010	1	29.6000	29.6000	-104.3000	-104.3000	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	Branch '1010' '1015' '1'	1010	1015	1	29.6000	30.2853	-104.3000	-104.0058	81.10	0.631	0.630	0.629	0.628	0.628	0.627	0.626	0.625
23	Branch '1010' '1030' '1'	1010	1030	1	29.6000	29.8021	-104.3000	-103.2224	106.67	-0.174	-0.176	-0.177	-0.179	-0.181	-0.182	-0.184	-0.186
24	Branch '1012' '1087' '1'	1012	1087	1	30.0281	30.5970	-101.9705	-101.7845	65.56	0.518	0.518	0.517	0.516	0.515	0.514	0.513	0.512
25	Branch '3051' '1012' '1'	3051	1012	1	29.8372	30.0281	-101.2124	-101.9705	76.18	0.527	0.528	0.529	0.530	0.531	0.532	0.533	0.535
26	Branch '1013' '1031' '1'	1013	1031	1	31.4846	31.0050	-103.1610	-103.7591	77.93	-0.450	-0.449	-0.448	-0.447	-0.445	-0.444	-0.443	-0.442
27	Branch '1047' '1013' '1'	1047	1013	1	31.5839	31.4846	-102.9633	-103.1610	21.77	-0.093	-0.092	-0.092	-0.092	-0.091	-0.091	-0.091	-0.090
28	Branch '1086' '1013' '1'	1086	1013	1	31.8035	31.4846	-103.5999	-103.1610	54.62	-0.380	-0.381	-0.382	-0.382	-0.383	-0.384	-0.384	-0.385

Running the HEMP Simulation



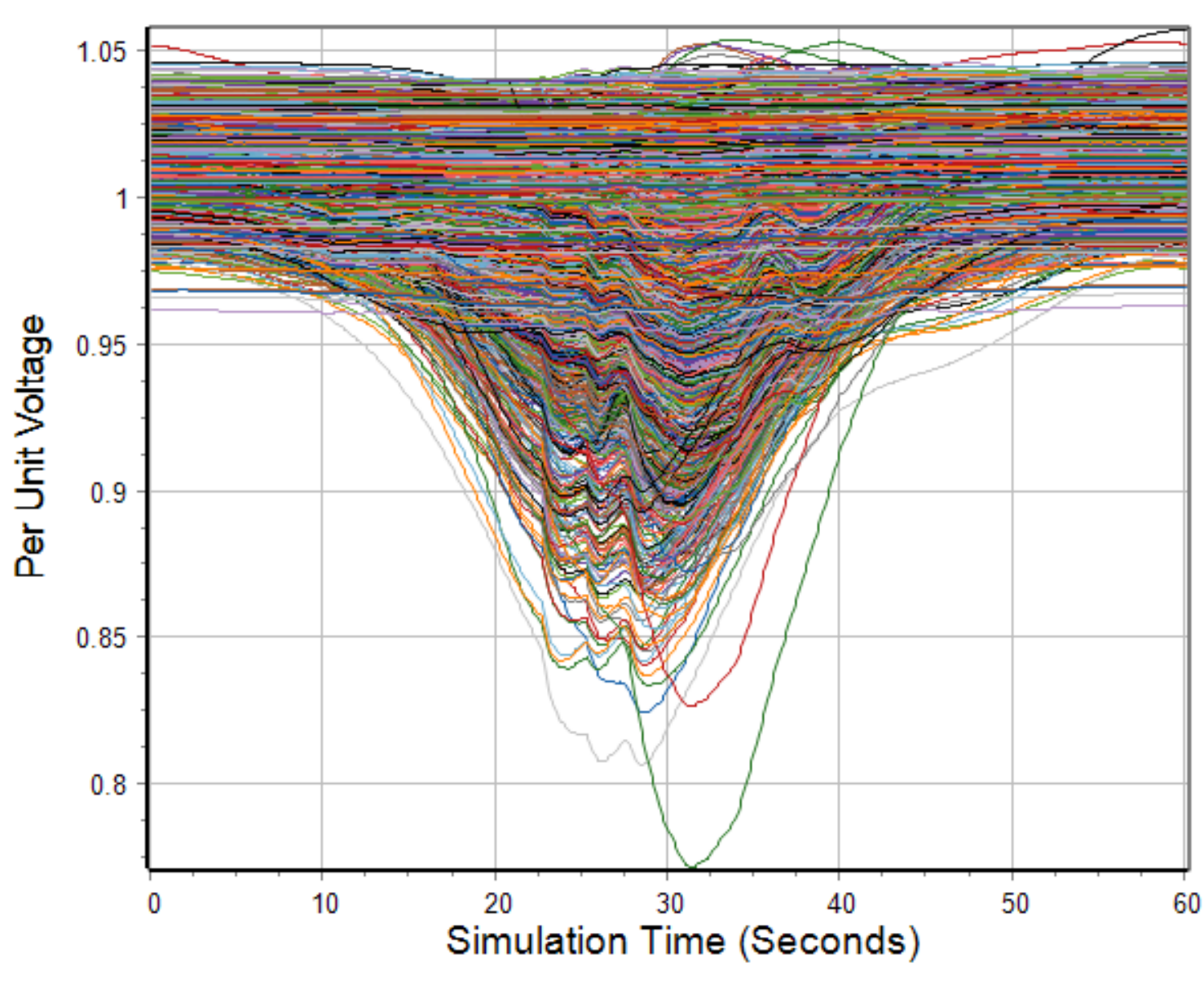
- Once the HEMP electric fields are defined, they are included in the stability simulation by just selecting, on the **GIC Analysis** form, **Include GIC in Power Flow and Transient Stability**
- On the **Transient Stability Analysis** Form be sure to select the desired fields to save
 - Usually they can be saved less often (say every 0.1 second)
 - If desired select the **Options, General, Store Full Power Flow State on Update** to store the power flow states (useful for later visualization)
- To run the simulation on the Transient Stability Analysis form just select **Run Transient Stability**
 - Usually run for the duration of the B3D file

Understanding the Results



- A key challenge after an EMP study is to understand the results, with an eye towards developing mitigation strategies
- Results include all of the stability results, along with the GIC related values
 - Many of the new PowerWorld visualization techniques can be leveraged to show the results, particularly when coupled with storage of the power flow states
- Looking at the **Results from RAM, Events** is usually a good place to start (and with the tested 30V/km waveform there were actually no protection system events)

2K Case Bus Voltage Variation



Using Stored Power Flow States to Create Visualizations

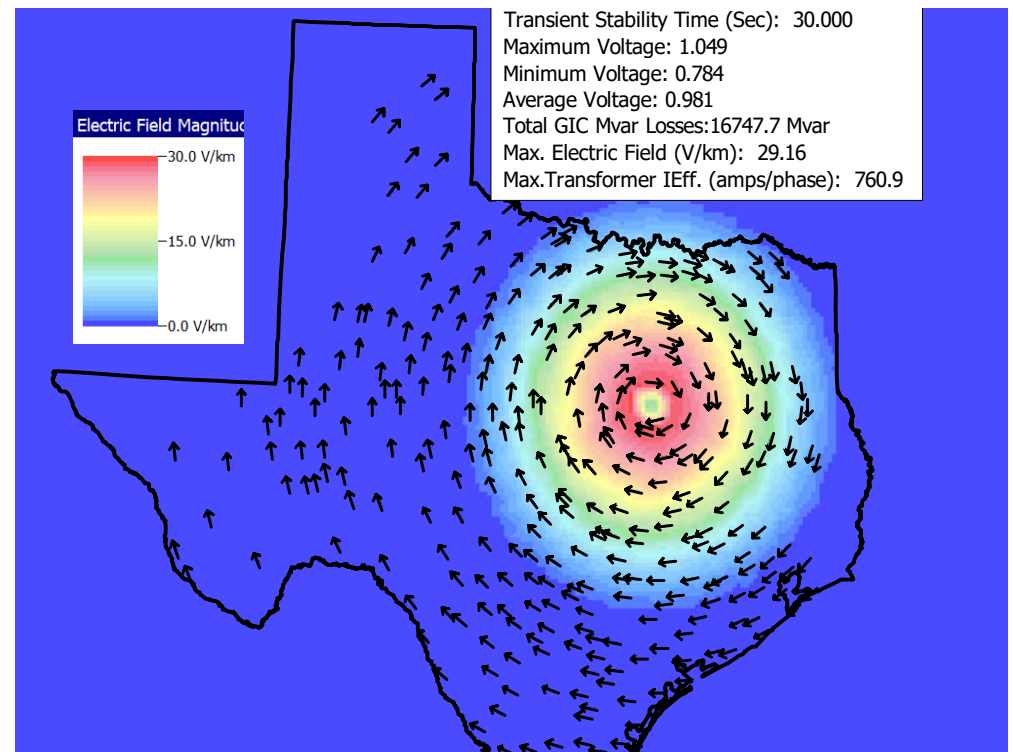
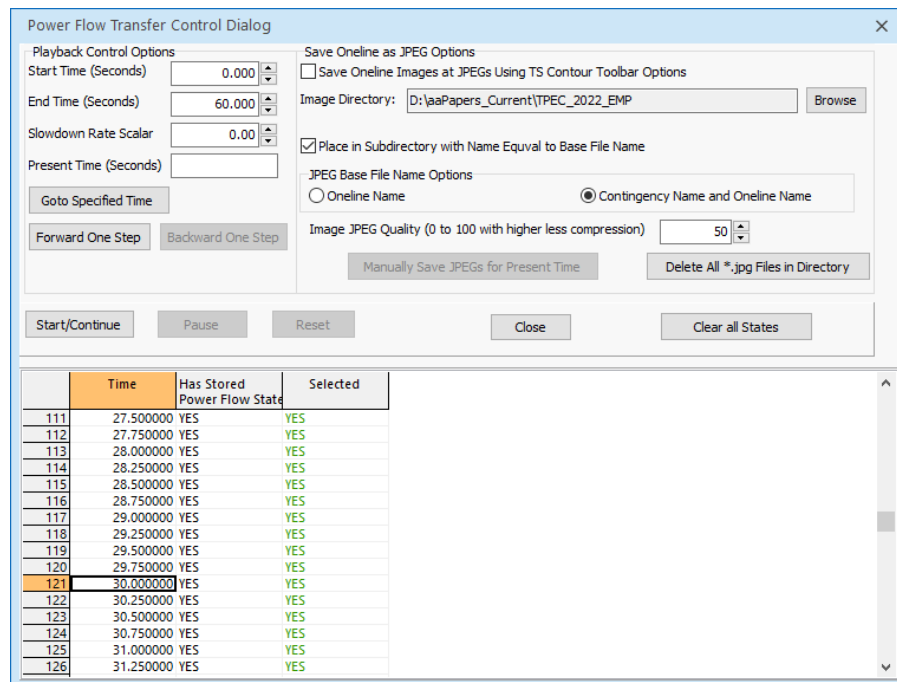


- With the stored power flow states and some of the new PowerWorld visualization techniques, it is straightforward to create movies and other ways to show the results
- As an example, to show the spatially varying input electric field and magnitude
 - Open the online **TSGC_Substations_Arrows** which has geographic data views (GDVs) for all the substations using an arrow symbol to show the electric field direction
 - Right-click and select **Contouring** and for the object type select **Spatial Data**.
- To view a specific time point in Transient Stability select **Results from RAM, Power Flow States**
 - Select the **Show Power Flow Transfer Control Dialog**

Using Stored Power Flow States to Create Visualizations



- Right-click on an individual time and select **Transfer State to Power Flow** to see one time; use the **Start/Continue** option to create image sequences for movies

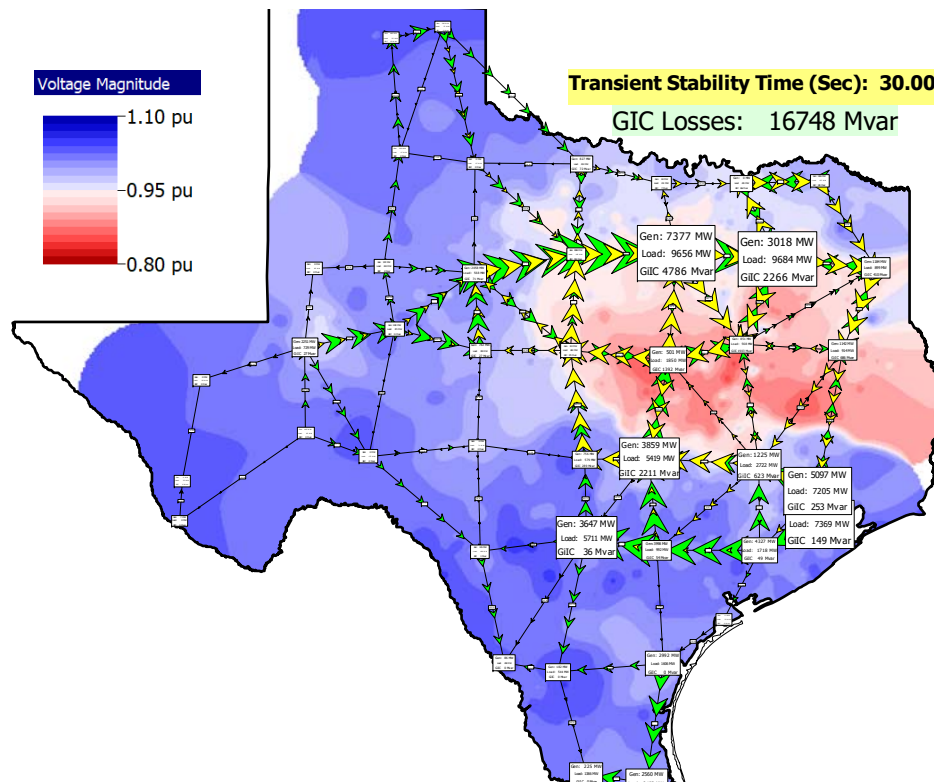


For this fictional waveform the vectors were set to rotate about the center

Visualizing GICs with MW Flows



- The online **Texas_GDV_Start_WithSubs_Grid8_8_MWFlows** combines a voltage contour with GDV summary objects and GDV line flow summary objects to show the overall system response



Increasing the Magnitude



- The magnitude and/or location of the HEMP can be scaled on the **GIC Analysis Form**
 - This is just an analysis technique; we are not implying this is correct from the physics of an HEMP

GIC Analysis Form

Calculation Mode
☐ Single Snapshot
☐ Time Varying Series Voltage Inputs
☒ Time Varying Electric Field Inputs
☐ Spatially Uniform Time-Varying E-Field

Calculate GIC Values Clear GIC Values ☒ Include GIC in Power Flow and Transient Stability Validate Input Data for GIC

Current Time 22.00 ☐ Calculate GIC on Time Change

Select Step
Field/Voltage Input

Field/Voltage Input
Non-uniform Electric Field Files (*.b3d, *.dat, *.json)
C:\AProjects_2022\PowerWorld_EMPTalk_Feb2022\Example_B3D.b3d Browse...

Options for Loading Multiple Files of Selected Type
☒ Just selected file
☐ All after last time in Time Points List
☐ All before first time in TimePoints List
☐ All files of selected type

Setup Time Varying Series Voltage Inputs
Start Time (Seconds) 1.65
End Time (Seconds) 119.95
Sampling Rate (Seconds) 0.00
Setup Time Varying Series
☒ Do All if Start and End Time = 0

Clear Existing Time Points or Merging
☒ Clear Existing
☐ Merge
☒ Setup Time-Varying Series on Load
☒ Save Non-uniform Fields in PWB File

Input Summary
Starting Time (Seconds) 1.65 Starting Latitude 18.71 Starting Longitude -111.32
Ending Time (Seconds) 119.95 Ending Latitude 43.86 Ending Longitude -80.51
Number of Time Points 1185 Number Data Points 23409
Interpolated Offset Time 0.000 View Interpolated Offset Time (Seconds) Starting Date and Time 1/1/1970 (UTC) Second Offset 0.000 ☐ Use Local Time Zone

Save Selected Time Points in B3D Format Clear All Time Points
B3D Save Format Version
☒ Latest (Four) ☐ Three
☐ Two

Scale or Shift All Input Points
Latitude Shift (Degrees) 0.000 Magnitude Scalar 2.500 Stretch Scalar 1.000
Longitude Shift (Degrees) 0.000
Shift, Scale and or Stretch all Time Point Grid Values

Time Points (Select Point to Preview)

	Time Offset, Seconds	Maximum Electric Field V/km	Maximum Electric Field Longitude	Maximum Electric Field Angle Latitude	Save in File	Date/Time
1	22.956	75.020	-97.6188	32.4515	YES	1/1/1970 12:0
2	22.856	75.008	-97.6188	32.4515	YES	1/1/1970 12:0
3	22.756	75.002	-97.6188	32.4515	YES	1/1/1970 12:0
4	23.056	75.000	-97.6188	32.4515	YES	1/1/1970 12:0
5	22.656	74.969	-97.6188	32.4515	YES	1/1/1970 12:0

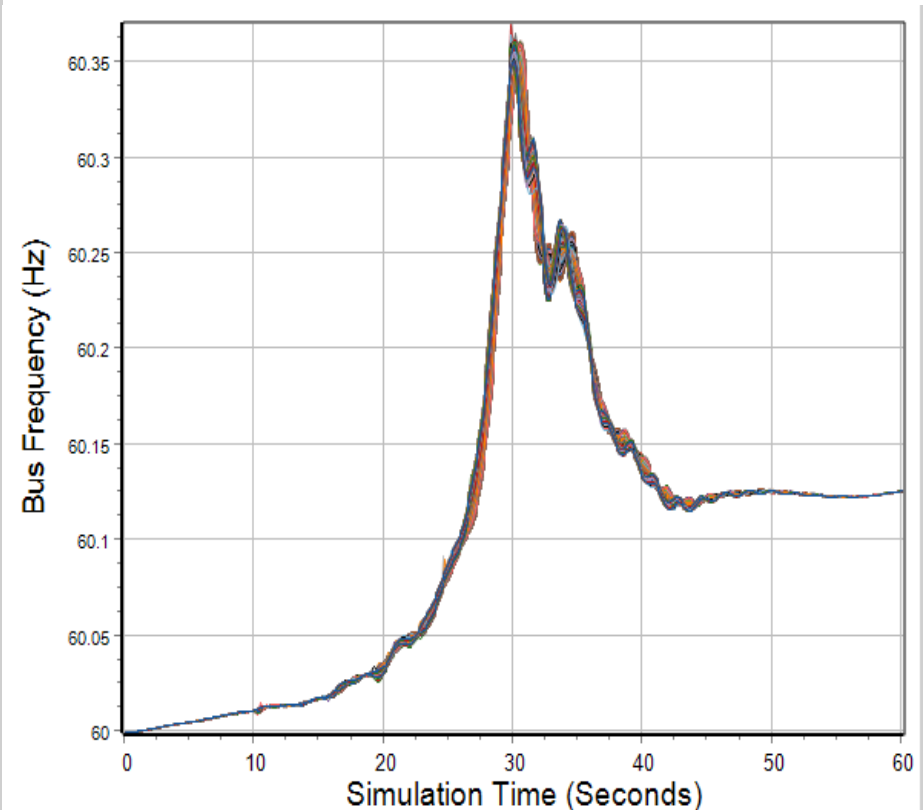
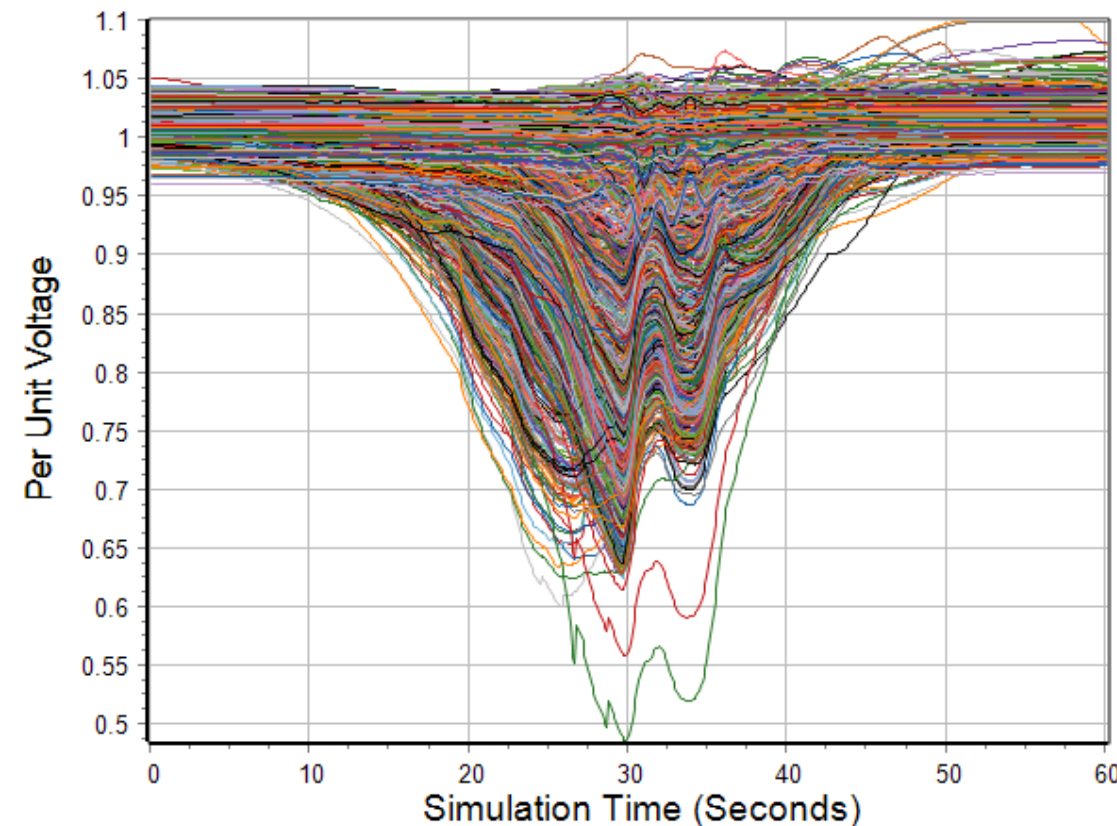
Time Point Grid Preview (First Entry is the Eastward Value, the Second the Northward)

	Longitude	Latitude	Distance to Station (km)	Electric Field East, V/km	Electric Field North, V/km	Electric Field Magnitude, V/km	Electric Field Angle, Degrees
1	-111.3249	43.8059	-1.0000	0.0011	0.0012	0.0016	42.5143
2	-111.3163	43.6411	-1.0000	0.0013	0.0014	0.0018	42.6039
3	-111.3079	43.4763	-1.0000	0.0014	0.0016	0.0021	42.4957
4	-111.2995	43.3115	-1.0000	0.0016	0.0018	0.0024	41.7132
5	-111.2911	43.1468	-1.0000	0.0018	0.0021	0.0028	40.3139

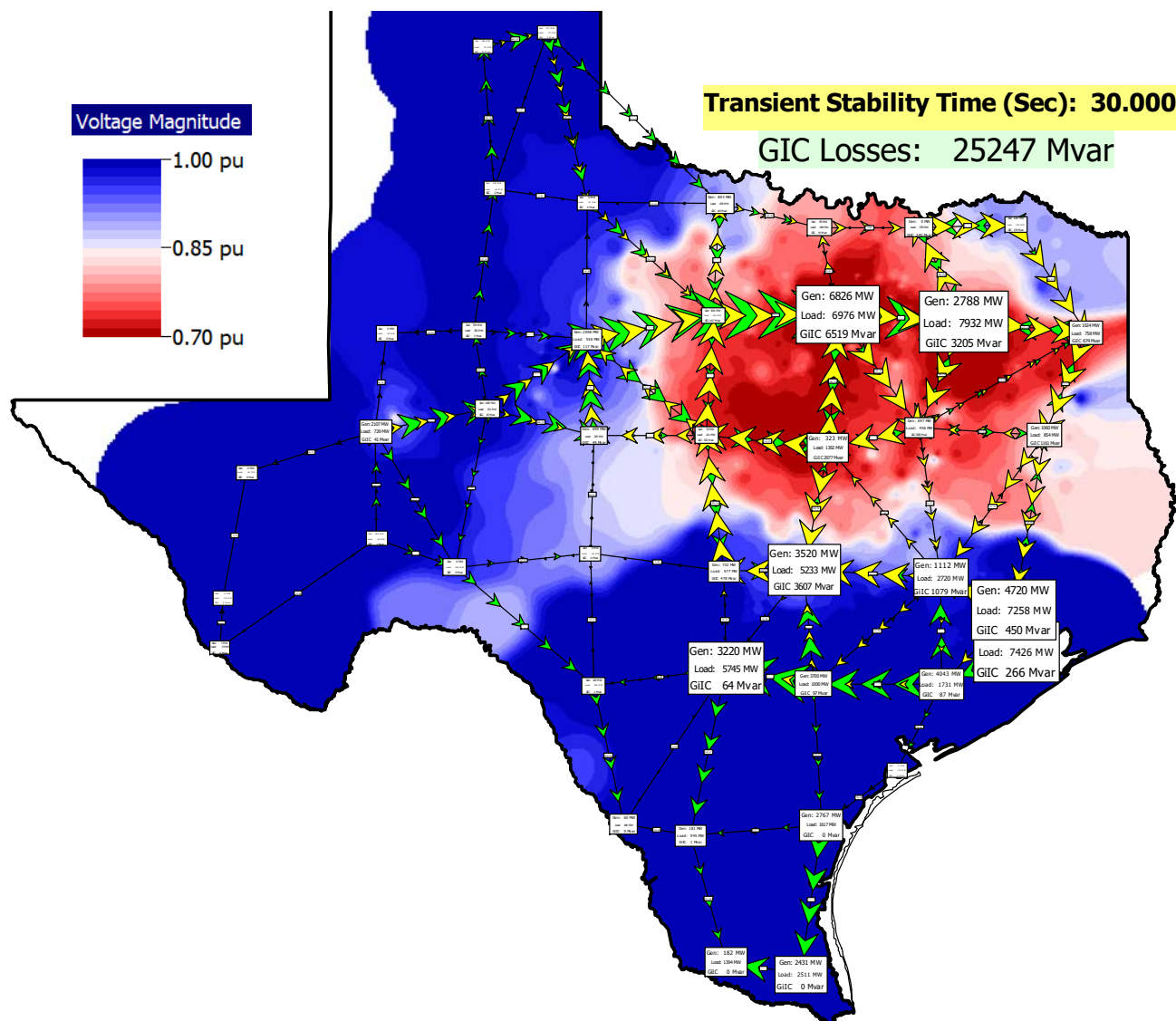
Results with Assumed Field Increased to Critical Point



- If the assumed field is scaled to 52 V/km the voltages and frequencies are as given below
 - When a b3d file is scaled, it should either be stored as a separate file or stored with the *.pwb



Voltage Contour Assumed Field Increased to Critical Point

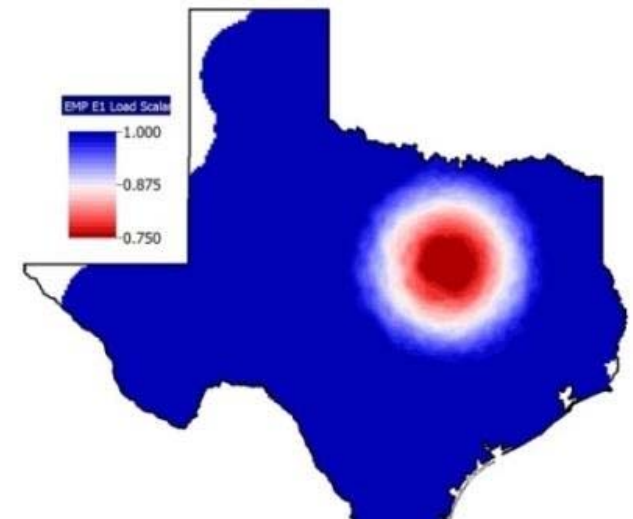


Note the wide contour color scale

Including E1 Impacts



- The E3 would be preceded by an E1. This impact of the E1 would be considered as modified initial conditions for the E3
 - Impacts could include lost system components including load and/or changes to the protection system
- PowerWorld currently has a very simple method for modeling load that might be lost as a result of an E1
 - A spatially varying percentage of the load is removed
 - Lost load causes an initial increase in system frequency and can actually be helpful in reducing the likelihood of a voltage collapse



Including E1 Impacts



GIC Analysis Form

- Calculation Mode
- ☐ Single Snapshot
 - ☒ Time Varying Series Voltage Inputs
 - ☐ Time Varying Electric Field Inputs
 - ☐ Spatially Uniform Time-Varying E-Field

Calculate GIC Values

Clear GIC Values

☒ Include GIC in Power Flow and Transient Stability

Validate Input Data for GIC

Current Time

30.00

☐ Calculate GIC on Time Change

Select Step

Field/Voltage Input

- Options
 - DC Current Calculation
 - AC Power Flow Model

Tables and Results

- Areas
- Buses
- Generators
- DC Lines
- Lines
- Line Shunts
- Loads
- Switched Shunts
- Substations
- Transformers
- Multi-Section Lines
- System Summary
- G-Matrix
- Multi-Terminal DC Lines
- VSC DC Lines
- Sensitivity Analysis
- Non-Uniform Electric Field Sc
 - Geomagnetic Latitude Sc
 - Earth Resistivity Scaling
 - Earth Resistivity Scaling

Field/Voltage Input

AC Line Input Voltages		Substation EField V/km (Display Only)		Substation EField Direction Degrees (Display Only)											
Branch ID	From Number	To Number	Circuit	From Latitude	To Latitude	From Longitude	To Longitude	Distance Between Substations (km)	Timepoint_1	Timepoint_2	Timepoint_3	Timepoint_4	Timepoint_5	Timepoint_6	Timepoint_7
1 Time in Seconds									0.000	0.103	0.201	0.303	0.408	0.508	
2 Branch '1001' '1064' '1'	1001	1064	1	31.9067	32.0011	-102.2623	-102.3124	11.49	0.186	0.186	0.186	0.186	0.187	0.187	
3 Branch '1001' '1064' '2'	1001	1064	2	31.9067	32.0011	-102.2623	-102.3124	11.49	0.186	0.186	0.186	0.186	0.187	0.187	
4 Branch '1001' '1071' '1'	1001	1071	1	31.9067	31.8403	-102.2623	-102.3264	9.54	-0.127	-0.127	-0.127	-0.126	-0.126	-0.126	
5 Branch '1001' '1071' '2'	1001	1071	2	31.9067	31.8403	-102.2623	-102.3264	9.54	-0.127	-0.127	-0.127	-0.126	-0.126	-0.126	
6 Branch '1002' '1007' '1'	1002	1007	1	29.8880	31.0935	-104.5191	-104.6245	134.02	2.338	2.337	2.337	2.336	2.336	2.335	
7 Branch '1010' '1002' '1'	1010	1002	1	29.6000	29.8880	-104.3000	-104.5191	38.33	0.657	0.657	0.657	0.657	0.658	0.658	
8 Branch '1004' '1003' '1'	1004	1003	1	32.9264	32.9264	-101.6478	-101.6478	0.00	0.000	0.000	0.000	0.000	0.000	0.000	
9 Branch '1022' '1003' '1'	1022	1003	1	32.9290	32.9264	-101.5786	-101.6478	6.48	-0.031	-0.031	-0.031	-0.031	-0.030	-0.030	
10 Branch '1055' '1003' '1'	1055	1003	1	32.9270	32.9264	-101.7644	-101.6478	10.91	0.042	0.042	0.042	0.041	0.041	0.040	
11 Branch '1004' '3133' '1'	1004	3133	1	32.9264	32.7471	-101.6478	-100.9547	67.87	-0.086	-0.089	-0.092	-0.096	-0.099	-0.102	
12 Branch '1006' '1005' '1'	1006	1005	1	32.2075	32.2075	-101.3883	-101.3883	0.00	0.000	0.000	0.000	0.000	0.000	0.000	
13 Branch '1025' '1005' '1'	1025	1005	1	32.0390	32.2075	-101.2200	-101.3883	24.52	0.321	0.321	0.322	0.323	0.324	0.325	
14 Branch '1005' '1061' '1'	1005	1061	1	32.2075	32.2732	-101.3883	-101.4224	7.96	0.125	0.125	0.125	0.125	0.126	0.126	
15 Branch '1067' '1005' '1'	1067	1005	1	32.1029	32.2075	-101.3654	-101.3883	11.80	0.203	0.203	0.203	0.204	0.204	0.204	
16 Branch '1007' '1015' '1'	1007	1015	1	31.0935	30.2853	-104.6245	-104.0058	107.44	-1.763	-1.764	-1.765	-1.766	-1.767	-1.768	
17 Branch '1031' '1007' '1'	1031	1007	1	31.0050	31.0935	-103.7591	-104.6245	83.19	0.394	0.397	0.399	0.401	0.404	0.406	
18 Branch '1009' '1008' '1'	1009	1008	1	30.9315	30.9315	-102.2014	-102.2014	0.00	0.000	0.000	0.000	0.000	0.000	0.000	
19 Branch '1008' '1032' '1'	1008	1032	1	30.9315	31.2092	-102.2014	-102.2417	31.03	0.546	0.546	0.546	0.546	0.546	0.546	
20 Branch '1008' '1069' '1'	1008	1069	1	30.9315	30.9178	-102.2014	-102.0867	11.07	-0.072	-0.072	-0.073	-0.073	-0.074	-0.074	
21 Branch '1011' '1010' '1'	1011	1010	1	29.6000	29.6000	-104.3000	-104.3000	0.00	0.000	0.000	0.000	0.000	0.000	0.000	
22 Branch '1010' '1015' '1'	1010	1015	1	29.6000	30.2853	-104.3000	-104.0058	81.10						1.108	
23 Branch '1010' '1030' '1'	1010	1030	1	29.6000	29.8021	-104.3000	-103.2224	106.67						-0.322	
24 Branch '1012' '1087' '1'	1012	1087	1	30.0281	30.5970	-101.9705	-101.7845	65.56						0.909	
25 Branch '3051' '1012' '1'	3051	1012	1	29.8372	30.0281	-101.2124	-101.9705	76.18						0.941	
26 Branch '1013' '1031' '1'	1013	1031	1	31.4846	31.0050	-103.1610	-103.7591	77.93						-0.785	
27 Branch '1047' '1013' '1'	1047	1013	1	31.5839	31.4846	-102.9633	-103.1610	21.77						-0.161	
28 Branch '1086' '1013' '1'	1086	1013	1	31.8035	31.4846	-103.5999	-103.1610	54.62						-0.678	
29 Branch '1014' '1047' '1'	1014	1047	1	31.1695	31.5839	-103.0851	-102.9633	47.38						0.778	

GMD EMP EMP E1 EMP Grid Analysis

E1 Input Fields

☒ Include E1 Effects as Initial Conditions

Input Type

☒ Simple Concentric Circles

Circular Input Fields

Latitude of Center

32.000

Longitude of Center

-97.400

Diameter (km)

400.0

Maximum Percent Lost Load

25.00

Maximum Percent Diameter (km)

100.00

Results

Potential Lost Load (MW)

2824.70

Potential Lost Load (Mvar)

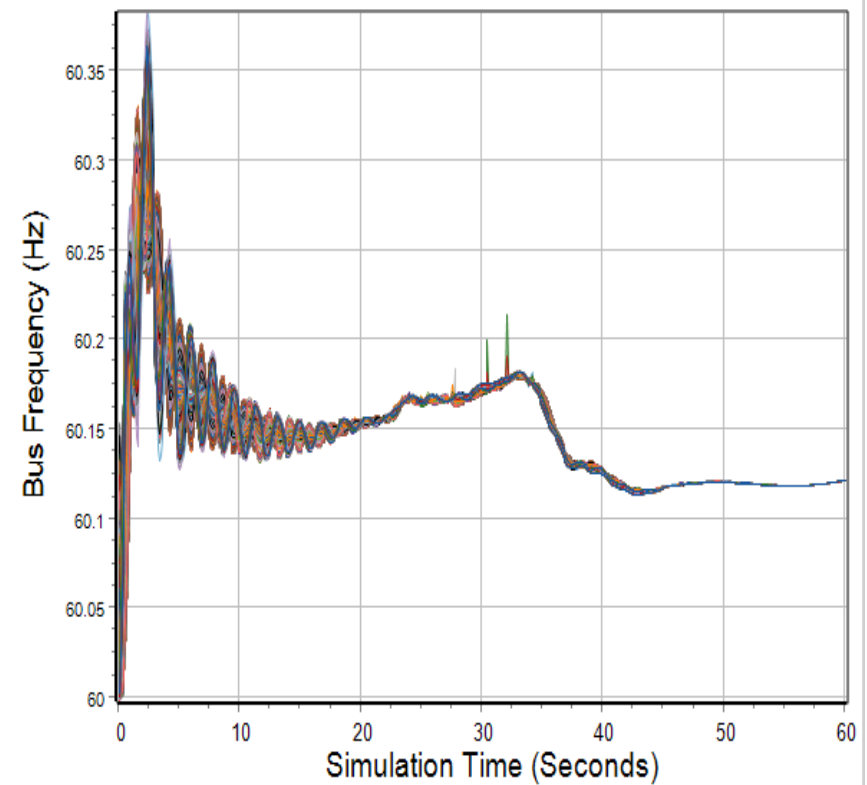
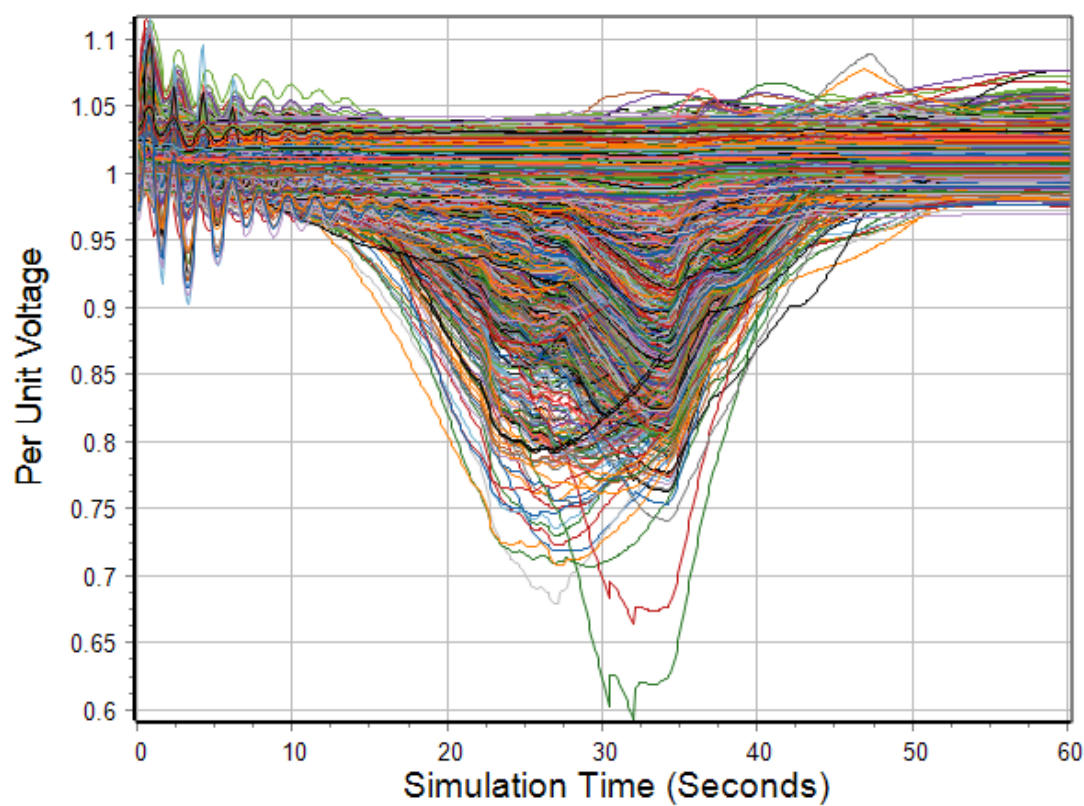
1188.01

☐ Automatically Update Fields

Update EMP E1 Lost Load Fields

Including the initial load drop is, of course, totally optional

Results with Assumed Field Increased to Critical Point with E1 Impacts



Impact of the Assumed Load Models



- The assumed load model has an impact on the results
- The previous examples used the widely available, but also quite detailed, composite load model
 - There are 130 parameters per load
- Simpler load models could be used, particularly when doing initial screenings to determine maximum tolerable values

Dealing with More Stressed Scenarios



- If the assumed electric field is too large in an actual grid the protection system should hopefully isolate the disturbance
 - Much of this will hopefully be done by the distance relays
 - The generator over excitation limits also need to be considered
- Currently most standard stability cases do not include much in terms of distance relays
- We are working on testing various solutions to address this issue

Automating the Process



- The previous slides provide the detailed procedures to setup individual studies
- Once the initial studies have been done, much of this analysis can be automated, allowing for parallel simulations to consider lots of different conditions
- An important value is knowing the maximum tolerable electric field; in at least some situations we anticipate that the impact will be minor
 - As an example, apps.dtic.mil/sti/pdfs/AD1082958.pdf presents some examples in which the maximum electric field is below 2V/km, a value much below what is commonly studied in GMD analysis

Developing Mitigation Plans



- Like other aspects of the grid HEMP mitigation plans need to strike a balance between cost and benefit
- HEMPs do certainly present some unique challenges since there is great uncertainty in their likelihood and impact
- Some mitigation plan assumptions
 - An HEMP could occur with little or no warning
 - The size and location of the HEMP would not be known a priori
 - Given their unique characteristics, an automatic system could be setup to determine within seconds if one has occurred
 - Given the time frame operator intervention cannot be assumed
 - Measurements could be available during the event
 - With a time frame of seconds, automatic EMS control could occur
 - Tools are now available to help engineers develop plans

Developing Mitigation Plans



- An HEMP mitigation plan needs to be able to quickly differentiate between small events, which do not need mitigation, and severe events in which heroic action is needed to save potentially an entire interconnect
 - Cascading events could also occur, in which operator intervention might be possible
- Any mitigation plan is going to be system specific, and needs to be robust to different HEMPs waveforms (e.g., magnitude, location)
- Some general thoughts are 1) adaptive islanding, 2) rapid load shedding, 3) pre-programmed transmission and generator switching
 - Spreading out the GICs could be helpful; transformers are not equal

A Possible Approach to Plan Development



- In testing various mitigation options, what I like to do is
 - Iteratively determine the critical electric field
 - Run the simulation to a stressed condition
 - Initialize the power flow at this location (easy to do in PowerWorld with the ability to store the power flow states during the stability simulation)
 - Test out various options
 - Repeat the simulation with the potential mitigation strategies
- This approach needs to be repeated over different assumed locations and electric field footprints
- The idea is to develop implementable rules of thumb
 - For example, if A and B and C then do D

PowerWorld Stability

Transfer to Power Flow Options



Transient Stability Analysis

Simulation Status: Not Initialized

Run Transient Stability | Pause | Abort | Restore Reference | For Contingency: Find | Tornado

Select Step

- Simulation
- Options
- Result Storage
- Plots
- Result Analyzer - Damping
- Results from RAM
 - Time Values
 - Minimum/Maximum Values
 - Summary
 - Events
 - Solution Details
 - Power Flow States
- Transient Limit Monitors
- States/Manual Control
- Validation
 - SMIB Eigenvalues
 - Modal Analysis
 - Dynamic Simulator Options

Options

Note: Changes made to option entries are saved immediately and will be applied during the next transient stability run.

General | Power System Model | Remedial Actions | Result Options | Generic Limit Monitors | User Defined Models | Distributed Computing | Transfer to Power Flow

Power Flow Modeling Options

Load ZIP Modeling

- ☒ Use Transient Stability Model
- ☐ Use Power Flow Model

Generator AVR Modeling

- ☐ Use Fixed Reactive Power Output
- ☒ Set Voltage Setpoints to Current Values, Expand Mvar Limits as Needed
- ☐ Set Voltage Setpoints to Current Values, Original Power Flow Limits
- ☐ Use Existing Power Flow Values

Generator and Area AGC Modeling

- ☐ Use Fixed MW Outputs and Original Area Interchange
- ☒ Change Area Interchange; Use Part. Factor Area Control; Expand MW Limits
- ☐ Change Area Interchange; Use Power Flow Area Control; Expand MW Limits
- ☐ Use Existing Power Flow Values Including Area Interchange

Discrete Switched Shunt Modeling

- ☒ Used Fixed Reactive Power Outputs
- ☐ Set Voltage Setpoints to Present Values
- ☐ Use Existing Power Flow Values

Continuous Switched Shunt and SVC Modeling

- ☐ Used Fixed Reactive Power Outputs
- ☒ Set Voltage Setpoints to Present Values
- ☐ Use Existing Power Flow Values

Transformer Taps

- ☒ Used Fixed LTC and Phase Shift Taps
- ☐ Set Setpoints to Present Values
- ☐ Use Existing Power Flow Values

Transformer Phase Shifter Taps

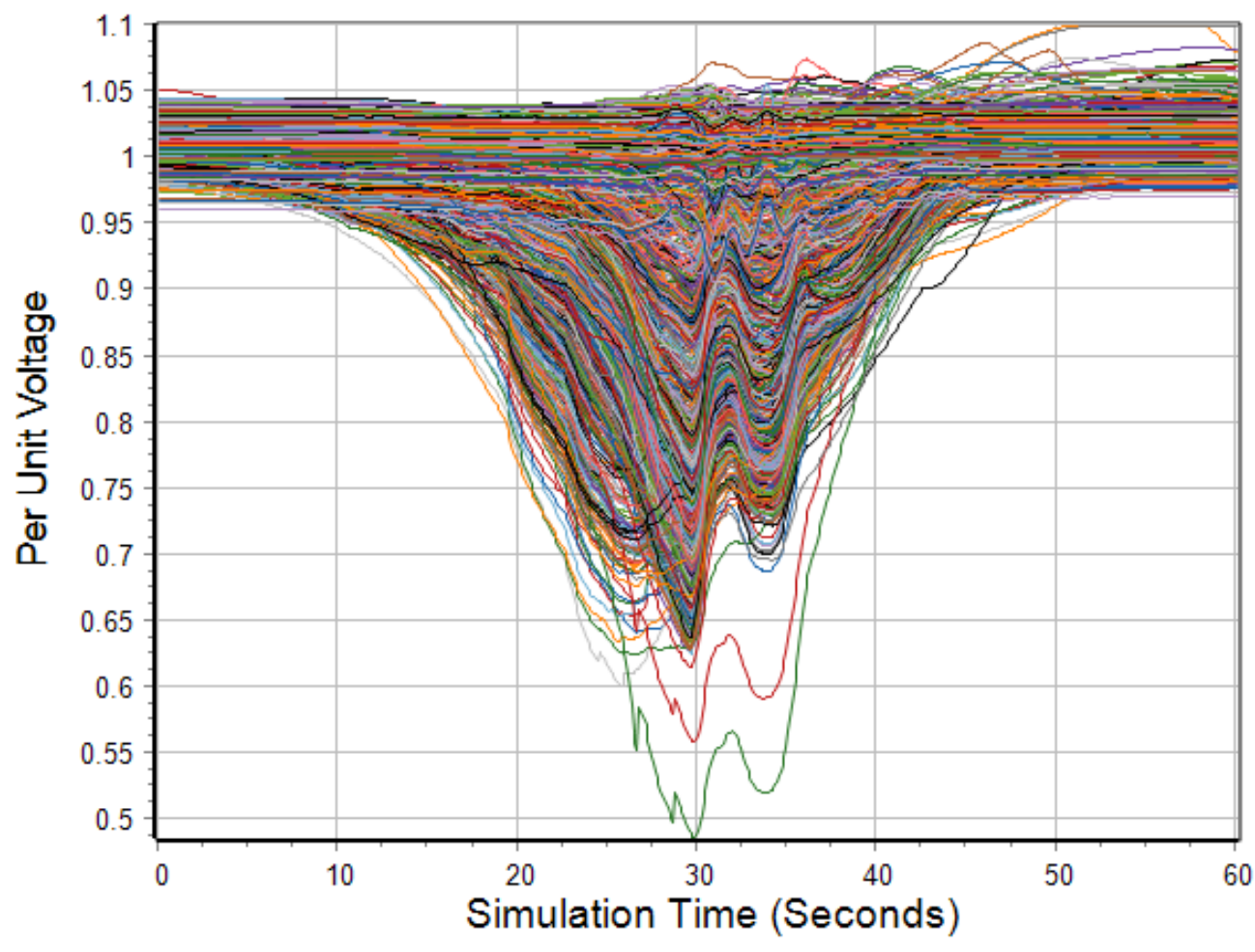
- ☒ Used Fixed Phase Shift Taps
- ☐ Set Setpoints to Present Values
- ☐ Use Existing Power Flow Values

This options specify how the transient stability result values are modeled in the power flow. This data can be transferred to the power flow either directly by using "Transfer Present State to Power Flow" or ☐ saving the data in a *.pwvfs file.

Mitigation Example

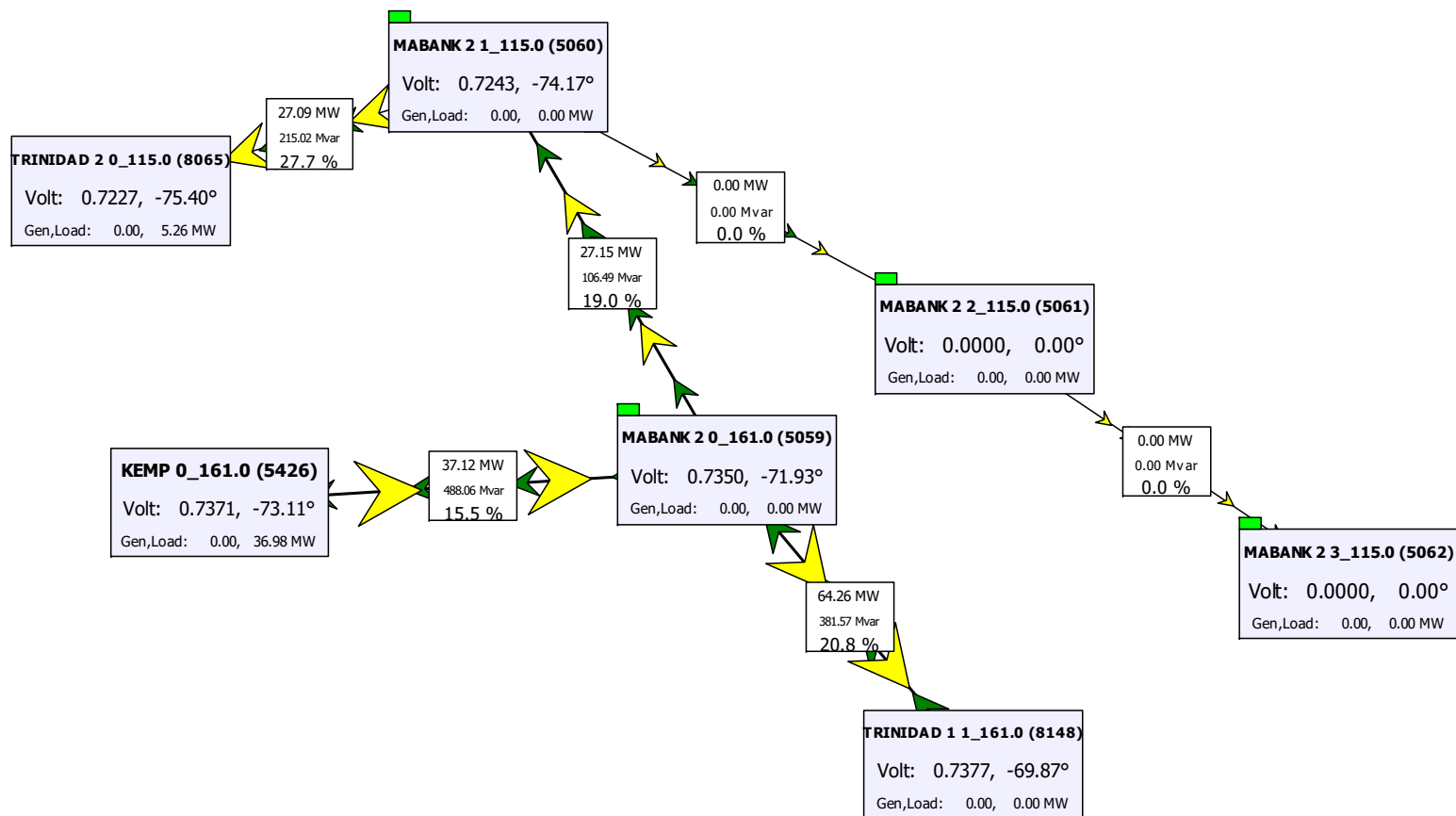


- Using the previous 52 V/km scenario, I transferred the power flow state to the power flow for time = 28 seconds



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Mitigation Example, Aggressive Load and Generator Shedding

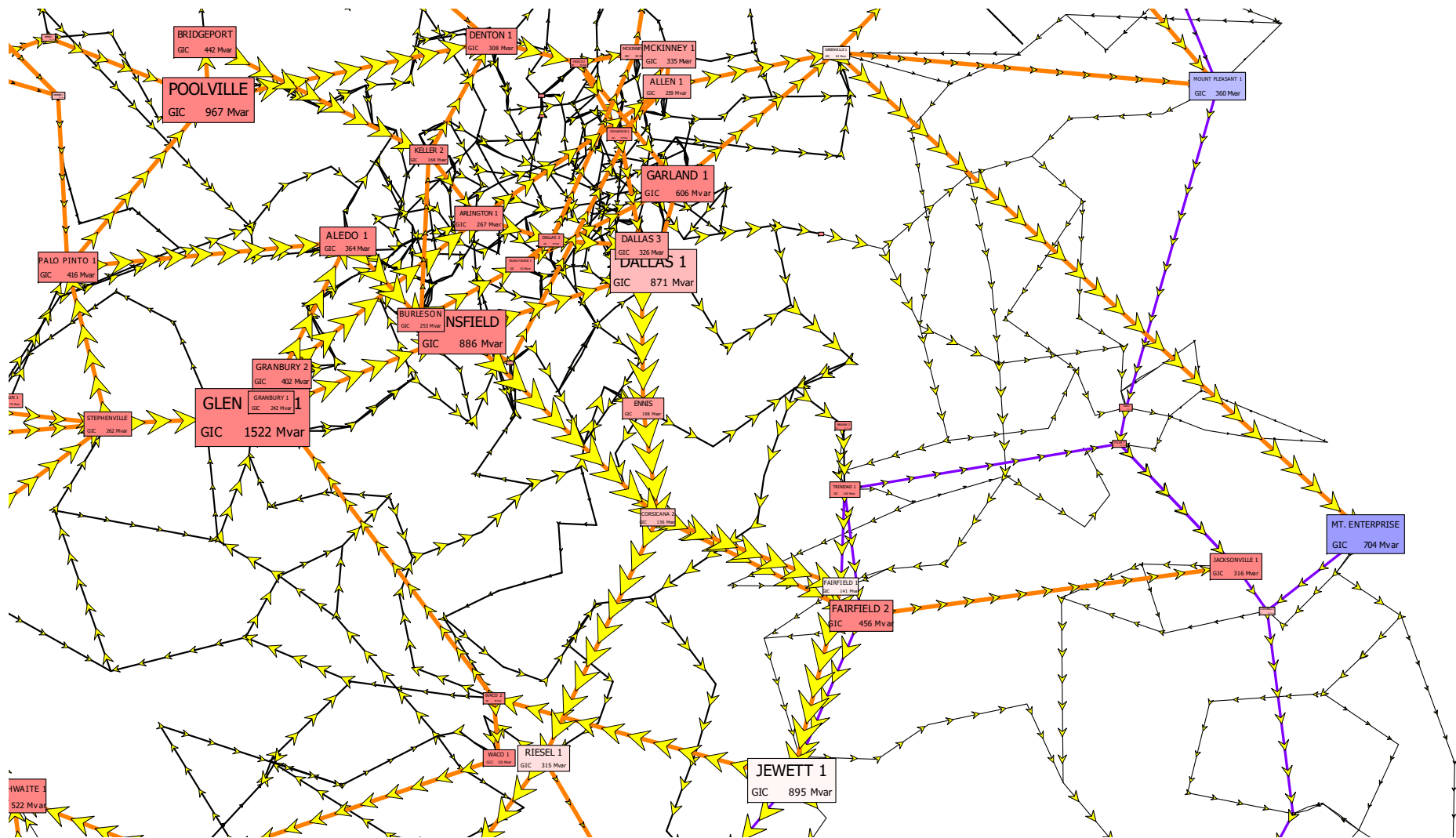


Mitigation Example, Heavy GIC Transformers at 28 Seconds



Tables and Results													
Areas	Buses	Generators	DC Lines	Lines	Line Shunts	Loads	Switched Shunts	Substations	Transformers	Multi-Section Lines	System Summary	G-Matrix	Multi-Terminal DC Lines
	Bus Num High	Bus Name High	Bus Num Med	Bus Name Med	Circuit	Transformer Per Phase Effective GIC, Amps	Transformer Per Unit Effective GIC	GIC Mvar Losses	Maximum Mvar Losses	Maximum IEffective Direction (Degrees)	Neutral Current (Amps)	Maxin Neutral	
1	8082	FRANKLIN 0	8088	FRANKLIN 6	1	1397.956	8.561	1289.77			-4193.868		
2	5260	GLEN ROSE 1 0	5263	GLEN ROSE 1 3	1	1083.803	6.637	911.74			-3251.409		
3	5047	MANSFIELD 0	5048	MANSFIELD 1	1	1227.447	7.517	885.88			-1564.093		
4	8067	JEWETT 1 0	8071	JEWETT 1 4	1	681.353	4.172	756.37			2044.060		
5	5451	COPPERAS COV	5452	COPPERAS COV	1	1064.288	6.517	738.20			3143.806		
6	5260	GLEN ROSE 1 0	5262	GLEN ROSE 1 2	1	650.282	3.982	562.48			-1950.845		
7	6107	ROCKDALE 1 0	6111	ROCKDALE 1 4	1	561.993	3.441	531.48			-1685.980		
8	5192	KILLEEN 4 0	5193	KILLEEN 4 1	1	684.049	4.189	494.16			2423.900		
9	6107	ROCKDALE 1 0	6110	ROCKDALE 1 3	1	524.527	3.212	456.47			-1573.581		
10	8057	FAIRFIELD 2 0	8058	FAIRFIELD 2 1	1	557.810	3.416	444.35			642.215		
11	5204	POOLVILLE 0	5205	POOLVILLE 1	1	537.892	3.294	440.62			-2598.330		
12	6033	PFLUGERVILLE 0	6034	PFLUGERVILLE 1	1	370.487	2.269	348.25			212.584		
13	5239	GOLDTHWAITE 0	5243	GOLDTHWAITE 1	1	423.512	2.593	328.66			1270.535		
14	5350	GARLAND 1 0	5351	GARLAND 1 1	1	362.168	2.218	302.78			1467.410		
15	5350	GARLAND 1 0	5351	GARLAND 1 1	2	362.168	2.218	302.78			1467.410		
16	8158	BRYAN 1 0	8159	BRYAN 1 1	1	311.939	1.910	298.15			844.624		
17	5045	STEPHENVILLE 0	5046	STEPHENVILLE 1	1	336.722	2.062	262.15			-751.813		
18	5304	ALLEN 1 0	5305	ALLEN 1 1	1	307.790	1.885	258.90			731.798		
19	5479	BURLESON 0	5480	BURLESON 1	1	343.833	2.106	253.10			-112.743		
20	5358	RIESEL 1 0	5360	RIESEL 1 2	1	224.819	1.377	249.30			674.456		
21	6342	ROUND ROCK 0	6343	ROUND ROCK 1	1	245.729	1.505	230.77			5.448		
22	5164	DENTON 1 0	5165	DENTON 1 1	1	270.712	1.658	224.63			445.776		
23	5204	POOLVILLE 0	5207	POOLVILLE 3	1	252.598	1.547	221.08			-757.795		
24	6210	MARBLE FALLS 0	6215	MARBLE FALLS 1	1	205.317	1.257	212.34			615.951		
25	5033	DALLAS 1 0	5039	DALLAS 1 6	1	208.594	1.277	202.22			625.781		
26	6003	BASTROP 0	6008	BASTROP 5	1	181.070	1.109	201.04			-543.210		

Looking at GICs, GIC Losses and Voltages



Summary



- HEMPs are well recognized potential high impact, low frequency events
- PowerWorld simulator has the ability to simulate HEMPs, and can be used to develop potential mitigation strategies
- PowerWorld has many different ways to visualize the complex results associated with HEMP studies

Questions?

overbye@tamu.edu

