

Future Studies, Including Transient Stability Integration and EMP



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Introduction



- Appropriate power system models depend on the timeframe of the underlying problems
- "All models are wrong but some are useful,"

George Box, *Empirical Model-Building and Response Surfaces*, (1987, p. 424)

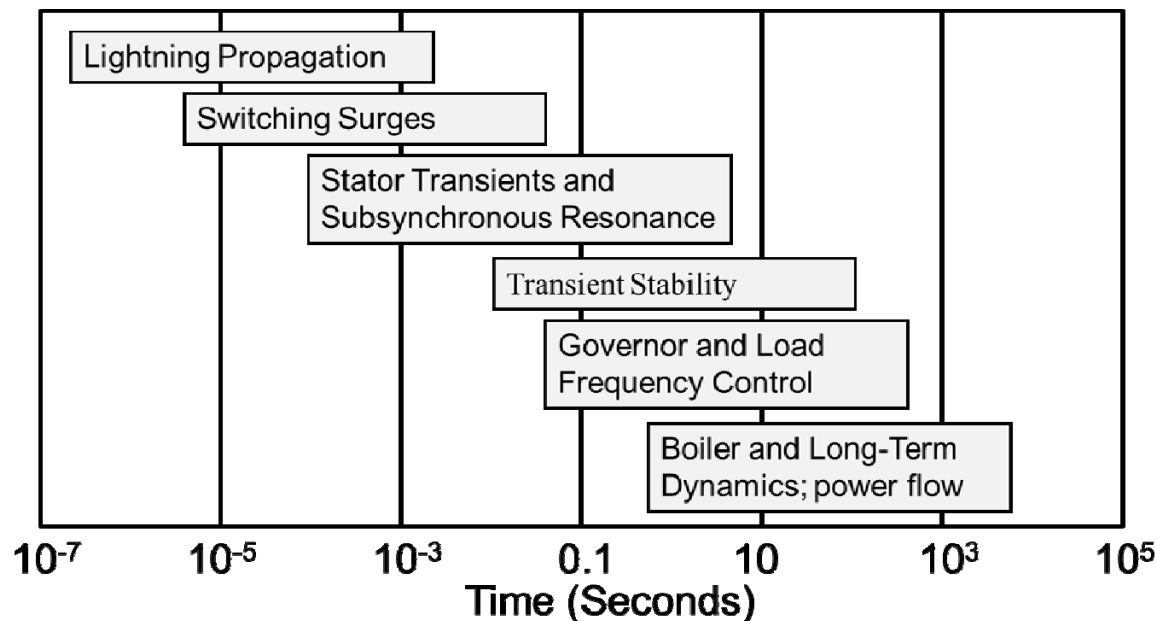


Image: Sauer, P.W., M. A. Pai, *Power System Dynamics and Stability*, Stripes Publishing, 2007

GMDs caused by solar corona mass ejections (CMEs) mostly fall in the power flow timeframe; EMP-induced GMDs move towards transient stability

Electromagnetic Pulses (EMPs) Introduction



- 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

Nuclear EMPs



- Talk focuses primarily on the impact of nuclear EMPs on the grid, mostly caused by high altitude explosions
- Much of the information on nuclear EMPs is classified
- This presentation contains no actual system modeling results; only results are on totally fictitious synthetic models
- Various public documents exist, including IEC 1000-2-9 (from 1996); some of the information presented here comes from this standard
 - Also J. R. Legro, N. C. Abi-Samra, F. M. Tesche, “Study to Assess the Effects of Magnetohydrodynamic Electromagnetic Pulse on Electric Power Systems: Phase I, Final Report,” Westinghouse Electric Corporation for ORNL, May 1985

Nuclear EMPs, cont.



- 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 HEMP impact can be almost continental
- More localized EMPs can be created by surface blasts; known as source region EMP (SREMP)

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
- Much of talk is on E3, which is similar to GMDs

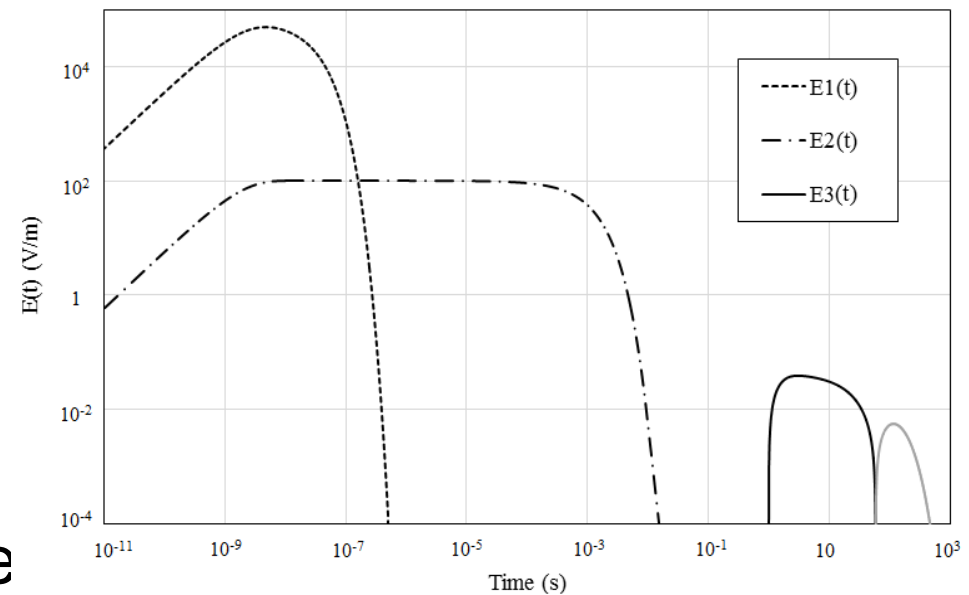
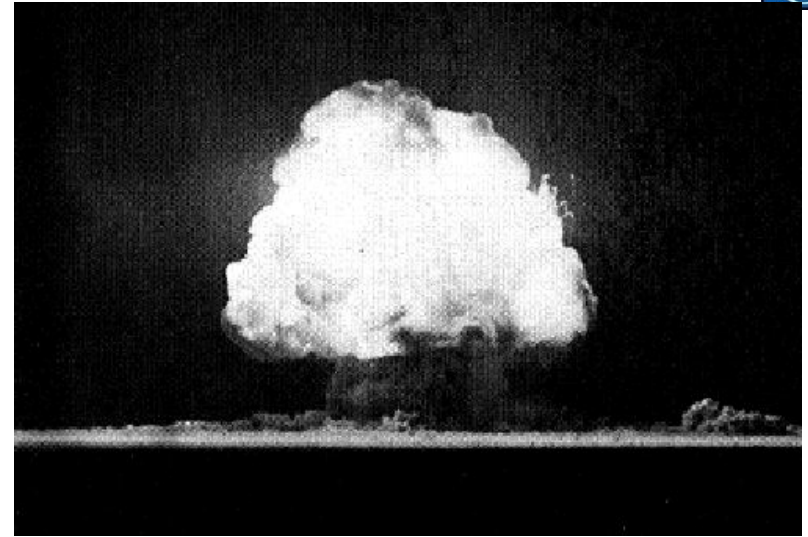


Image Source: IEC 1000-2-9 Figure

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 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
- Hardtack tests in 1958 (up to 80 km) 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 flash seen in Honolulu;

source: Wikipedia

Nuclear EMP History



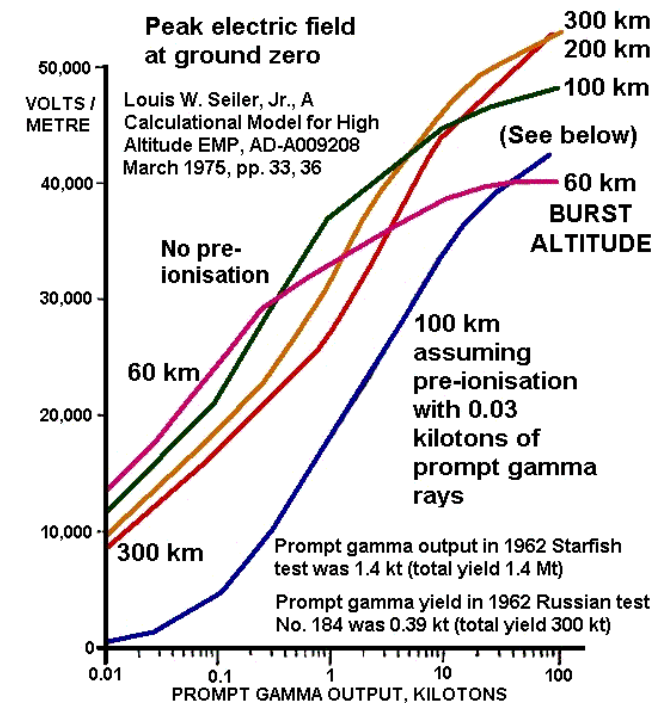
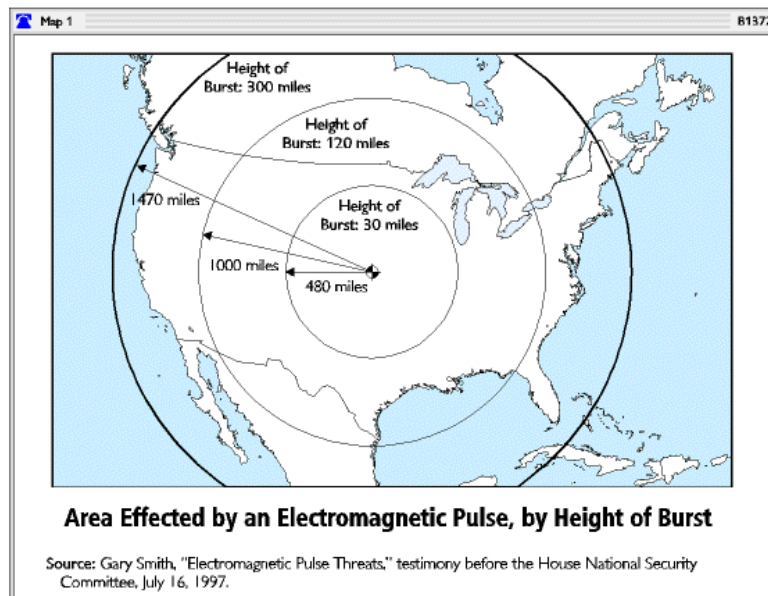
- Soviet HEMP tests in the early 1960's were reported to have damaged power equipment
- Nuclear tests in the atmosphere, space and under water were banned in 1963
 - There is a United Nations underground test ban from 1996, though not all countries have agreed to it
- Various countries have optimized nuclear weapons for HEMP impacts
 - Russian military writings claim to have a super EMP weapon that can generate 200 kV/m^{*}

*Source: Congressional Research Service, Clay Wilson, High Altitude Electromagnetic Pulse (HEMP) and High Power Microwave (HPM) Devices: Threat Assessments,” July 2008

HEMP Impacts versus Size and Altitude



- EMP impacts do not scale linearly with weapon size
 - Even quite small weapons (such as 10 kilotons) can produce large EMPs



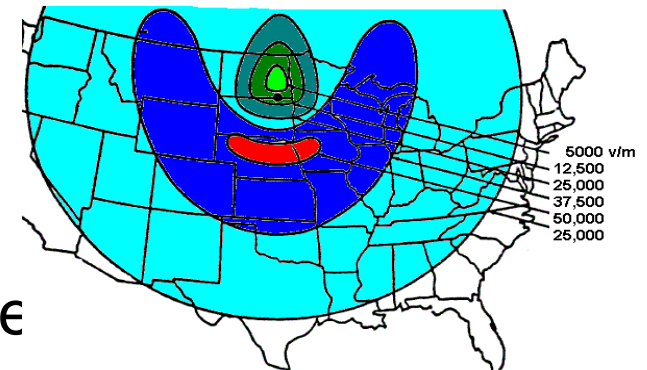
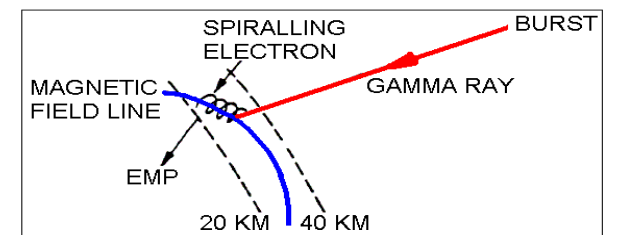
Low altitude EMPs can still have large footprints

Image Sources: en.wikipedia.org/wiki/Nuclear_electromagnetic_pulse

EMP E1 and E2 Mechanisms



- In a nuclear explosion, the E1 pulse is produced by the gamma radiation stripping electrons from atoms
Known as the Compton effect;
explained by Conrad Longmire at Los Alamos in 1963
 - Electron flow is diverted by earth's magnetic field
 - Mostly line of sight impacts; highest impacts south of detonation in Northern Hemisphere
- The E2 pulse is created by scattered gamma rays and neutron gamma



Source: Nuclear
S. Army, report

Known as “Smile
Diagrams”

EMP E1 Protection



- Because of large footprint, small energy density in the E1, so devices can be protected by Faraday cages
 - The allowable size of apertures depends on the wavelength and hence the frequency ($\lambda=c/f$); a ballpark figure is no larger than 1/10 the wavelength; for 1 GHz this is about 3 cm
 - Incoming wires are also an issue
 - Military Standard 188-125-1 (“HIGH-ALTITUDE ELECTROMAGNETIC PULSE (HEMP) PROTECTION FOR GROUND-BASED C41 FACILITIES PERFORMING CRITICAL, TIME-URGENT MISSIONS PART 1 FIXED FACILITIES”) provides useful guidance
 - Another useful reference is MetaTech Report R-320, “The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid”

Source: “The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid,
MetaTech-R-320, January 2010

Non-Nuclear EMP (NNEMP) Generators



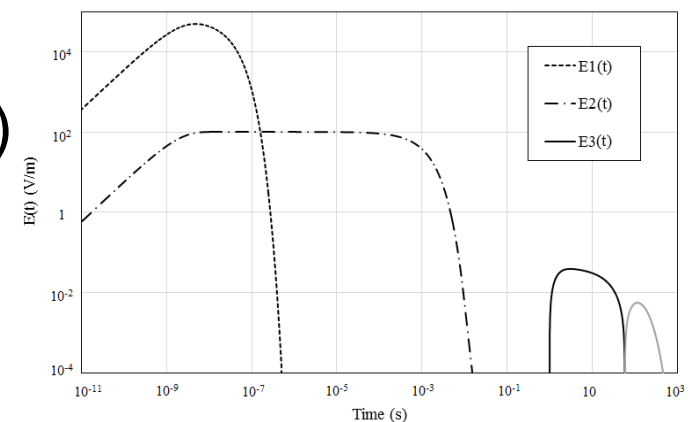
- E1 EMPs can be generated by non-nuclear sources
 - It is easy to find “how to” manuals on-line
- The magnitude of the pulses produced by NNEMPs can exceed that of nuclear EMPs
- However, the range is greatly reduced – perhaps up to several dozen meters for nonmilitary, mobile systems
 - Can be used for stopping many types of automobiles, and destroying electronics

Source: spectrum.ieee.org/aerospace/military/electromagnetic-warfare-is-here, August 2014

HEMP E3



- The earth's magnetic field is disturbed by 1) the fireball generated by the blast and 2) energized metallic debris
- E3 causes a geoelectric field induced by the earth's changing magnetic field
- E3 is very similar to CME caused GMDs except with faster rise times and potentially larger magnitudes
 - Time frames range from seconds to several minutes
 - A useful reference is Metatech report R-321, "The Late-Time (E3) HEMP and Its Impact on the US Power Grid," January 2010



Amplitude Spectrum of Each HEMP Component

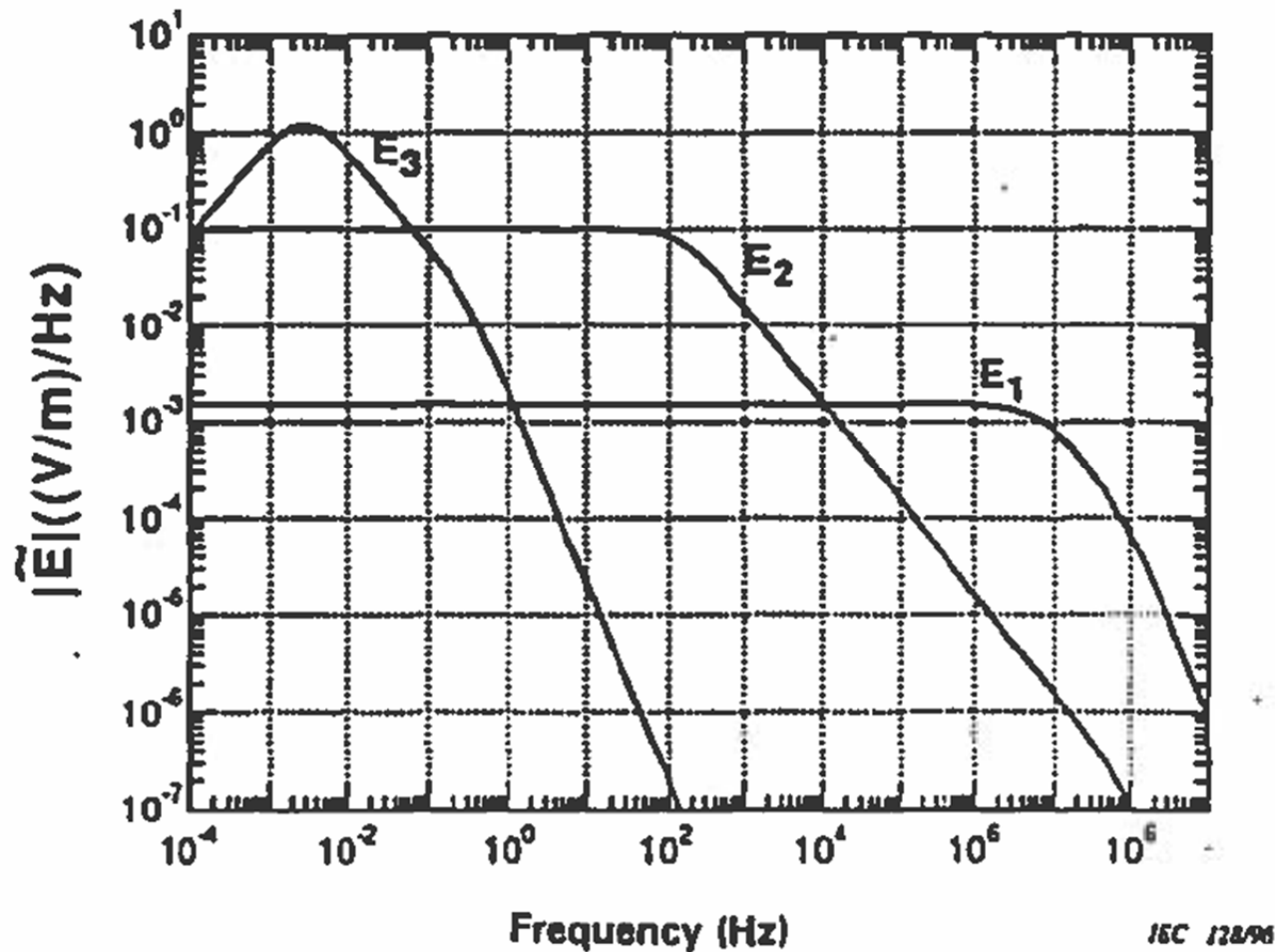
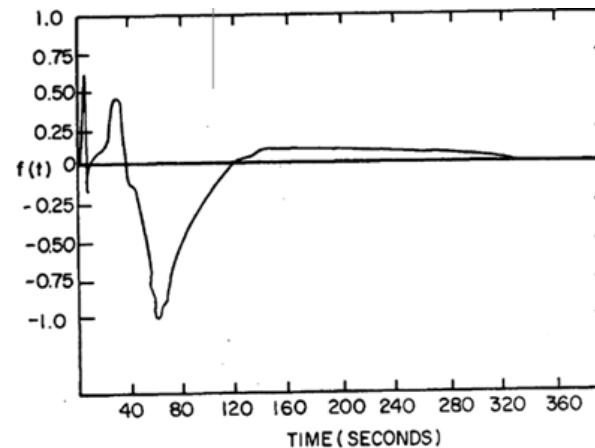
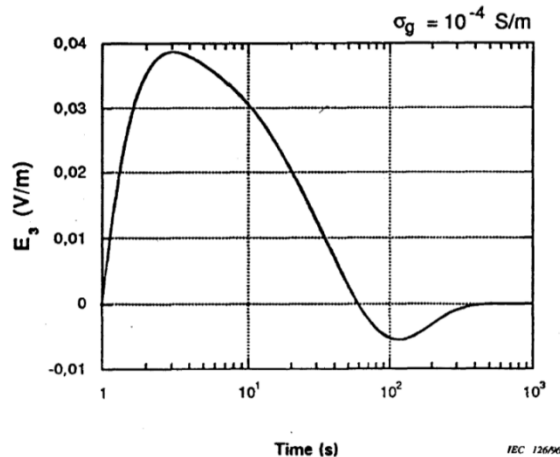


Image Source: IEC 1000-2-9, Figure 11

HEMP E3A and E3B



- The E3 is usually broken into two components
 - the E3A “Blast Wave” caused by the expansion of the nuclear fireball, expelling the Earth’s magnetic field
 - the E3B “Heave” as bomb debris and air ions follow geomagnetic lines at about 130 km, making the air rise, which gives rise to a current and an induced electric field



Left Image: IEC 1000-2-9, Figure 9, Right Image: ORNL “Study to Assess the Effects of Magnetohydrodynamic Electromagnetic Pulse on Electric Power Systems Phase I Final Report,” May 1985, Figure 8
G3: GMD Future Studies © 2017 PowerWorld Corporation

Measured Change in B During Fishbowl Tests

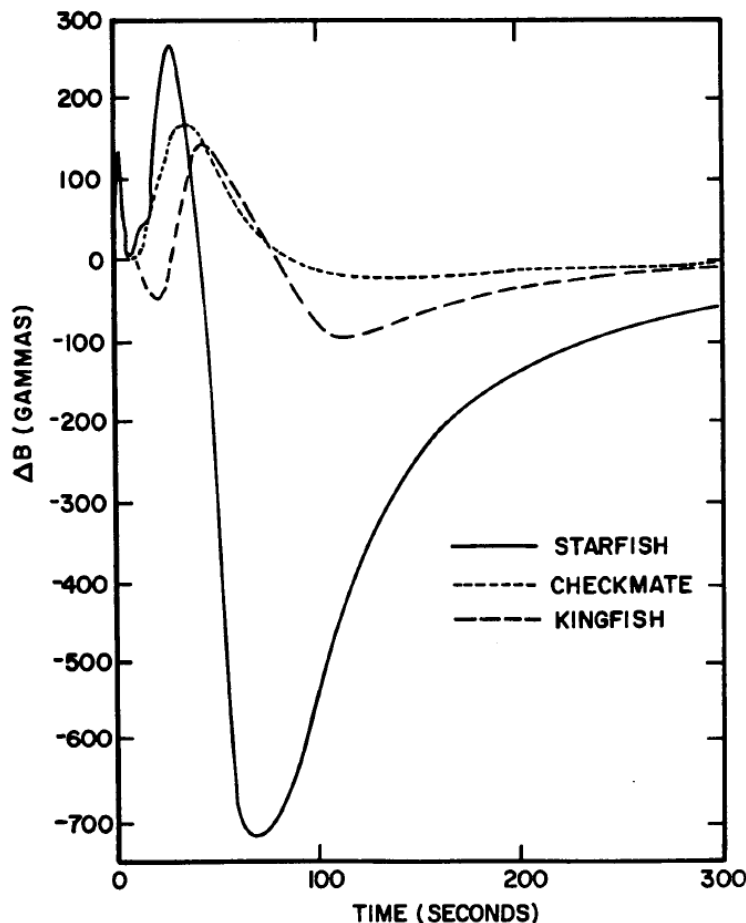


Image: ORNL 1985 Report, Figure 1

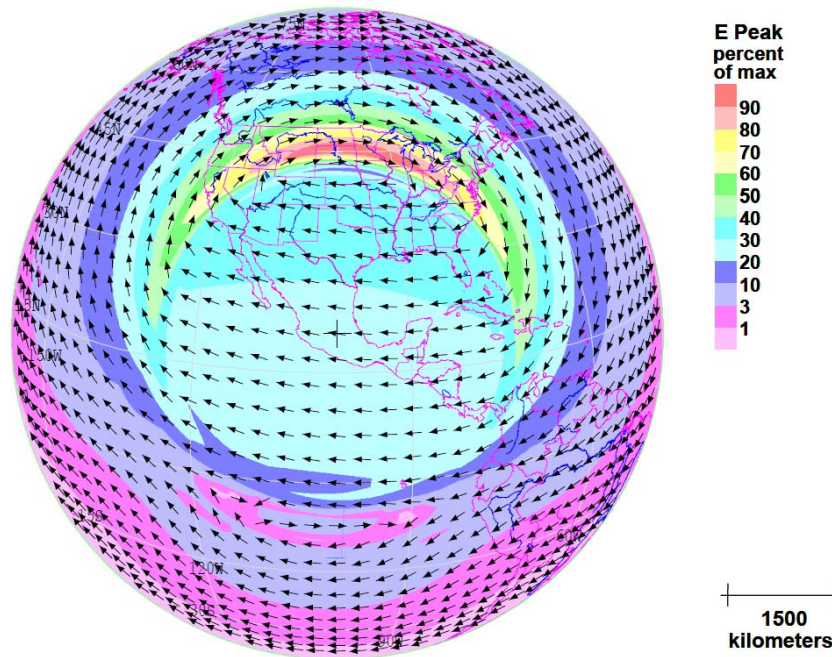
Checkmate and Kingfish were nuclear tests that were part of Operation Fishbowl. Checkmate was at 147 km, with a classified yield (less than 20 kilotons). The Kingfish yield is classified, but believed to be about 400 kiloton at 97 km.

A gamma is one nT.
For reference the Quebec GMD had 500 nT/minute and the 1859 Carrington is estimated to be perhaps 2500 nT/minute

EMP E3A



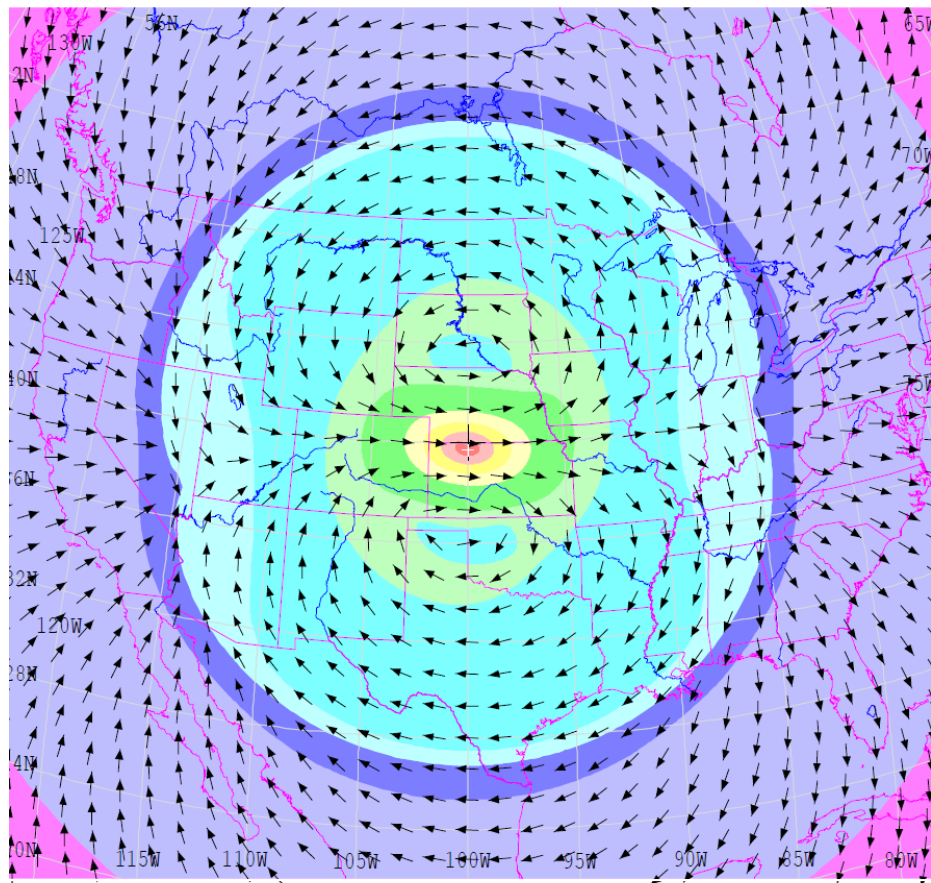
- For a uniform earth conductivity model, the E3A Blast wave can be modeled as a fairly uniform east-west electric field; hence it is very similar to a standard GMD



Because of the relatively large, uniform electric field area, the results are somewhat insensitive to location

Image Source: Metatech R-321, Figure 2-4

E3B Electric Field Magnitude and Direction

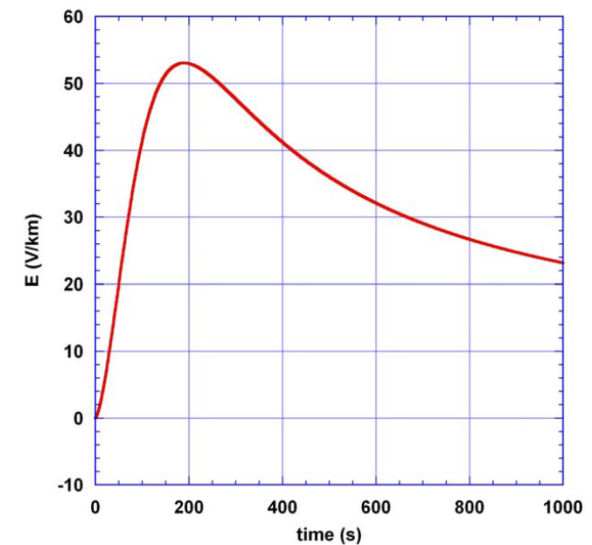


**E Peak
percent
of max**

99
96
90
80
50
30
10
3
1
0.3
0.1

600
kilometers

The heave electric fields are largest for blasts at about 130 km altitude



The assumed time duration and footprint is larger than in the 1985 ORNL report

Image Source: Left is Figure 2-11 from R-321, Right is Figure 2-8 form R-321

Alternative E3B Assumed Electric Field Magnitude and Direction

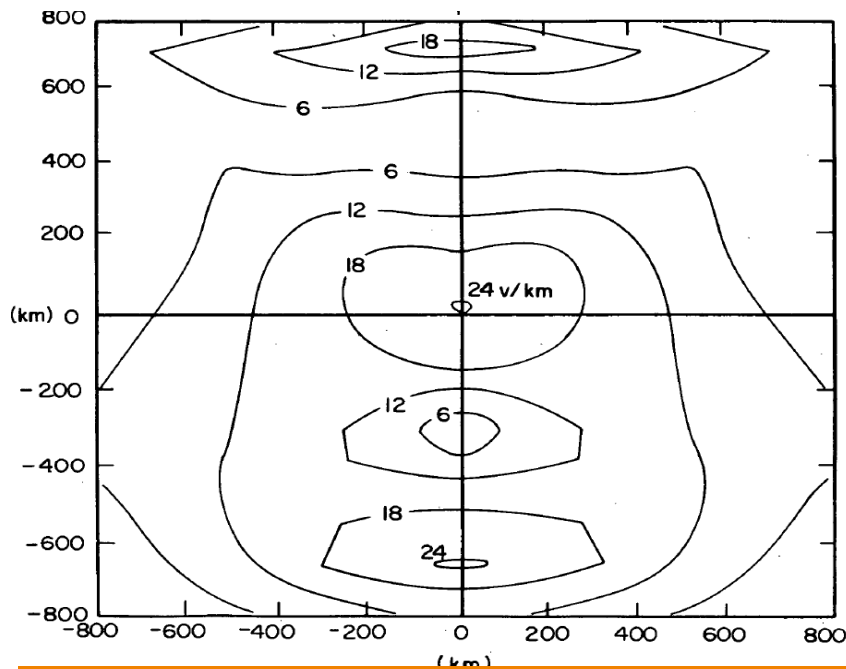


Fig 9: Electric Field Magnitude

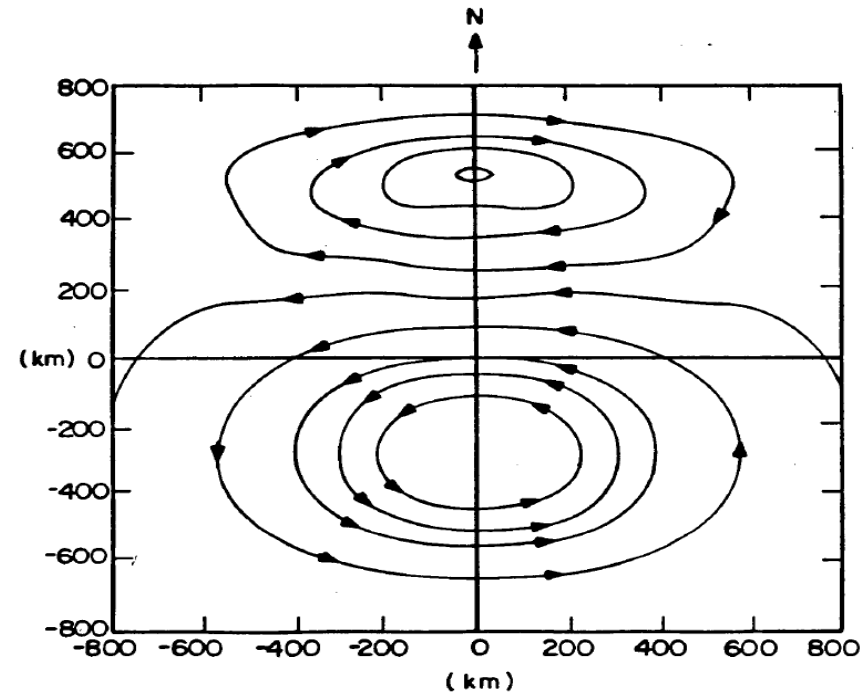


Fig 10: Electric Field Direction

The 1985 ORNL suggests modeling the electric field as the product of a spatially independent time function (fig 8), and time independent spatial magnitude and directions (fig 9 and 10)

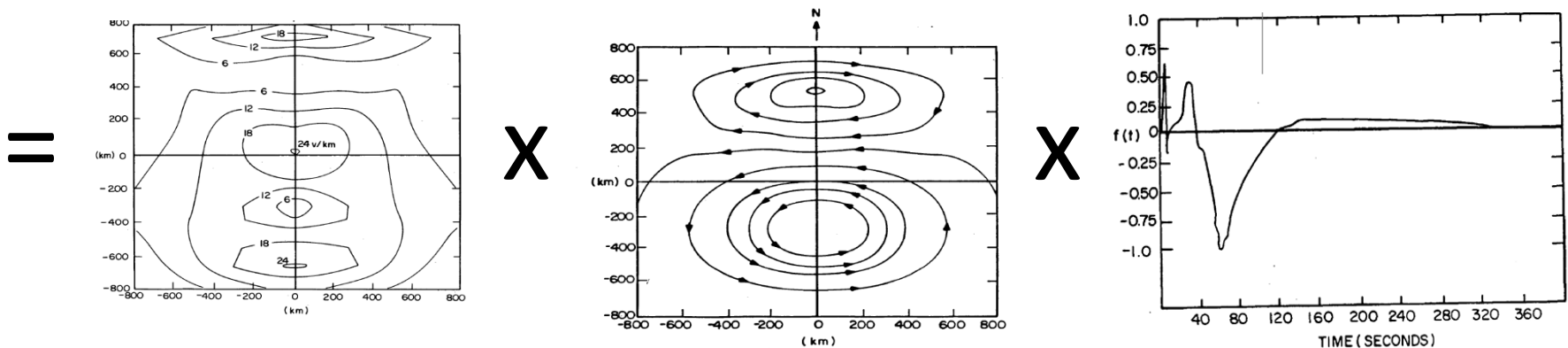
Images: ORNL 1985 Report, Figures 9 and 10

1985 ORNL Report Time-Varying Model



- The 1985 ORNL report models the electric field during the E3B as the product of a spatially independent time function (fig 8), and time independent spatial magnitude and directions (fig 9 and 10)

$$\bar{E}(x, y, t) = \varepsilon(x, y) \bar{e}(x, y) f(t)$$



Values were calculated assuming a uniform conductivity of 0.001 S/m

Modeling Time-Varying Electric Fields in PowerWorld Simulator



- The PowerWorld GMD add-on has long had the ability to model time-varying electric field inputs
 - Piecewise linear (in time) models can be defined for each transmission line in a model
 - Data can be loaded from *.aux files or pasted in

Case: TEXAS-CASE_MAY-25-2016_default-dynamics.PWB Status: Initialized | Simulator 20 Beta

File

Case Information

Draw

Onelines

Tools

Options

Add Ons

Window

TEXAS-CASE_MAY-25-2016

GIC Analysis Form

Calculation Mode

☐ Single Snapshot

☒ Time Varying Series Voltage Inputs

☐ Time Varying Electric Field Inputs

Calculate GIC Values

Clear GIC Values

☐ Include GIC in Power Flow

Validate Input Data for GIC

Current Time

60.00

☐ Calculate GIC on Time Change

☒ Use EMP as Input

Select Step

Field/Voltage Input

Options

Tables and Results

Sensitivity Analysis

Non-Uniform Electric Field Simulation

Field/Voltage Input

AC Line Input Voltages

	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	Timepoint_9
1	Time in Seconds									0.000	3.134	3.582	5.373	6.716	7.164	8.507	11.642	
2	Branch '1' '1874' '1'	1	1874	1	32.2984	32.2984	-97.7855	-97.7855	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	Branch '2' '4' '1'	2	4	1	32.9290	32.9474	-96.8045	-96.8957	8.77	0.000	32.152	60.477	118.657	72.725	-29.856	-0.766	9.956	
4	Branch '2' '39' '1'	2	39	1	32.9290	33.0213	-96.8045	-96.7416	11.80	0.000	-15.640	-29.418	-57.719	-35.376	14.523	0.373	-4.843	
5	Branch '2' '112' '1'	2	112	1	32.9290	32.8924	-96.8045	-96.7328	7.84	0.000	-26.477	-49.801	-97.711	-59.887	24.585	0.631	-8.198	
6	Branch '2' '115' '1'	2	115	1	32.9290	32.8986	-96.8045	-96.8157	6.80	0.000	7.272	13.679	26.839	16.450	-6.753	-0.173	2.252	
7	Branch '3' '13' '1'	3	13	1	33.0896	33.0744	-96.6078	-96.7357	12.06	0.000	40.922	76.971	151.020	92.561	-37.999	-0.975	12.671	
8	Branch '3' '16' '1'	3	16	1	33.0896	32.8517	-96.6078	-96.4362	30.88	0.000	-73.914	-139.028	-272.776	-167.185	68.634	1.761	-22.886	
9	Branch '3' '1921' '1'	3	1921	1	33.0896	33.0096	-96.6078	-96.6078	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	Branch '4' '5' '1'	4	5	1	32.9474	33.0053	-96.8957	-96.8967	6.42	0.000	3.284	6.177	12.119	7.428	-3.049	-0.078	1.017	
11	Branch '4' '109' '1'	4	109	1	32.9474	32.8792	-96.8957	-96.8711	7.91	0.000	-12.082	-22.726	-44.589	-27.329	11.219	0.288	-3.741	
12	Branch '4' '109' '2'	4	109	2	32.9474	32.8792	-96.8957	-96.8711	7.91	0.000	-12.082	-22.726	-44.589	-27.329	11.219	0.288	-3.741	
13	Branch '4' '1934' '1'	4	1934	1	32.9474	32.9474	-96.8957	-96.8957	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Auto-Creating Time-Varying Electric Fields



- PowerWorld has capabilities to auto-create time-varying electric fields associated with public EMP waveforms

GIC Analysis Form

Calculation Mode
☐ Single Snapshot
☒ Time Varying Series Voltage Inputs
☐ Time Varying Electric Field Inputs

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

Current Time 60.00 ☐ Calculate GIC on Time Change ☒ Use EMP as Input

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

Field/Voltage Input

AC Line Input Voltages

	Timepoint_8	Timepoint_9	Timepoint_10	Timepoint_11	Timepoint_12	Timepoint_13	Timepoint_14	Timepoint_15	Timepoint_16	Timepoint_17	Timepoint_18	Timepoint_19	Timepoint_20	Timepoint_21	Ti
1	11.642	17.463	21.045	23.284	23.731	24.627	25.970	26.866	29.104	32.239	33.134	34.478	35.821	36.269	
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
3	9.956	19.904	27.559	37.511	48.994	62.773	75.787	83.443	88.801	84.974	75.022	47.463	21.435	10.714	
4	-4.843	-9.682	-13.406	-18.247	-23.832	-30.535	-36.866	-40.589	-43.196	-41.334	-36.493	-23.088	-10.427	-5.212	
5	-8.198	-16.390	-22.694	-30.889	-40.345	-51.692	-62.409	-68.713	-73.126	-69.974	-61.779	-39.084	-17.651	-8.823	
6	2.252	4.502	6.234	8.485	11.082	14.199	17.142	18.874	20.086	19.220	16.969	10.736	4.848	2.423	
7	12.671	25.332	35.076	47.742	62.357	79.894	96.458	106.201	113.021	108.150	95.484	60.408	27.281	13.636	

GMD EMP EMP Grid Analysis

Footprint Location and Scaling
 Latitude of Center 0.000 East-West Footprint Width Scalar 1.000
 Longitude of Center 0.000 North-South Footprint Height Scalar 1.000
 Rotation Degrees (0 is North) 0.0 ☒ Lock Scaling Aspect Ratio
☐ Rotate to Magnetic North Time Scaling (<1 is Faster) 1.000
 Line Segment Length (km) 10.0 Start Time Delay (Sec.) 0.000

E3A Time and Spatial Functions
 Normalized Electric Field (V/km) 24.00
 Time Function ORNL_Fig8_3A
 Spatial Function Uniform Westward Field
 Spatial Width (km) 4000.00
 Spatial Height (km) 4000.00

E3B Time and Spatial Functions
 Normalized Electric Field (V/km) 24.00
 Time Function ORNL_Fig8_3B
 Spatial Function ORNL_Fig9_Fig10
 Spatial Width (km) 2400.00
 Spatial Height (km) 2600.00

Calculate EMP Input Time Series Delete All Time Series Entries Show EMP Induced Line Voltage Details

Save Setting to Aux Load AUX Save in PSSE GIC Format Load in PSSE GIC Format Clear All GIC Input Fields

Auto-Creating Time-Varying Electric Fields



- This functionality just populates the time-varying electric fields data structure; hence it is just a more convenient way for functionality that could be done manually by pasting
- Remaining analysis is exactly the same as for regular GMD
 - Issue is the need to account for the faster time-variation, suggesting the need for transient stability integration

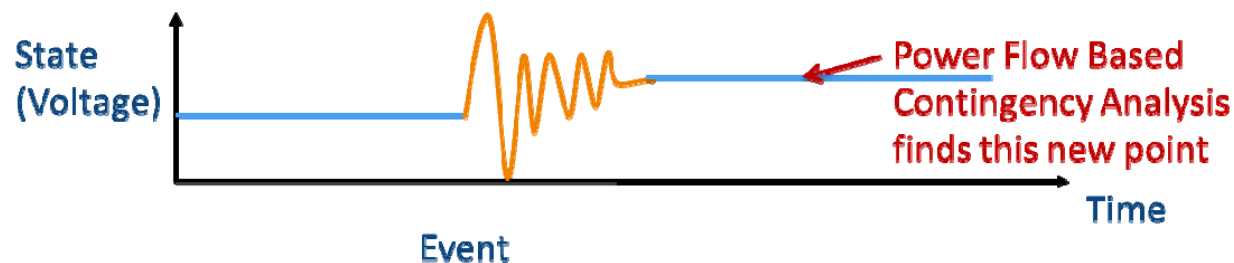
	Timepoint_8	Timepoint_9	Timepoint_10	Timepoint_11	Timepoint_12	Timepoint_13	Timepoint_14	Timepoint_15	Timepoint_16	Timepoint_17	Timepoint_18	Timepoint_19	Timepoint_20	Timepoint_21
1	11.642	17.463	21.043	23.294	23.731	24.627	25.970	26.866	28.104	32.239	33.134	34.475	35.821	36.259
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	5.955	19.504	27.559	37.511	48.994	62.775	75.787	81.443	88.801	94.974	75.822	47.463	21.435	10.714
4	-4.543	-9.682	-13.406	-16.347	-23.632	-30.335	-36.866	-43.589	-43.196	-41.334	-38.493	-23.088	-10.427	-5.212
5	-5.198	-16.390	-22.694	-30.889	-40.343	-51.892	-62.409	-68.713	-73.126	-69.974	-61.779	-39.084	-17.651	-8.523
6	-2.252	4.502	6.234	5.485	11.062	14.199	17.142	18.874	20.086	19.220	16.969	10.736	-4.848	-2.423
7	12.671	25.332	35.076	47.742	62.357	79.894	96.458	106.201	113.021	108.150	95.484	68.408	27.281	13.636

The time-varying electric fields are created by superposition of public E3A and E3B waveforms.

Power Flow vs Transient Stability



- The power flow is used to determine a quasi steady-state operating condition for a power system
 - Goal is to solve a set of algebraic equations
 - $\mathbf{g}(\mathbf{y}) = \mathbf{0}$ [$\mathbf{y}$ variables are bus voltage and angle]
 - Models employed reflect the steady-state assumption, such as generator PV buses, constant power loads, LTC transformers
- Using a power flow, after a contingency occurs (such as opening a line), the algebraic equations are solved to determine a new equilibrium



Power Flow vs. Transient Stability



- Transient stability is used to determine whether following a contingency the power system returns to a steady-state operating point
 - Goal is to solve a set of differential and algebraic equations,
 - $\frac{dx}{dt} = f(x, y)$ [y variables are bus voltage and angle]
 - $g(x, y) = 0$ [x variables are dynamic state variables]
 - Models reflect the transient stability time frame (up to dozens of seconds)
 - Slow Values → Treat as constants
 - Some values assumed to be slow enough to hold constant
 - Ultra Fast States → Treat as algebraic relationships
 - Example: synchronous machine stator current dynamics

GIC Transient Stability Integration



- GICs can be integrated into transient stability by calculating their values at every time step
 - The algebraic modeling is the same as in the power flow (GICs impact transformer reactive losses as a constant reactive current)
- This functionality has existed in PowerWorld for several years
- The integration of GIC with transient stability is described in
 - T.R. Hutchins, T.J. Overbye, "Power System Dynamic Performance During the Late-Time (E3) High-Altitude Electromagnetic Pulse," Proc. 19th Power Systems Computation Conference (PSCC), Genoa, Italy, June 2016

Power System Modeling of GICs



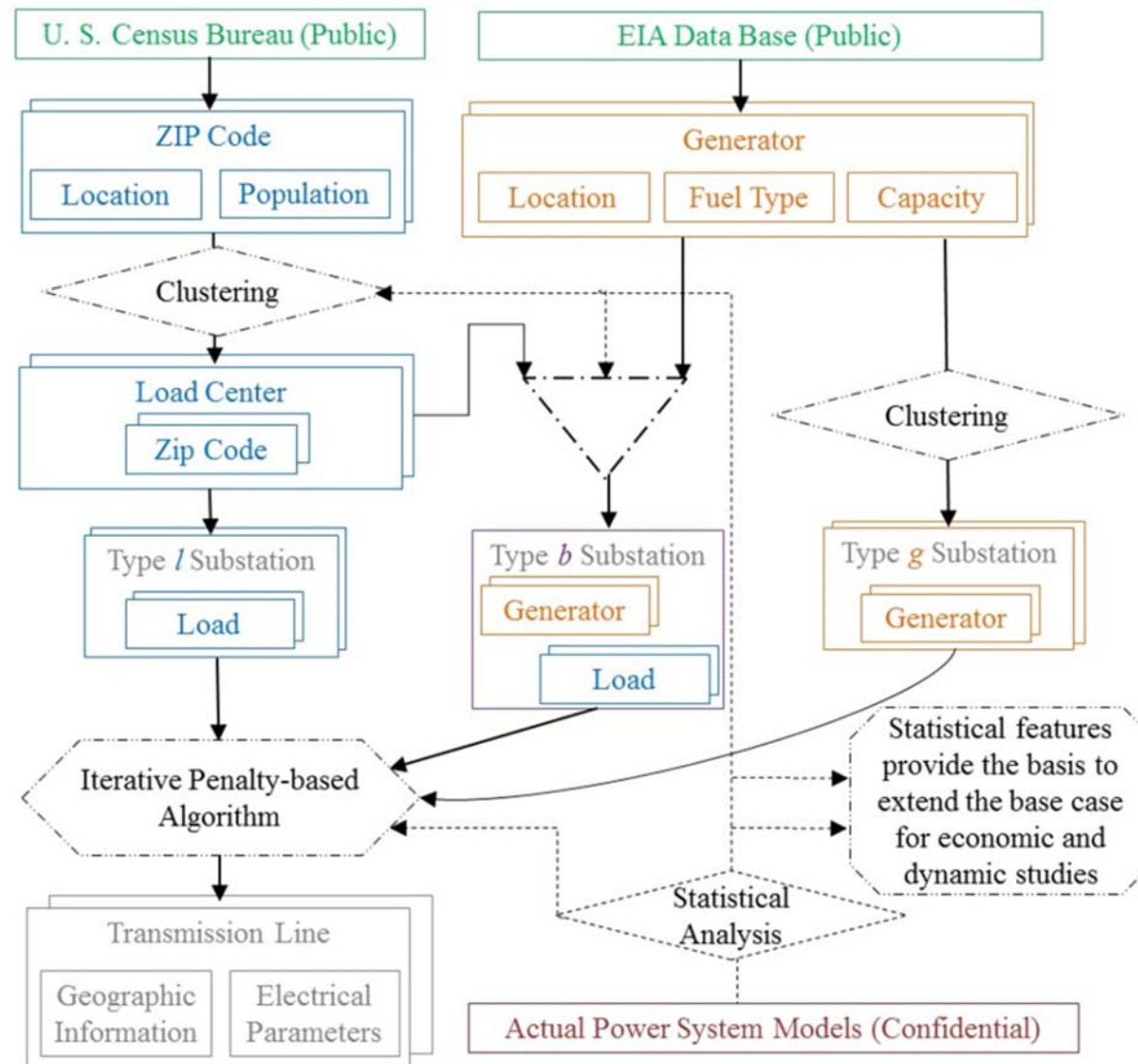
- PowerWorld has four different ways to model GICs
 - Snapshot calculation of GICs with no power flow solution
 - Very fast, gives reasonable solutions but no voltage impact
 - Snapshot calculation of GIC with a power flow solution
 - More accurate, but slower because of need to solve the power flow; possible convergence issues
 - Time-varying GIC calculations with no power flow solution (currently implemented in the transient stability application)
 - Time-varying GIC calculations in the transient stability
 - Allows more model integration, and addresses some convergence issues; regular transient stability speed

Synthetic (Fictitious) Power System Models



- To avoid any data confidentiality concerns, these techniques will be demonstrated using a synthetic power grid model
- Synthetic power system models are entirely fictitious models that share characteristics of the actual grid models, but contain no confidential information
 - Hence the models and any results can be freely shared
- Through an ARPA-E project, TAMU (with others) is creating geographically based synthetic models that include GIC parameters and transient stability models
 - Currently we've created 200, 500 and 2000 bus models
 - Now available at <https://electricgrids.engr.tamu.edu/>

Overall Synthetic Model Design Process

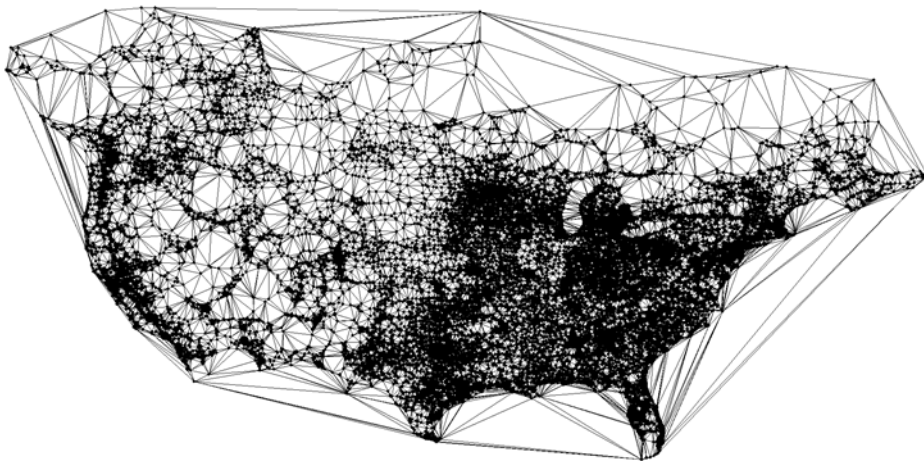


Synthetic Model Design: Matching Transmission System Structure



- One interesting challenge is matching the structure of transmission grids
- We use Delaunay Triangulation and minimum spanning trees to gain system insight

Below image shows Delaunay triangulation of 42,000 North America substations; statistics only consider single voltage levels; this is computationally fast (order $n \ln(n)$)



The minimum spanning tree (MST) is a subset of the Delaunay triangulation

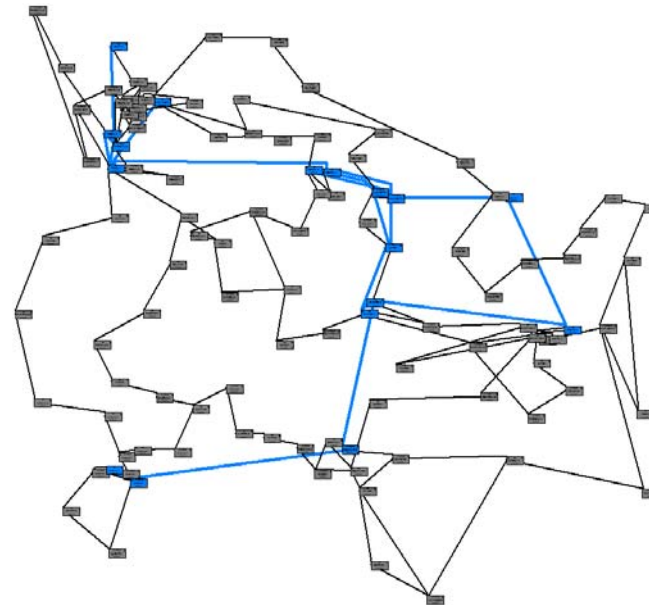


MST for the EI 500 kV grid; black actual on MST, green other

200 Bus Central Illinois Model



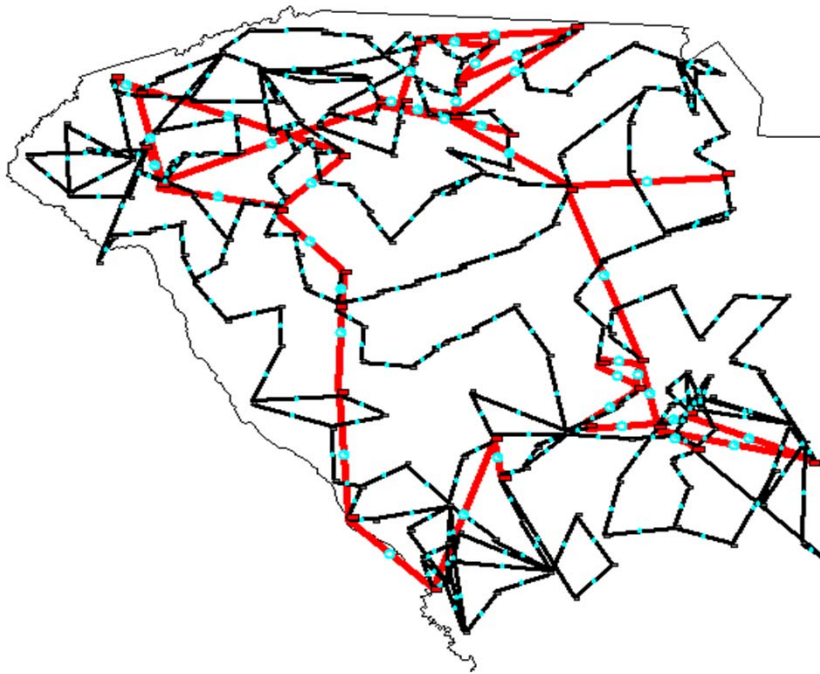
- 200-bus case with footprint of Central Illinois; fourteen counties, about 1.1 million people, simple terrain
 - One area, two voltage levels (230/115 kV)
 - Augmented with transient stability and GMD parameters



South Carolina 500 Bus Case



- 500-bus case with footprint of western South Carolina
- 21 counties, 2.6 million people, net export region
- Two areas, two system voltage levels (345/138 kV)
- All initial validation metrics are met



Visual depiction of the case, with 345 kV lines in red and 138 kV lines in black

Synthetic Model Validation



#	Validation Metric	Criteria	Illinois200	SouthCarolina500
1	Buses per substation	Mean 1.7-3.5	1.8	2.40
		Exponential decay	(next slide)	(next slide)
2	Percent of substations containing buses in kV range	< 200 kV, 85-100%	100%	100%
		> 201 kV, 7-25%	15.3%	15%
3	Substations with load	75-90%	90%	90%
4	Load per bus	Mean 6-18 MW	11 MW	15.5 MW
		Exponential decay	(next slide)	(next slide)
5	Generation capacity / load	1.2-1.6	1.59	1.57
6	Substations with generators	5-25%	15.3%	15%
7	Generator Capacities	25-200 MW, 40+%	47%	44%
		200+ MW, 5-20%	6%	16%
8	Committed Generators	60-80%	78%	62%
9	Generators dispatched > 80%	50+%	63%	93%
10	Generator MaxQ/MaxP	0.40-0.55, > 70%	86%	93% (incl. 0.38)

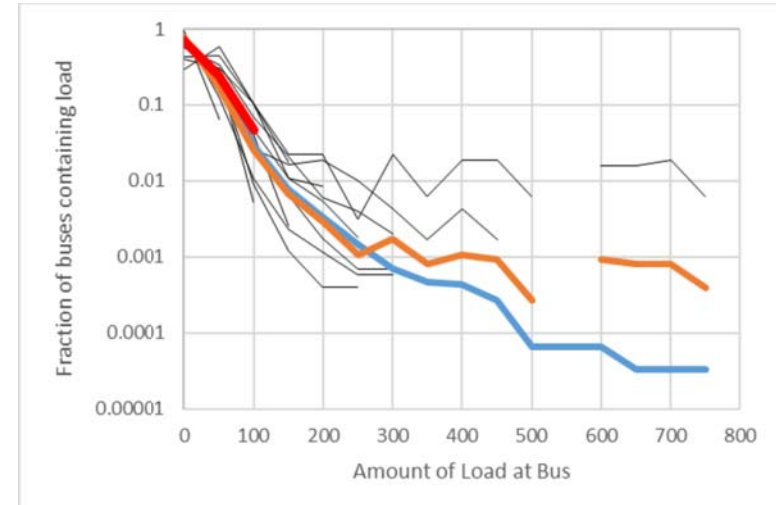
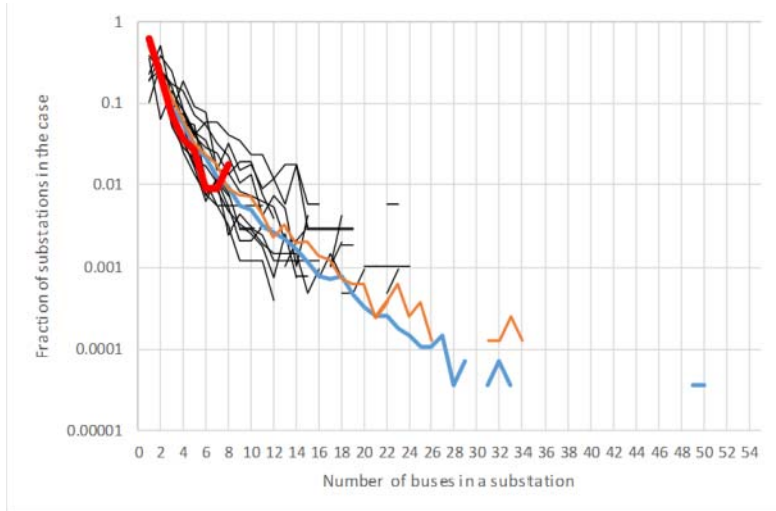
Synthetic Model Validation



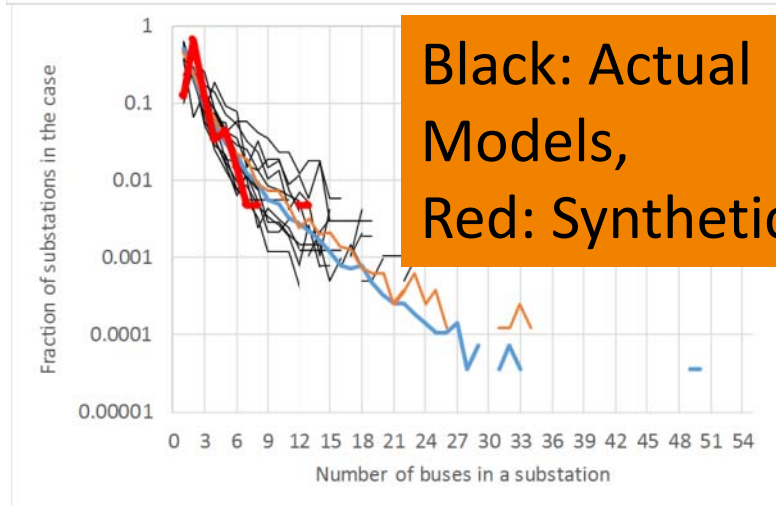
Number of buses in substation

Amount of load per bus

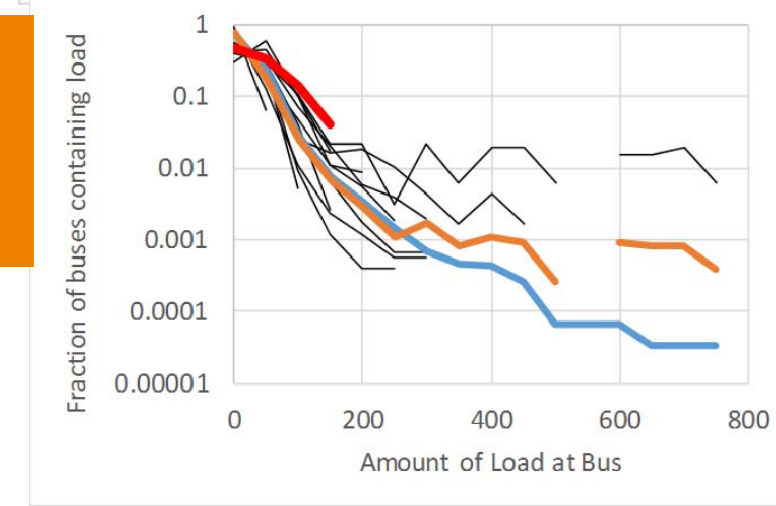
Illinois
200



South
Carolina
500



Black: Actual
Models,
Red: Synthetic



Synthetic Model Validation

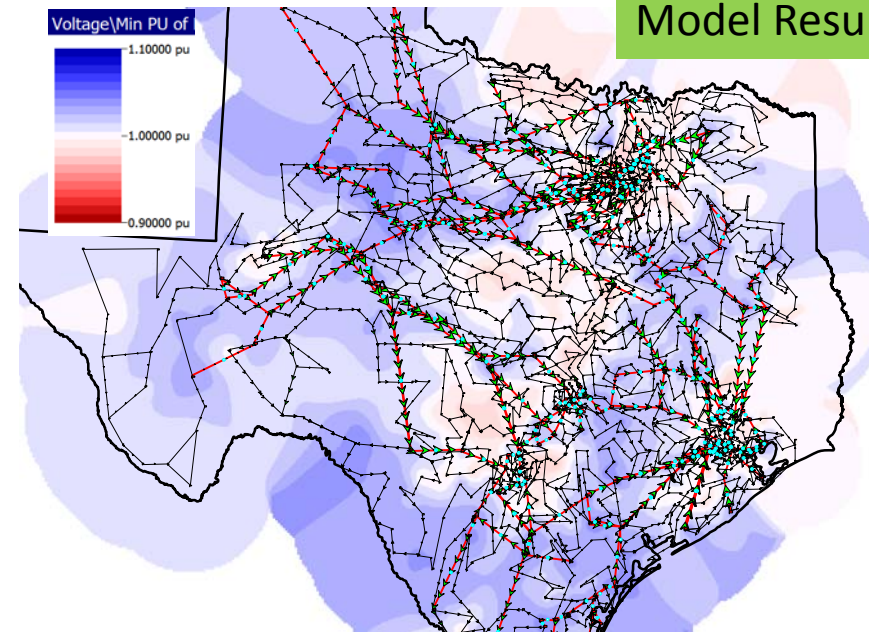


#	Validation Metric	Criteria	Illinois200		SouthCarolina500	
11	Transformer per-unit reactance, on own base.	80% within [0.05, 0.2]	230 kV	115 kV	345 kV	138 kV
			98%	94%	100%	95%
12	Transformer X/R ratio and MVA limits, by kV level (Table II)	40% below median	50/44	59/47	45/45	46/44
		40% above median	50/56	41/53	55/55	54/56
		80% within 10-90 range	90/84	85/88	100/100	97/87
13	Line per-unit, per-distance reactance, by kV level (Table III)	70% within 10-90 range	71%	93%	100%	100%
14	Line X/R ratio and MVA limits, by kV level (Tables IV and V)	70% within 10-90 range	100/100	100/100	100/100	100/100
15	Lines / Substations, by kV level	1.1-1.4	1.24	1.22	1.22	1.22
16	Lines on min. spanning tree	40-50%	52%*	50%	47%	50%
17	Distance of line along Delaunay triangulation, by kV level	1, 65-80%	71%	70%	68%	70%
		2, 15-25%	24%	25%	26%	25%
		3+, 3-10%	5%	5%	5%	5%
18	Total line length / MST	1.2-2.2	1.49	1.80	1.74	1.83

Texas 2000 Bus Model Used Here



- Model is set in the ERCOT footprint, but every transmission line and substation is totally fake!!
 - Underlying load density is similar to ERCOT since it is based on zip code populations
- We're happy to work with utilities to create synthetic models of footprints to allow easier discussions of methodologies while keeping actual grid data confidential



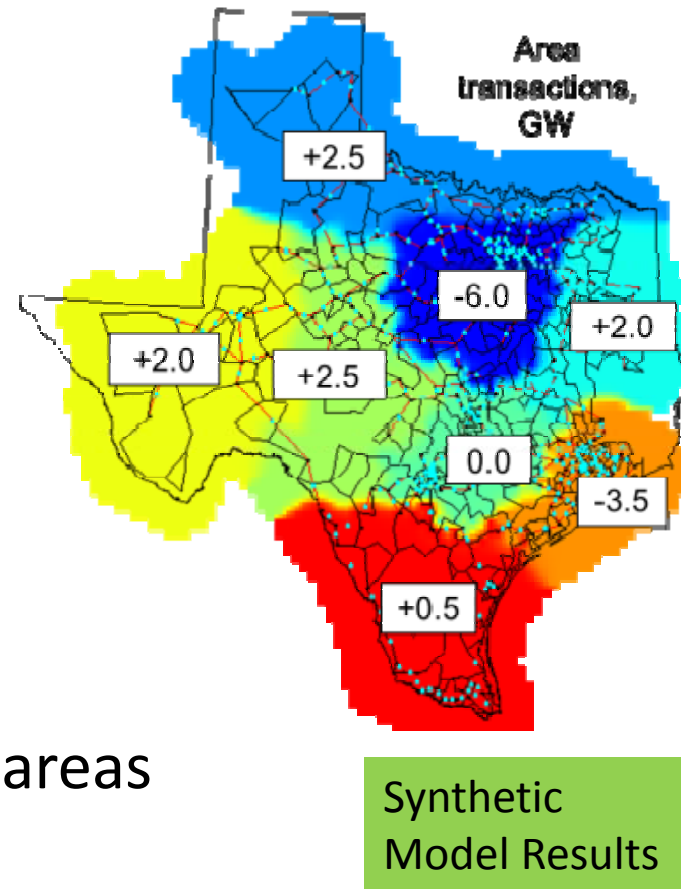
Synthetic
Model Results

Model has a 345 and 115
kV transmission system

Texas 2000 Bus Model, Areas



- System divided into 8 areas
 - NorthCentral, North, East, SouthCentral, West, FarWest, Coast, South
- Total load is about 50 GW and 14 GVar
- Two areas have more load than generation capacity
- Transactions set up from other areas
- Generators dispatched proportionally to meet load + transaction commitments



GIC Calculation: Single Snapshot, No Power Flow Solution



- Single snapshot GIC values can be quickly calculated, and the worst directions determined
 - Below results are for a 1V/km uniform east-west electric field

GIC Analysis Form

Calculation Mode
☒ Single Snapshot
☐ Time Varying Series Voltage Inputs
☐ Time Varying Electric Field Inputs

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

☒ Update Line Voltages (Show be True Unless Explicitly Entered)

Select Step

Field/Voltage Input
 Options
 DC Current Calculation
 AC Power Flow Model
 Tables and Results
 Areas
 Buses
 Generators
 G-Matrix
 Lines
 Line Shunts
 Switched Shunts
 Substations
 System Summary
 Transformers
 Sensitivity Analysis
 Non-Uniform Electric Field Sc
 Geomagnetic Latitude Sc
 Earth Resistivity Scaling
 Earth Resistivity Scaling
 Time Varying Electric Field Ir

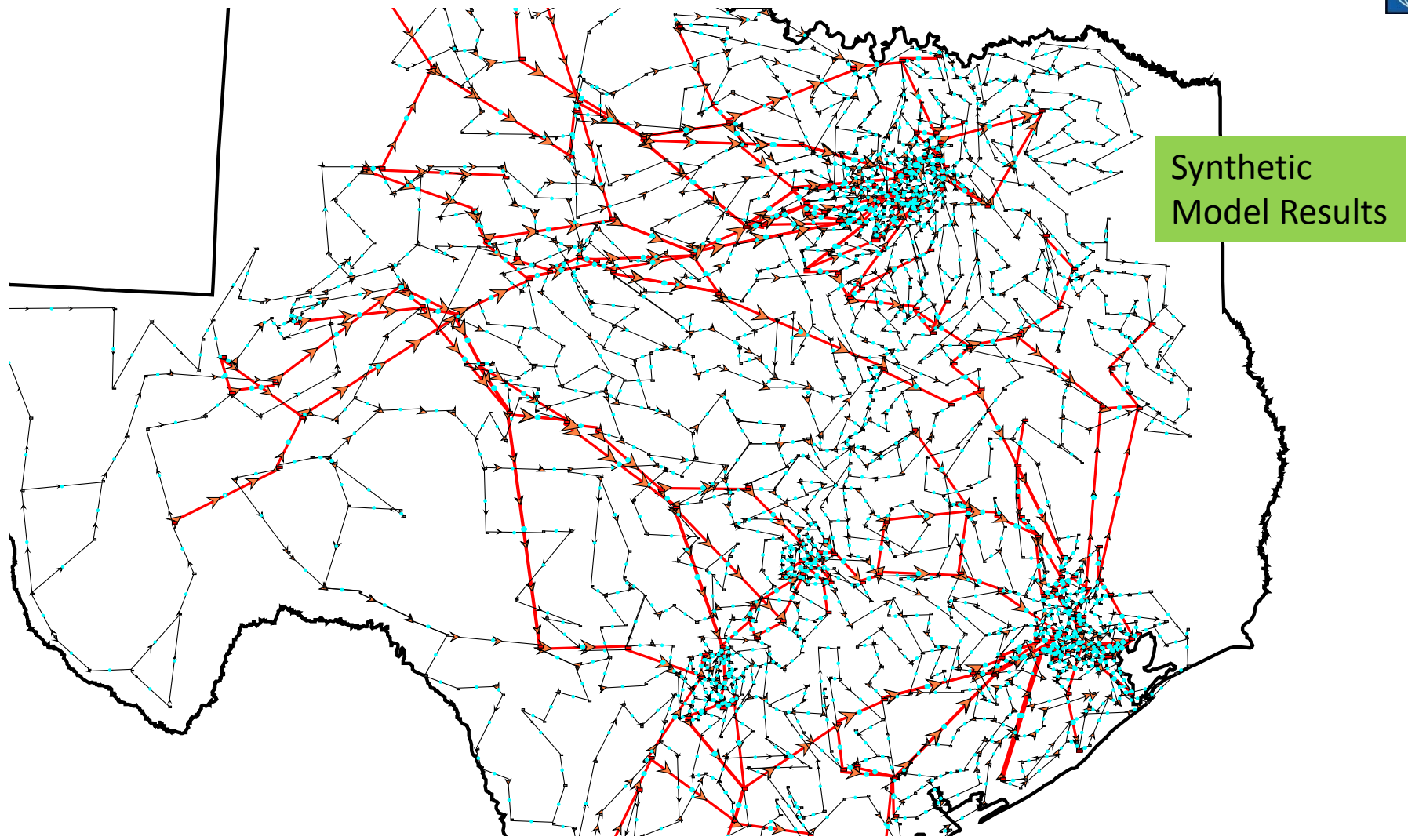
Tables and Results

Areas Buses Generators G-Matrix Lines Line Shunts Switched Shunts Substations System Summary Transformers

	Area Num	Area Name	Ignore GIC Losses	Mvar Losses	Ignore GIC DC Volts	Maximum Mvar Losses	Maximum Direction (Degrees)	Minimum Mvar Losses	Minimum Direction (Degrees)	Use Case Default Trans/Dist Voltage	Minimum Trans. kV	Default Trans. Side XF Config	Default Dist. Side XF Config
1	1	NCENT	NO	523.64	NO	525.92	81.0	281.47	158.0	YES	100.0	Case Default	Case Default
2	2	NORTH	NO	139.40	NO	158.82	148.0	106.59	59.0	YES	100.0	Case Default	Case Default
3	3	EAST	NO	83.28	NO	106.50	18.0	82.71	93.0	YES	100.0	Case Default	Case Default
4	4	SCENT	NO	179.52	NO	199.49	140.0	161.34	36.0	YES	100.0	Case Default	Case Default
5	5	WEST	NO	116.64	NO	127.35	62.0	104.30	111.0	YES	100.0	Case Default	Case Default
6	6	FWEST	NO	121.49	NO	124.85	105.0	91.00	177.0	YES	100.0	Case Default	Case Default
7	7	COAST	NO	238.47	NO	282.00	49.0	223.57	111.0	YES	100.0	Case Default	Case Default
8	8	SOUTH	NO	224.55	NO	245.00	117.0	181.49	52.0	YES	100.0	Case Default	Case Default

Synthetic Model Results

Uniform E-W Field GIC Flow Visualization



GIC Calculation: Single Snapshot, With Power Flow Solution



Include GIC in Power Flow Checked

GIC Analysis Form

Calculation Mode
☒ Single Snapshot
☐ Time Varying Series Voltage Inputs
☐ Time Varying Electric Field Inputs

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

☒ Update Line Voltages (Show be True Unless Explicitly Entered)

Select Step

- Field/Voltage Input
- Options
 - DC Current Calculation
 - AC Power Flow Model
- Tables and Results
 - Areas
 - Buses
 - Generators
 - G-Matrix
 - Lines
 - Line Shunts
 - Switched Shunts
 - Substations
 - System Summary
 - Transformers
- Sensitivity Analysis
- Non-Uniform Electric Field Solution
 - Geomagnetic Latitude Scaling
 - Earth Resistivity Scaling
 - Time Varying Electric Field Inputs

Tables and Results

Areas Buses Generators G-Matrix Lines Line Shunts Switched Shunts Substations System Summary Transformers

	Area Num	Area Name	Ignore GIC Losses	Mvar Losses	Ignore GIC DC Volts	Maximum Mvar Losses	Maximum Direction (Degrees)	Minimum Direction Mvar Losses	Minimum Direction (Degrees)	Use Case Default Trans/Dist Voltage	Minimum Trans. kV	Default Trans. Side XF Config	Default Dist. Side XF Config
1	1	NCENT	NO	521.53	NO	525.92	81.0	281.47	158.0	YES	100.0	Case Default	Case Default
2	2	NORTH	NO	138.68	NO	158.82	148.0	106.59	59.0	YES	100.0	Case Default	Case Default
3	3	EAST	NO	83.14	NO	106.50	18.0	82.71	93.0	YES	100.0	Case Default	Case Default
4	4	SCENT	NO	179.24	NO	199.49	140.0	161.35	36.0	YES	100.0	Case Default	Case Default
5	5	WEST	NO	116.32	NO	127.35	62.0	104.30	111.0	YES	100.0	Case Default	Case Default
6	6	FWEST	NO	120.79	NO	124.85	105.0	91.00	177.0	YES	100.0	Case Default	Case Default
7	7	COAST	NO	238.12	NO	282.00	49.0	223.57	111.0	YES	100.0	Case Default	Case Default
8	8	SOUTH	NO	204.03	NO	218.43	117.0	181.49	52.0	YES	100.0	Case Default	Case Default

Save Setting to Aux Load AUX Save in PSSE GIC Format Load in PSSE GIC Format Clear All GIC Input Fields

Note the total MVAR losses have changed slightly

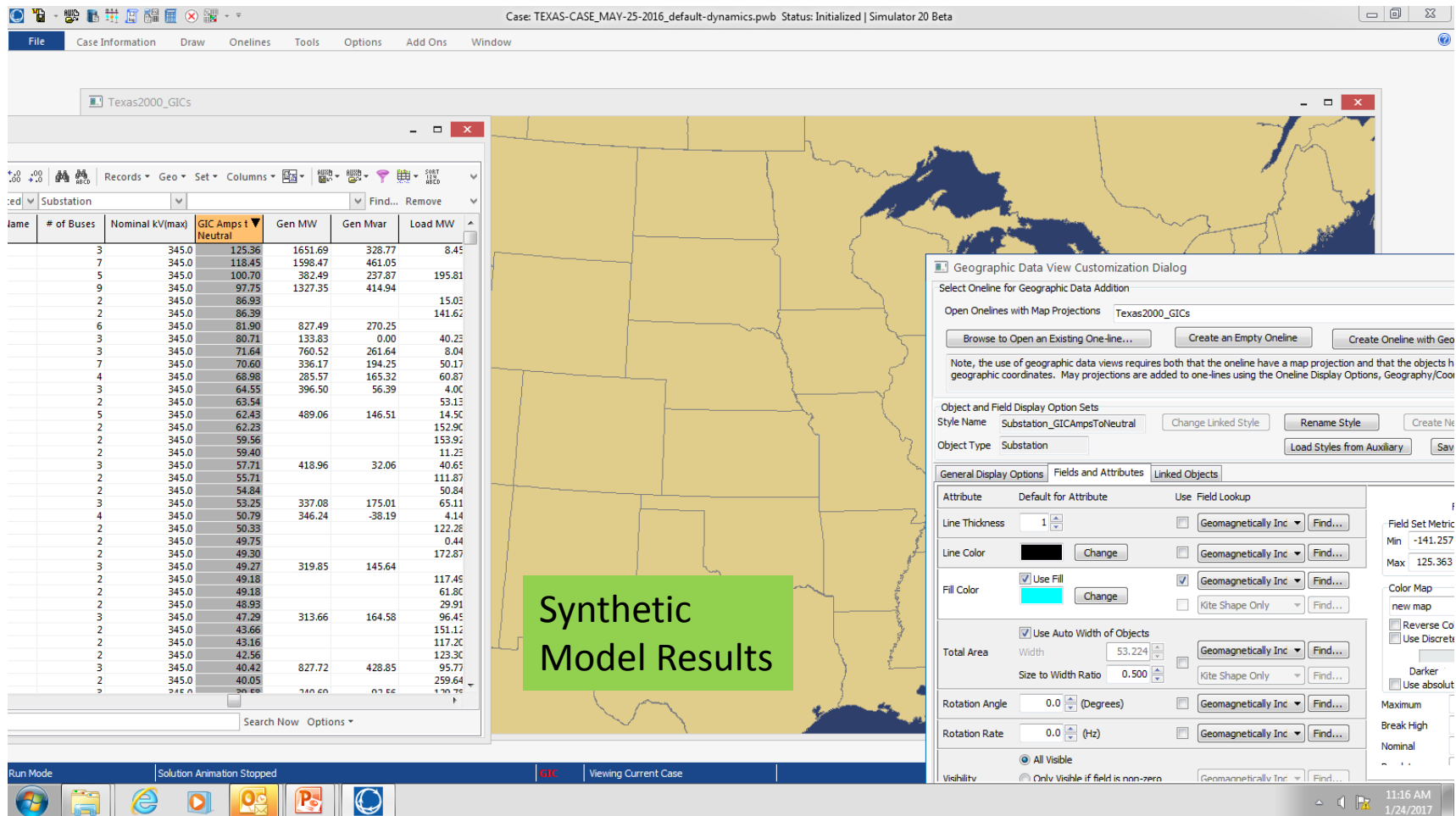
Synthetic Model Results

Visualization of Results with GDVs

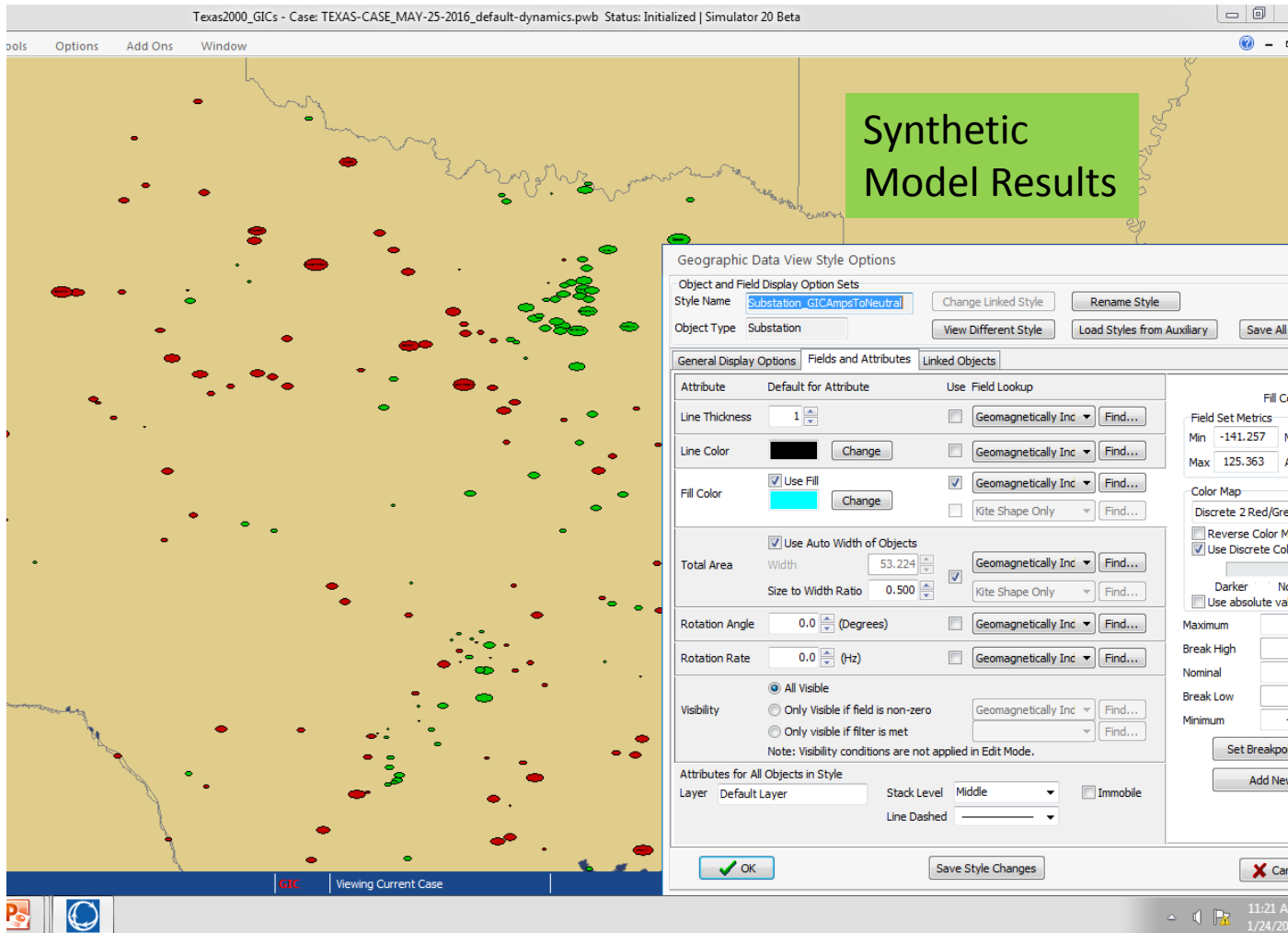


- Geographic data views (GDVs) provide a quick way for visualizations large amounts of geographic data
 - Ideal for GIC visualization since geographic coordinates are available
- Example shows how GDVs can be used to show the net substation GIC injections
- From a case information display with geo-linked objects, like substations, select the field of interest, and then select Geographic Data View
 - GDVs are usually shown on a map-based (often empty) one-line, which can be provided by PowerWorld

GDV Substation GICs Example



GDV Substation GICs Example



Once customized, GDVs can be saved liked regular onelines, and can also be readily modified; red and green are used to show the neutral flow direction

Generating Time-Varying Input Electric Fields



- A time-varying electric field input can be quickly calculated for the public E3A and E3B waveforms
- Because of high degree of non-linearity in the E3B function, it needs to be centered for a particular latitude and longitude

GICs can then be calculated at a particular time, either with or without a power flow solution

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	Timepoint_9
1 Time in Seconds																	
2 Branch '1' '1874' '1'	1	1874	1	32.2984	32.2984	-97.7855	-97.7855	0.00	0.000	3.134	3.582	5.373	6.716	7.164	8.507	10.000	10.000
3 Branch '2' '4' '1'	2	4	1	32.9290	32.9474	-96.8045	-96.8957	8.77	0.000	33.856	63.682	124.946	76.580	-31.438	-0.807	0.000	0
4 Branch '2' '39' '1'	2	39	1	32.9290	33.0213	-96.8045	-96.7416	11.80	0.000	-23.340	-43.902	-86.137	-52.794	21.673	0.556	0.000	0
5 Branch '2' '112' '1'	2	112	1	32.9290	32.8924	-96.8045	-96.7328	7.84	0.000	-26.617	-50.066	-98.230	-60.205	24.716	0.634	0.000	0
6 Branch '2' '115' '1'	2	115	1	32.9290	32.8896	-96.8045	-96.8157	6.80	0.000	4.156	7.818	15.338	9.401	-3.859	-0.099	0.000	0
7 Branch '3' '13' '1'	3	13	1	33.0896	33.0744	-96.6078	-96.7357	12.06	0.000	47.395	89.148	174.911	107.204	-44.010	-1.129	0.000	0

Synthetic Model Results

Example GICs using GDVs

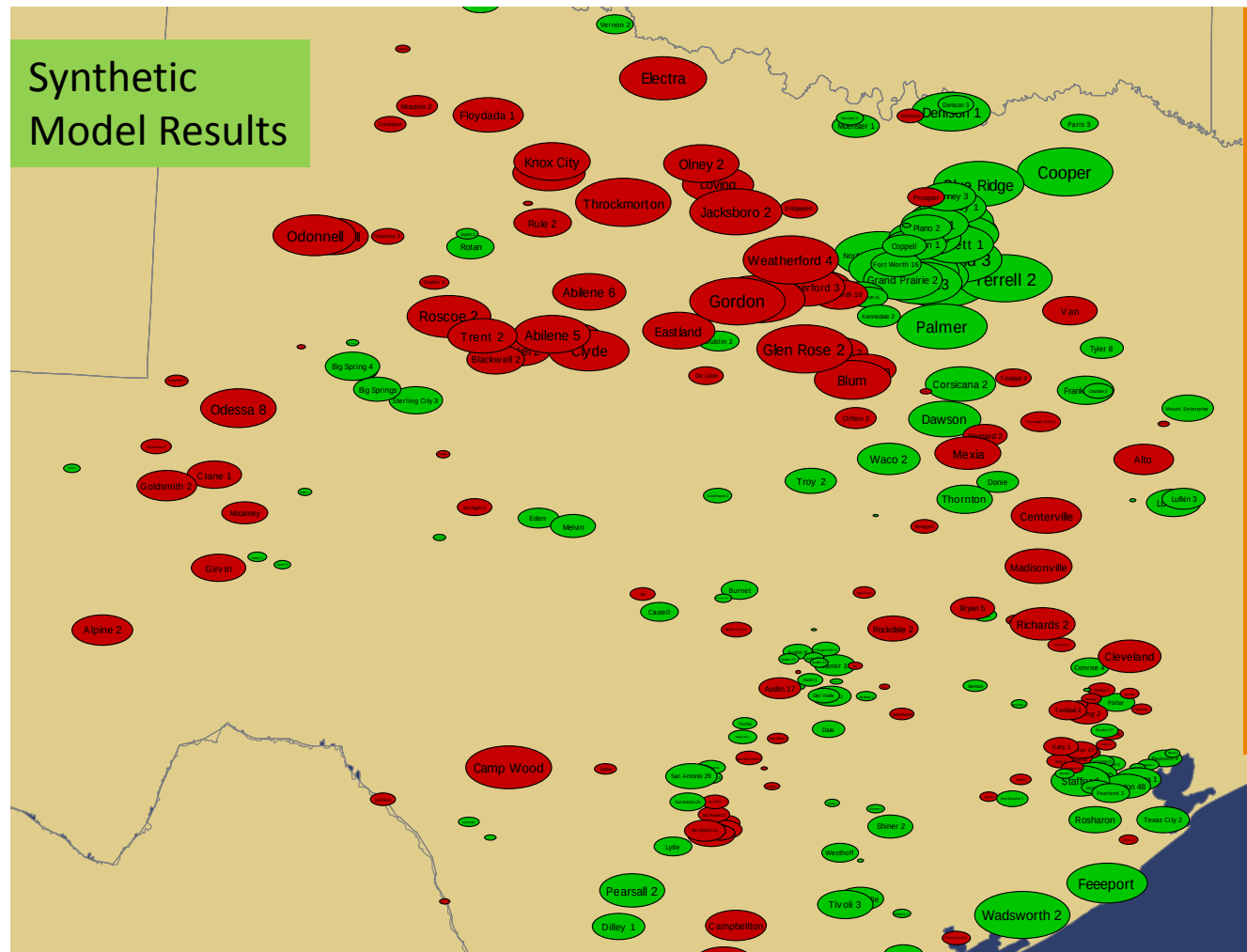
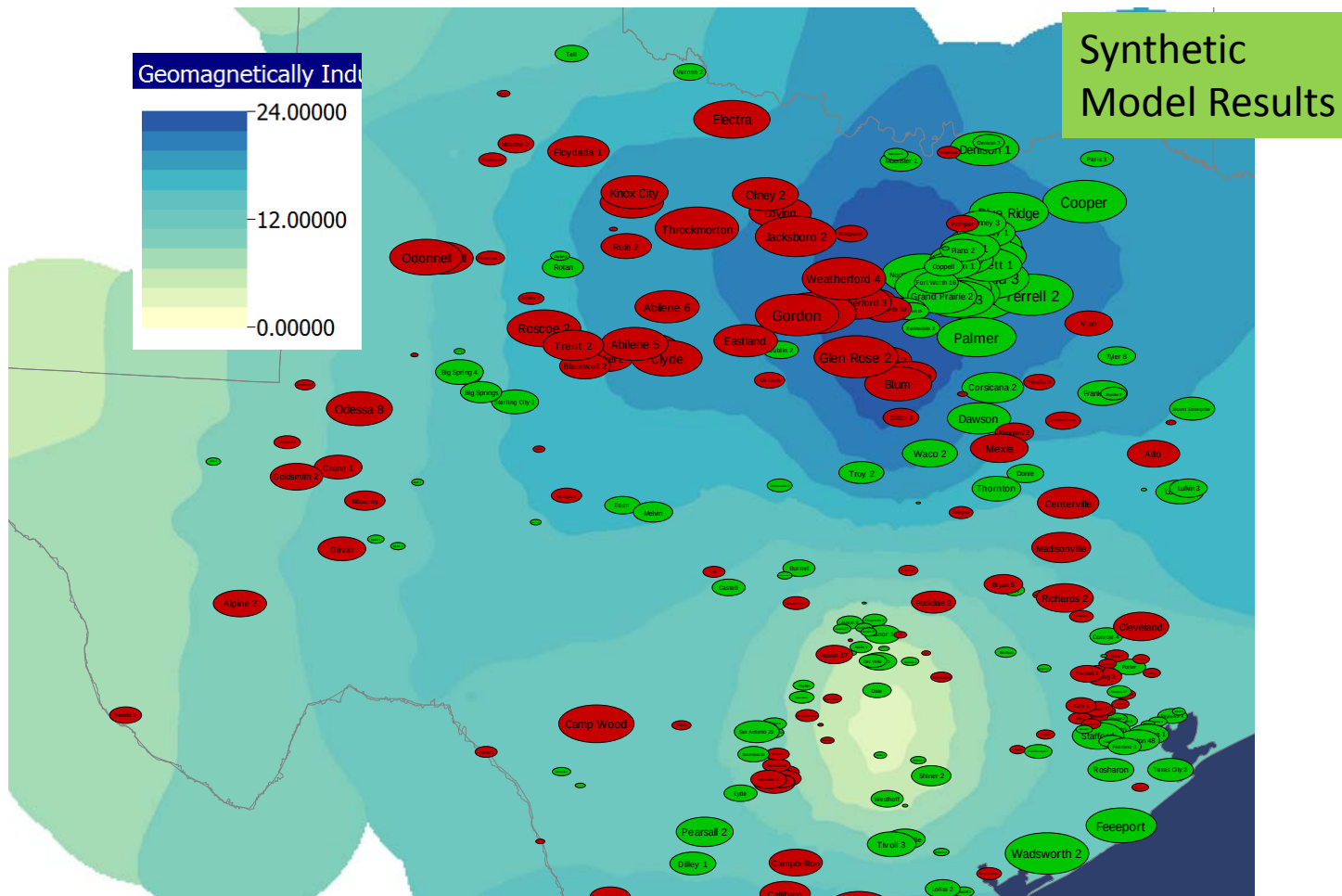


Image uses GDVs to visualize the GICs at a particular time point; red and green are used to show substation neutral flow direction

GDV Contouring



- GDVs can also be used to easily contour results



Time-Varying GIC Calculations with no Power Flow Solution



- The full consideration of rapidly varying GICs requires a full transient stability solution. This will be considered shortly
- PowerWorld also provides a quick, screening tool in which transient stability storage functionality can be used while not solving the full network solutions
 - This is equivalent to a time-varying solution of the regular GICs without a power flow solution
 - The method accurately calculates the GICs, which can be used for other studies, but not the voltage impacts
 - This is done by setting the “transient stability time step to a large value, like one second

Time-Varying GIC Calculations with No Power Flow Solution



Transient Stability Analysis

Simulation Status: Not Initialized

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

Select Step

- Simulation
 - Options
 - General
 - Power System Model
 - Common
 - Compatibility Options
 - Result Options
 - Generic Limit Monitors
 - User Defined Models
 - Distributed Computing
 - Result Storage
 - Store to RAM Options
 - Generator
 - Bus
 - Load
 - Switched Shunt
 - Branch
 - Transformer
 - DC Transmission Line
 - VSC DC Line
 - Multi-Terminal DC Recc
 - Multi-Terminal DC Conv
 - Area
 - Zone
 - Interface
 - Injection Group
 - Substation
 - Line Shunt
 - Case Information
 - Measurement Model

Options

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

General | Power System Model | Result Options | Generic Limit Monitors | User Defined Models | Distributed Computing

Common | Compatibility Options

Power System Values

Nominal System Frequency (Hz) 60.0

Initial System Frequency (Hz) 60.000

☒ When Using Playin Models Set Initial Hz to First Value

System MVA Base 100.00

Network Equations Solution Options

Solution Tolerance (MVA) 0.10000

Maximum Iterations 25

Force Network Equation Update 0.00

☒ Use Voltage Extrapolation

Inner Loop Mismatch Scalar 1.0

Infinite Bus Modeling

☒ No infinite buses (recommended setting)

☐ Model the power flow slack buses as infinite buses

Handling of Initial Limit Violations

☒ Modify Limits and Run

☐ Abort

☐ Run without Changing Limits

Default Load Model

☐ Constant Impedance

☐ ZIP Model from Power Flow Model

☐ Constant Current

☒ Constant Current P, Impedance Q

Minimum Per Unit Voltages for Models with

Constant Power 0.700

Constant Current 0.500

Change

When to use Complex Load Models

Minimum Load P (MW) 0.500

Minimum Load P/Q Ratio 0.25

Minimum Initial per unit voltage 0.00000

Complex Loads represent a composite of various of load types. Examples include CLOD, CPMLDW, and MOTORW.

These filters are also used for Distribution Equivalent Models.

Distribution Equivalent Models Options

Min Nom kV for Transformer 0.00

Integration Method

☒ Second Order Runge-Kutta

☐ Euler

Geomagnetic Induced Current Options

☒ Include GIC Effects

☒ Just Calculate GIC with No Network Solution

GIC XF Time Constant (Sec) 0.0

Frequency Measurement Options

Bus Frequency Measurement Time Constant (Sec.) 0.050

Minimum PU voltage for relay frequency measurement 0.300

Option to ignore the network solution

Time-Varying GIC Calculations with No Power Flow Solution

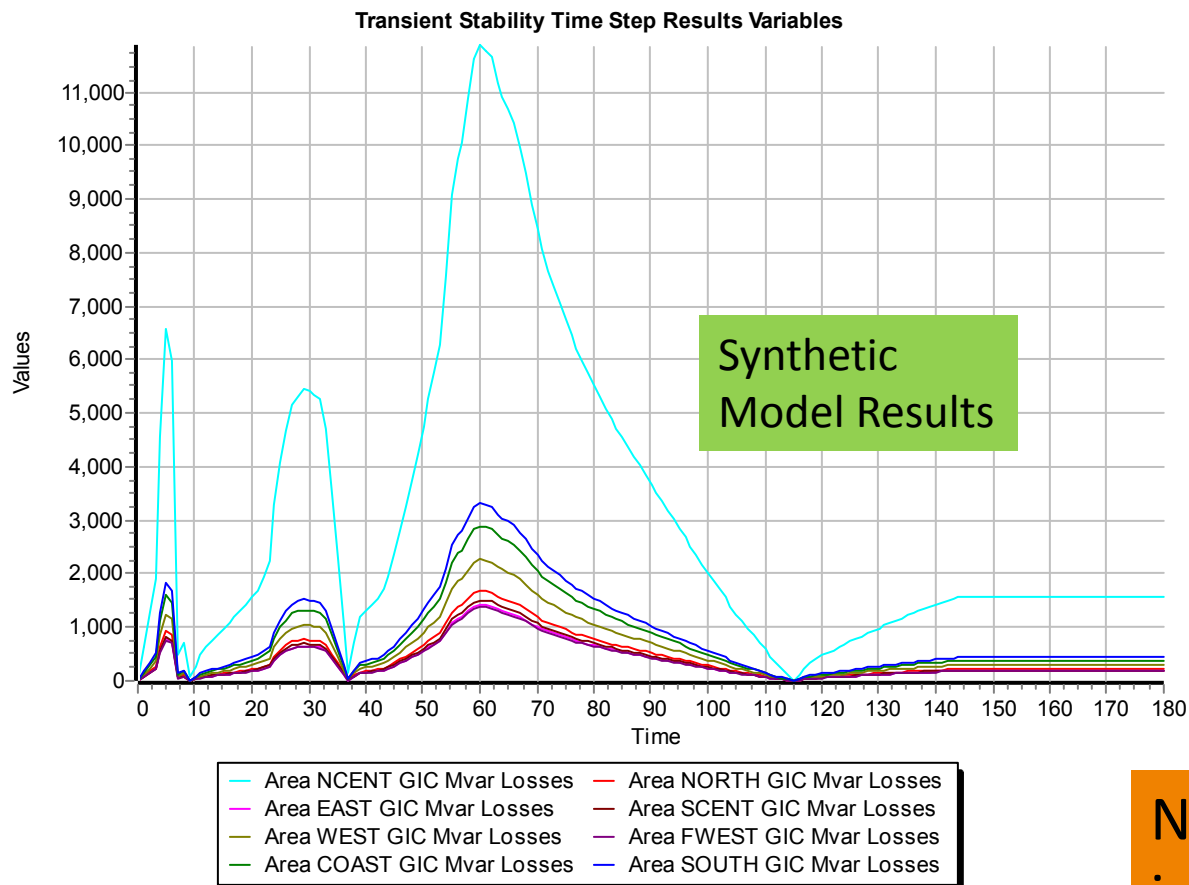


Image shows the variation in the time variation by area in the GIC induced reactive power losses for the synthetic 2000 bus system

No voltage variation is modeled with this approach

Transient Stability Solution with Time-Varying GIC Calculations

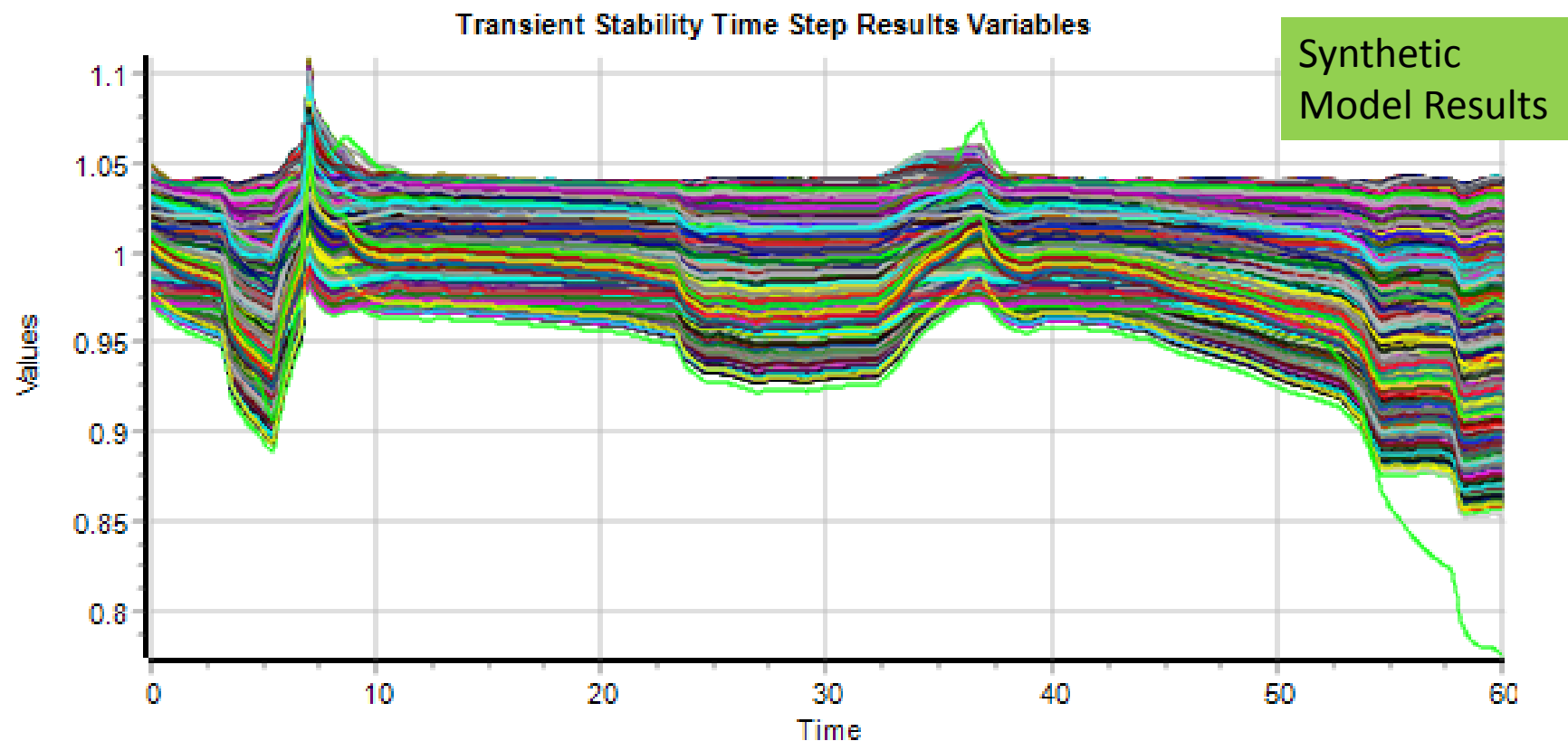


- The final option is to do a regular transient stability solution in which the GICs, and any associated reactive currents, are determined each time step
 - Compared to the previous example, the time step needs to be set to a small value, such as $\frac{1}{4}$ cycle
- This approach allows full consideration of GICs, while including all the transient stability models
- Like any transient stability solution, the results depend upon the input assumptions, including the load model

Transient Stability Solution GIC Results



- Below graph plot the time-variation in system voltages over 60 seconds of simulation using a static load model



Transient Stability Toolbar



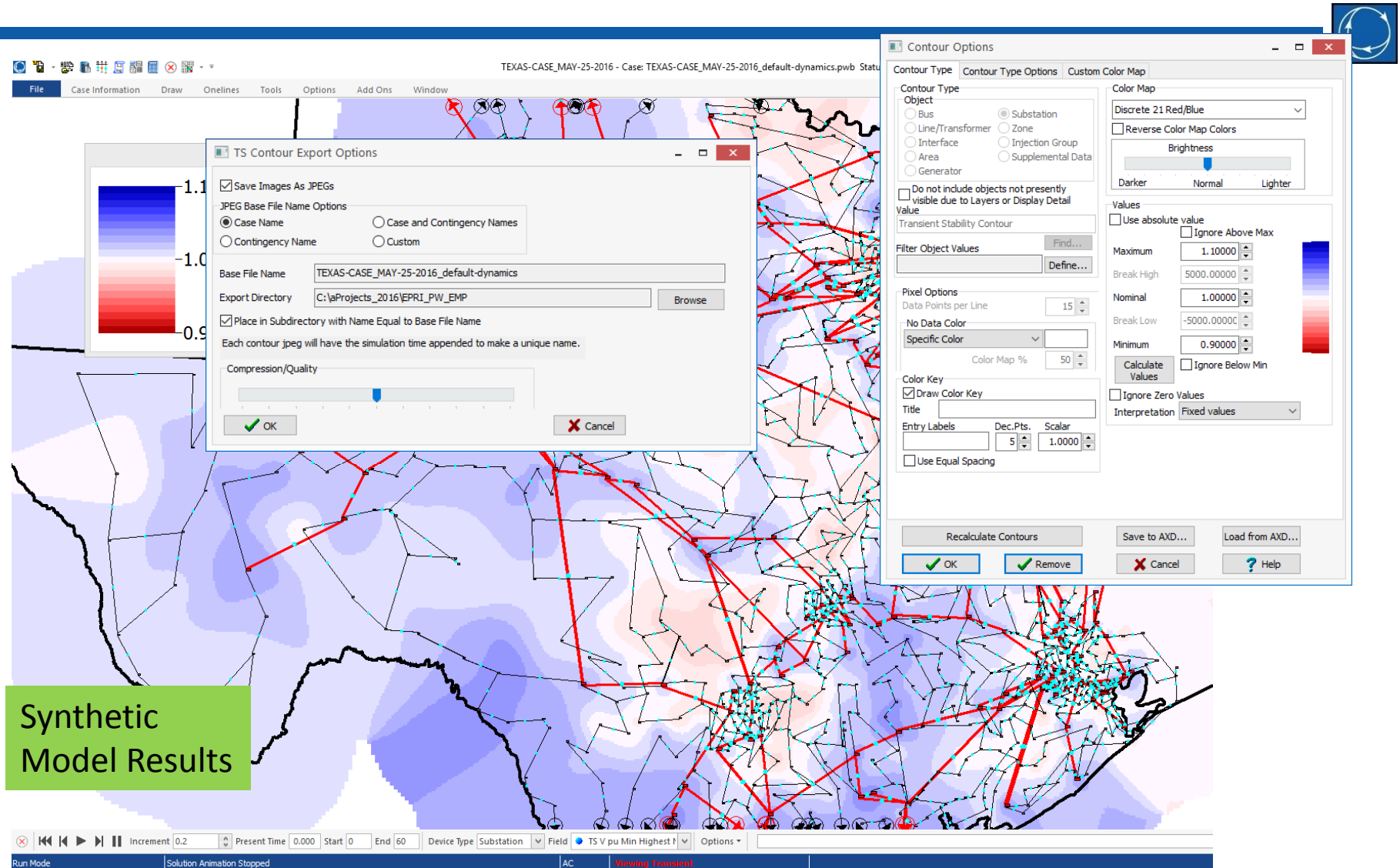
- The transient stability contour toolbar allows for the rapid creation of a time-sequenced online contours of transient stability results
 - Can leverage displays created with GDVs
- These displays can then be made into a movie by either
 - Capturing the screen as the contours are creating using screen recording software such as Camtasia
 - Or having Simulator automatically store the contour images as jpegs and then creating a movie using software such as Microsoft Movie Maker
- Will be used here to visualize the time-varying substation voltage magnitudes

Transient Stability Toolbar, cont.

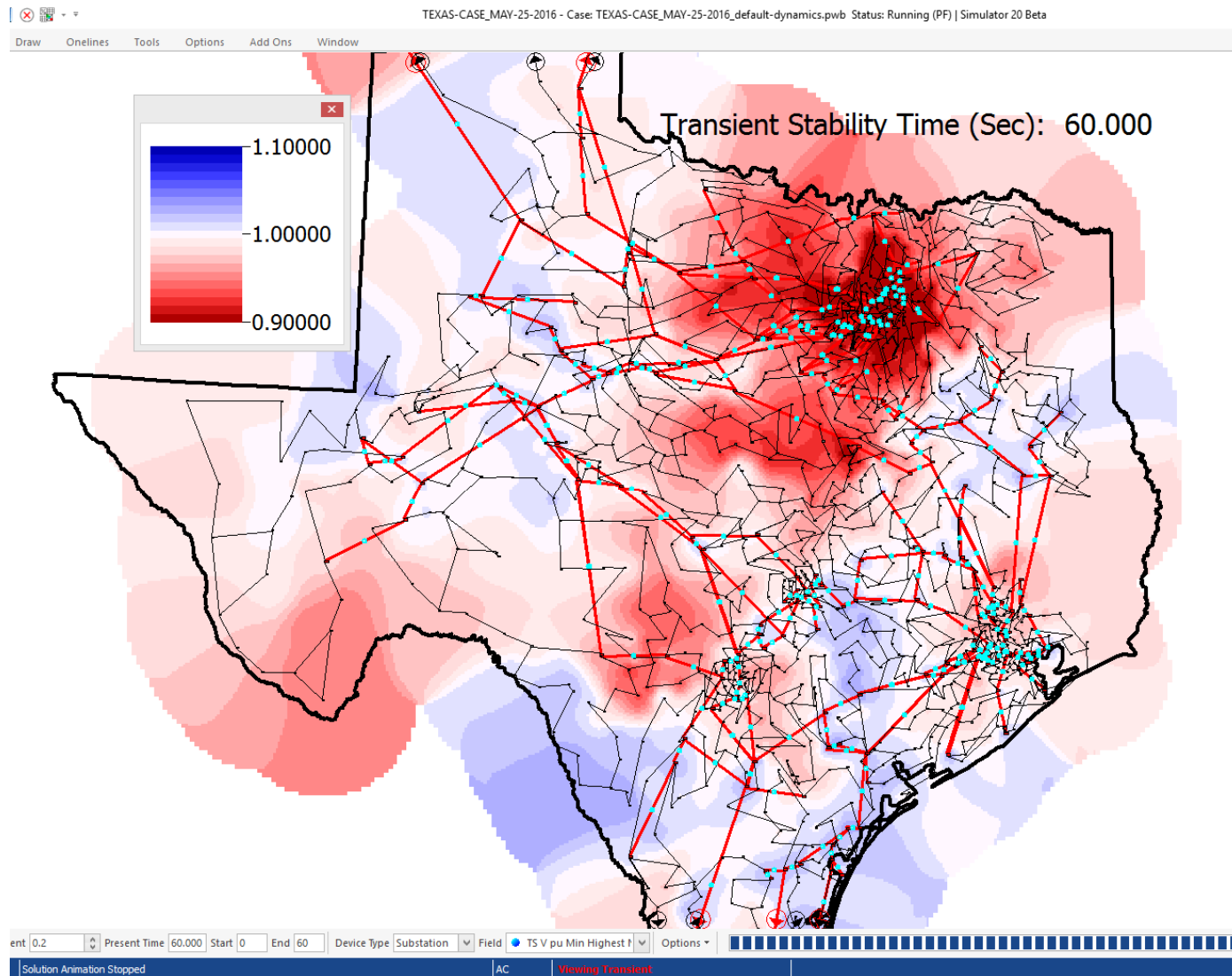


- The contour toolbar uses stored transient stability results, and hence it is used only after the transient stability solution has finished
 - It can be used with results that are either saved RAM or saved to the hard drive
- It requires having a oneline with objects associated with the desired results (such as buses, generators, substations, etc)
 - Again these can be auto-created with GDVs
- The contour toolbar is shown by either
 - **Add-ons, Stability Case Info, Show Transient Contour Toolbar**
 - On the Transient Stability Analysis Form select the **Show Transient Contour** Toolbar button at the bottom of the form

Transient Stability Toolbar Example



Voltage Stability Movie





Wrap-up Questions and Comments