Application of Synthetic Networks for PMU Data Synthesis, Analysis, and Visualization

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Acknowledgments and Thanks

- Work presented in these slides is based on the results of several projects including
  - PSERC S-62G (Seamless Bulk Electric Grid Management with EPRI)
  - PSERC T-57 (High Impact)
  - BPA project TIP 353 (Improving Operator Situation Awareness by PMU Data Visualization
  - BPA project TIP 359 (Improved System Modeling for GMD and EMP Assessments)
  - ARPA-E GRID DATA Synthetic Data for Power Grid R&D
- Support is gratefully acknowledged!
  - Thanks also to Tom Overbye, Adam Birchfield, Kathleen Gegner, Ti Xu, Richard Macwan, Bob Thomas, Anna Scaglione, Zhifang Wang, and Ray Zimmerman

Outline

- Synthetic Networks
  - Why they are needed
  - Creation methodology
  - Example
- Synthetic PMU Data
  - Streaming and C37.118 protocol
  - Saving in COMTRADE format (C37.111)
- Visualizing Synthetic PMU Data
  - Transient Stability
  - EMP

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Why Synthetic Networks?

- Access to PMU data for researchers is often restricted because of requirements for data confidentiality
  - Research and development of algorithms / applications hindered by this
- “Synthetic PMU data” can be generated from dynamic simulations of power grid models
  - Actual grid model data is also hard to acquire due to CEII concerns
  - NDA’s restrict the publishing and reproducibility of results

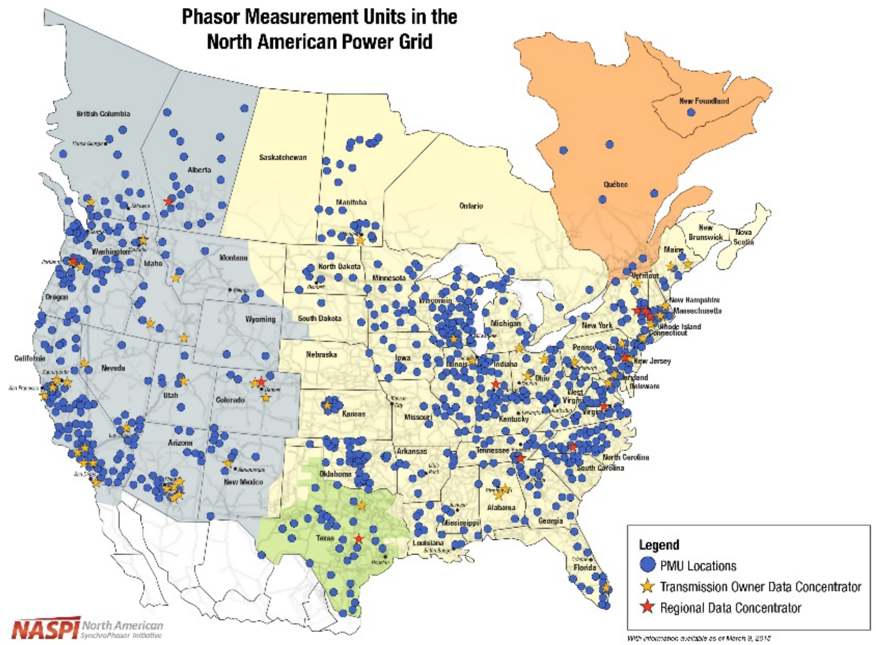

Image source: https://www.naspi.org/documents

Why Synthetic Networks? - Goals

- Goal of this work is to create Synthetic Power Grid (fictitious) models that mimic the complexity of the actual grid cases but will contain no confidential data and can be publicly available
  - Focus here is on high voltage power flow, optimal power flow, transient stability models, SCADA, PMUs
  - Models that incorporate both the average characteristics and outlier characteristics of the actual grid
  - Models and scenarios suitable for security constrained optimal power flow (SCOPF) studies; they will also be set for use in transient stability and geomagnetic disturbance analysis
  - All models will have embedded geographic coordinates

- We want to partner with industry!

Why Synthetic Networks? - Complexity

- Few, if any, of the existing public models (such as the IEEE 300 bus) match the complexity of the models used for actual large-scale grids
- Issues include size, with Eastern Interconnect models now > 70,000 buses, and also model complexity
  - Eg. voltage magnitude is controlled at about 19,000 buses (by Gens, LTCs, switched shunts) 94% regulate their own terminals with about 1100 doing remote regulation. Of this group 572 are regulated by two or more devices, 277 by three or more, twelve by eight or more, and three by twelve devices!
- Innovation is hindered by not being able to compare results for complex models

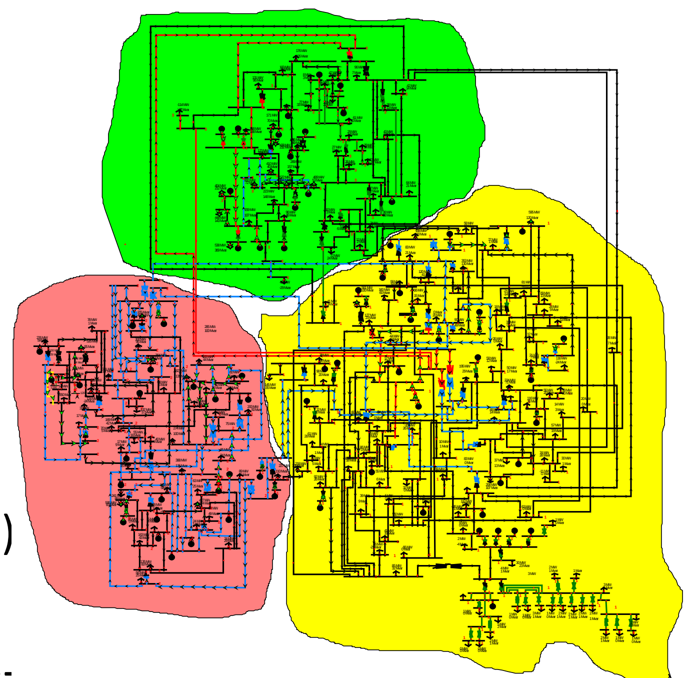

Image: IEEE 300 Bus case downloaded from http://icseg.iti.illinois.edu/ieee-300-bus-system/

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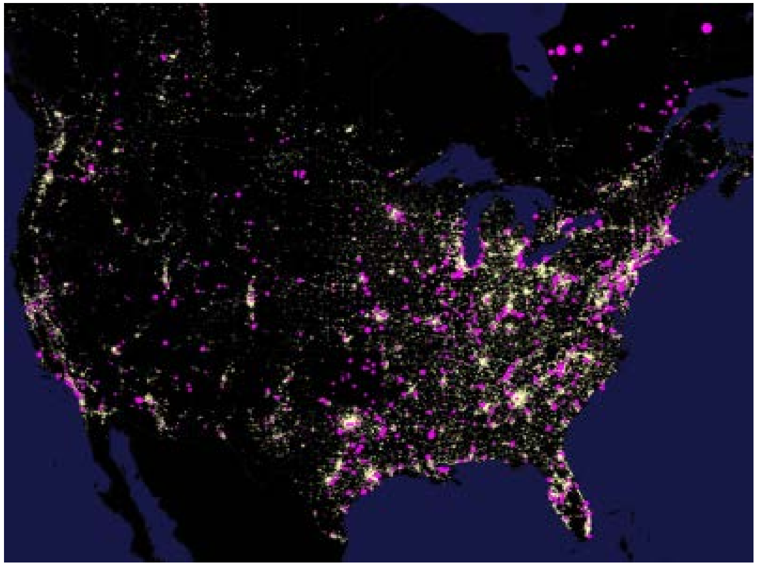
Creation Methodology - Realistic yet Synthetic

- The challenge is to capture the essence of what makes actual grid models different
- Statistics used to quantify characteristics
  - topology, parameters for buses, generators, loads,
    transmission lines, transformers, switched shunts, transient stability and GMD parameters
- System-wide metrics are also needed
- Idea is to make models that look real and familiar by siting these synthetic models in North America, and serving a population density the mimics that of North America
  - The transmission grid is, however, totally fictitious
- Goal is to leverage available public data
  - Geography, Population density, Load by utility and state-wide averages, generation



Generation and Load Density in North America

Creation Methodology: 1. System Size and Footprint

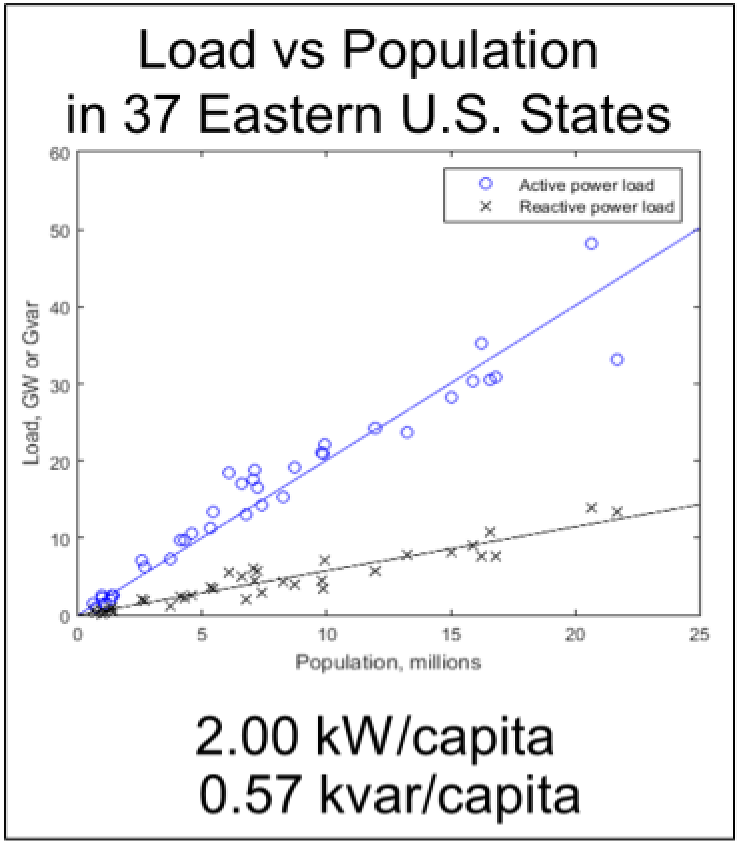
- First step is to select a desired size (bus count) and geographic footprint
  - These are two independent parameters: for example, geographically large with a small number of buses
  - Our approach does not require that we use actual geography; however most, if not all, of our models will
  - Requires an assumption on underlying load density
  - Nominal transmission voltages need to be selected (e.g., 500/230/115 kV); we will allow multiple levels
  - On larger models the geographic footprint is divided into balancing authority areas and fictitious owners

Creation Methodology: 2. Substation Selection

- The next step is to site the substations
  - Buses are located in substations; number of buses in a substation can vary widely
  - Most substations have load and/or generation; number of buses can depend on model assumptions, such as whether generator step-up transformers are modeled
- Substation are sited geographically primarily in order to meet load and generation requirements
  - One approach for the assumed load density is mimic population density as given by zip code information
  - Number of substation depends on the desired model size; in actual models the amount of substation load can widely vary (from 1 MW to more than 500 MW)

Creation Methodology: 2.a Substation Selection - Loads

- In our approach substations are placed geographically at post offices (i.e. by zip code)
- The load is proportional to population, taking into account state variation
- Hierarchical clustering is used to reduce the number of substations as needed
- Load is usually attached at lowest-voltage bus



Creation Methodology: 2.b Substation Selection - Generation

- Form EIA-860 contains information about generators 1 MW and larger; data includes location, capacity and fuel type
  - Actual company names will not be used
- Based on actual model statistics, some generation is located at existing load substations
- Other plants are combined into generator-only substations
- Generator parameters, including reactive power limits and cost information, are derived from statistics
- Transient stability models are added

Statistics derived from real power system case

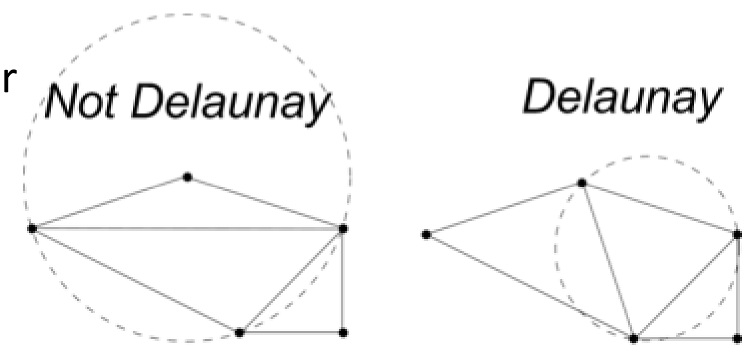
Governor Type	Max Mvar as fraction of MW capacity	Mvar range as fraction of MW capacity
Steam	0.466	0.588
Gas	0.509	0.620
Gas Turbine	0.560	0.624
Hydro	0.384	0.433
Nuclear	0.368	0.450
Wind	0.213	0.357

Creation Methodology: 2.c Substation Selection – Voltage Levels

- Each substation now has load/generation defined
  - Statistically about 90% in actual grid have load or gen
- Different system voltage levels are chosen
  - E.g., 500/161, 765/345/138, 500/230/115
- Almost all substations have lower voltage bus
- A percent of substations (e.g.,15%) also include higher voltage buses and transformers
- Higher-voltage substations are iteratively selected with probabilities proportional to load
- All large (> 250 MW) generators are placed at the higher voltage level, but with a GSU

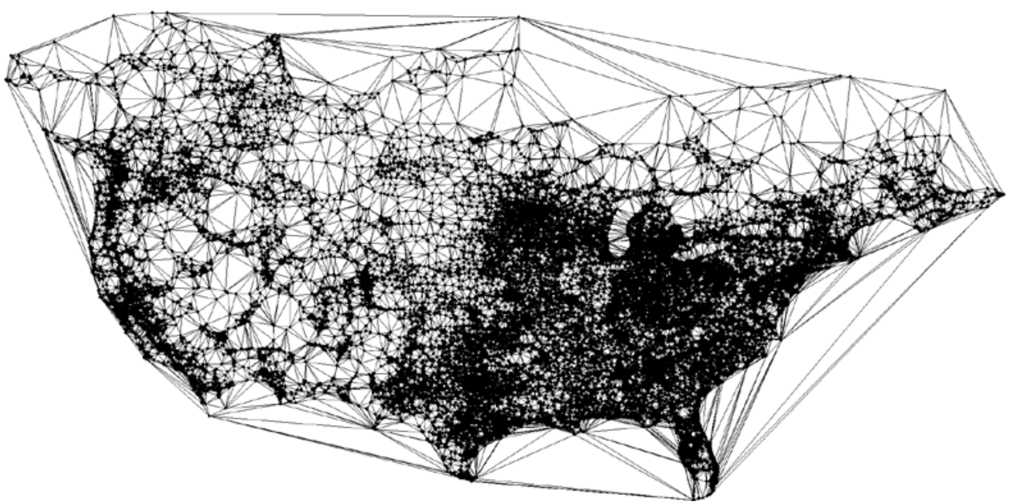
Creation Methodology: 3.a Transmission Line Placement

- Substations are connected together by transmission lines
  - Need to match statistics for number of connected substations at each voltage level
  - Average nodal degree $\langle k \rangle = 2.43$, nearly constant with n for single-voltage networks in EI
  - Number of lines $m = \frac{\langle k \rangle n}{2} = 1.22n$
- Graph theory used to determine which substations are connected
  - An approach is Delaunay triangulation with minimum spanning tree analysis
  - Delaunay triangulation
    - No triangle's circumcircle contains another point
    - Nearest few neighbors are connected
  - Contains 70% of real lines on average

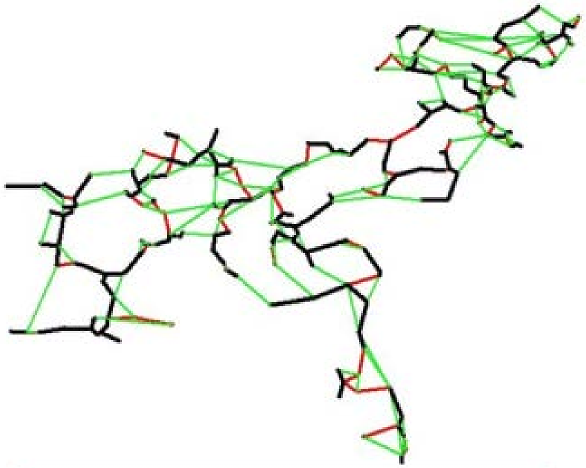


Creation Methodology: 3.a Transmission Line Placement

- Graph theory used to determine which substations are connected
  - Typical actual power system contains 60% of its substations' MST at each nominal voltage level (percent varies by voltage level). Approach is to match this %
- Then other lines are added to match the typical average m



Delaunay triangulation of 42,000 North America substations; statistics only consider single voltage levels; computationally fast (order n ln(n))



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

Creation Methodology: 3.b Transmission Line Parameters

- Transmission line parameters from EPRI & ACSR guides
- Different configurations for each voltage level:

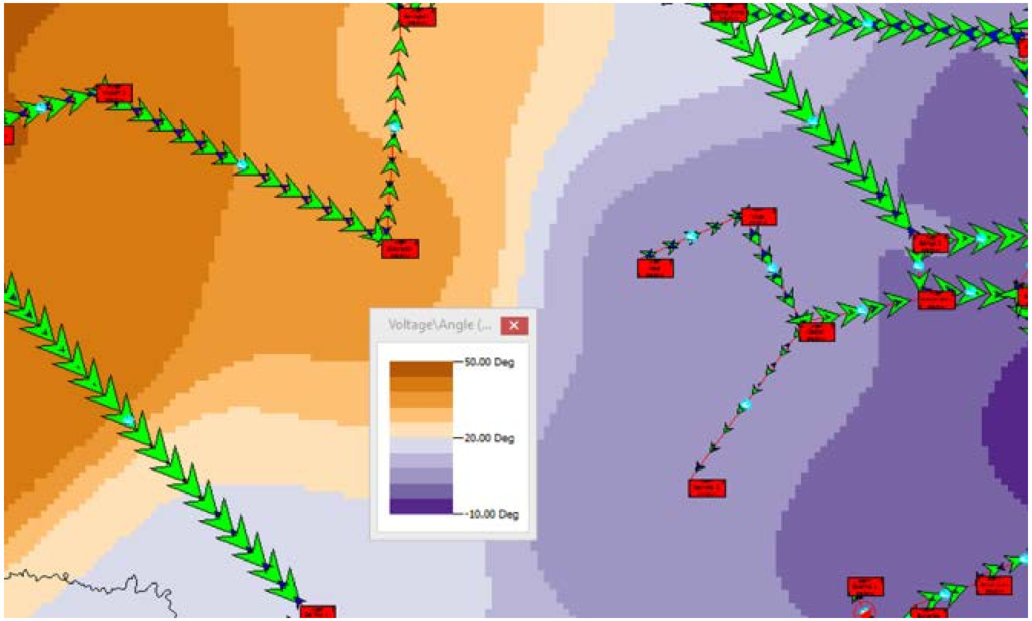
Example: 345 kV lines

Conductor	Tower Type	X, pu, per 100 miles	X/R ratio	B, pu, per 100 miles	MVA limit
Martin 2-bundle	Steel Horizontal	0.049	10.40	0.850	1207
	Steel Triangular	0.046	9.61	0.922	1207
	Wood Horizontal	0.050	10.53	0.839	1207
Finch 2-bundle	Steel Horizontal	0.049	12.01	0.857	1327
	Steel Triangular	0.045	11.09	0.930	1327
	Wood Horizontal	0.049	12.16	0.846	1327
Cardinal 2-bundle	Steel Horizontal	0.048	14.34	0.866	1494
	Steel Triangular	0.045	13.23	0.941	1494
	Wood Horizontal	0.049	14.52	0.855	1494

These parameters are validated against real transmission lines

Creation Methodology: 4. Iterative Updates to Obtain a Feasible DC Power Flow Solution

- A connected graph allows dc power flow solutions
- Iteratively add lines to obtain a dc power flow with no line flow violations
- Candidate lines are segments of the Delaunay triangulation or near neighbors
- Select lines based on:
  - Voltage angle gradient, indicating likely power flow
  - Avoid radial substations
  - Encourage parallel circuits to overloaded lines
  - Forbid lines exceeding a maximum length



Based on voltage angle gradient, this might be a good location to place a transmission line

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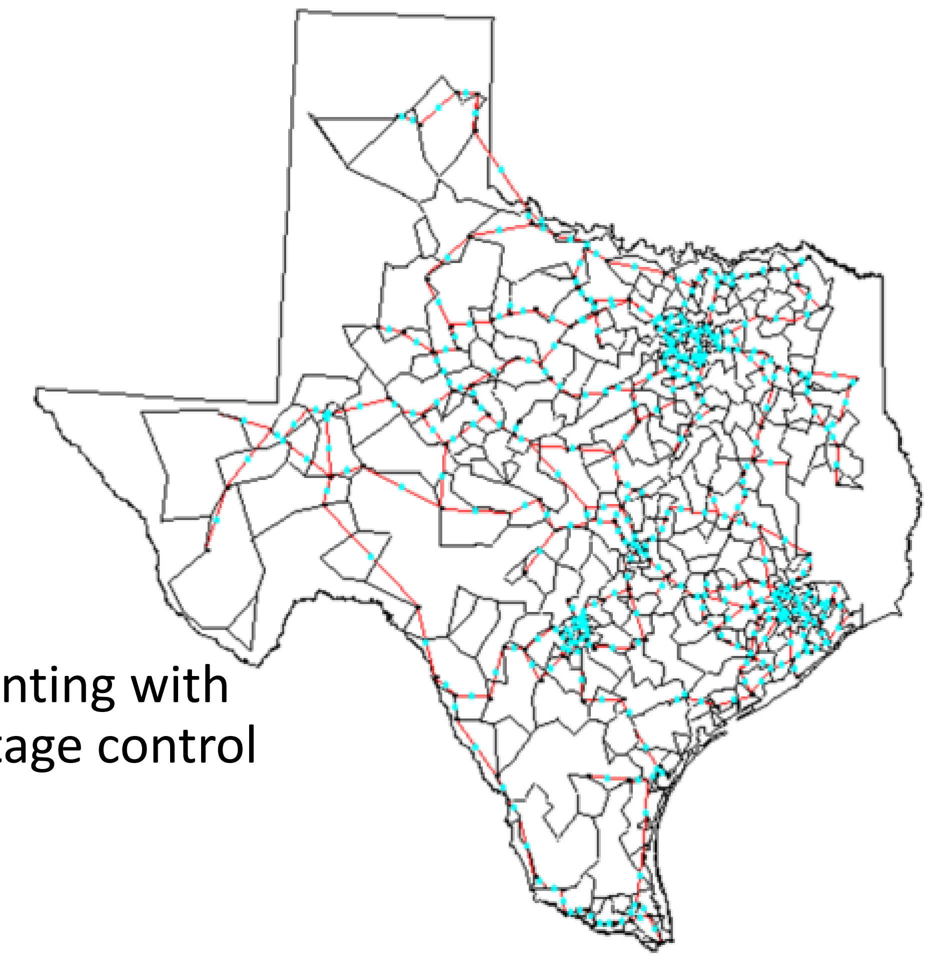
1500 Substation, 2100 Bus Texas Example

- Texas geographic footprint
- No relationship to actual transmission grid
  - Nominal 345/115 kV grid
- 1500 substations, 2092 buses, 282 gens, 2857 branches
- Automatic line placement takes about 70 seconds
- Currently we are supplementing with manual adjustment for voltage control



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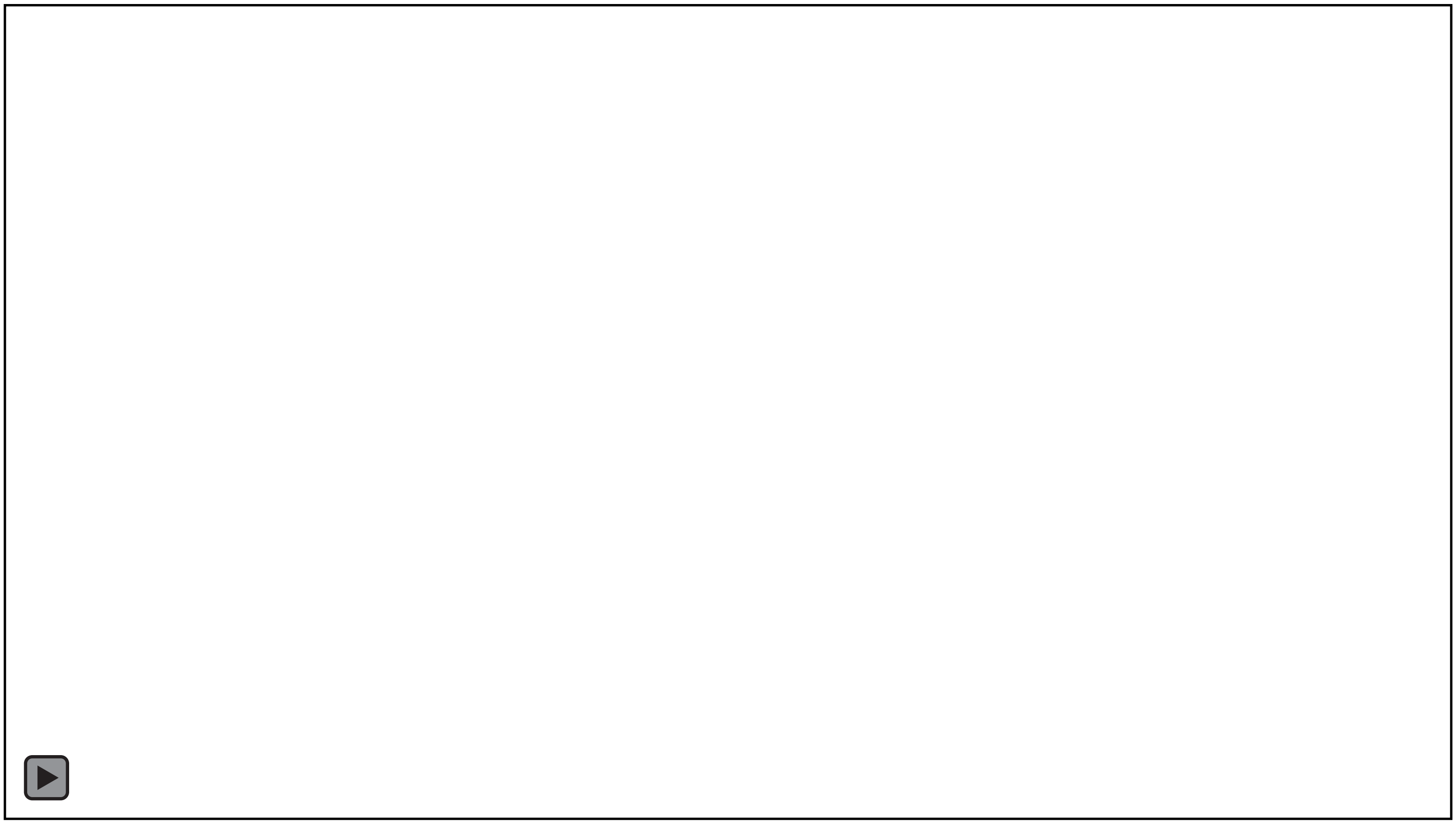
Streaming and C37.118 protocol

- Using PowerWorld Dynamic Studio (DS)
  - Demo version download: http://www.powerworld.com/gloveroverbyesarma
- DS acts a server, outputting dynamic simulation results of a *.pwb case in C37.118 format over TCP
  - Easy to convert RAW/DYR, and EPC/DYD files to PWB
- Client(s) can be written to interact with the simulation
  - Issue control commands
  - Get output channels
  - Tested with GPA's PMU Connection Tester (https://pmuconnectiontester.codeplex.com)
- Contingencies, output channels, and strip charts for visualization can be pre-defined for the *.pwb case in PowerWorld Simulator
- Real-time simulation and streaming possible
  - Depends on size of the system, computing capabilities

Streaming and C37.118 protocol



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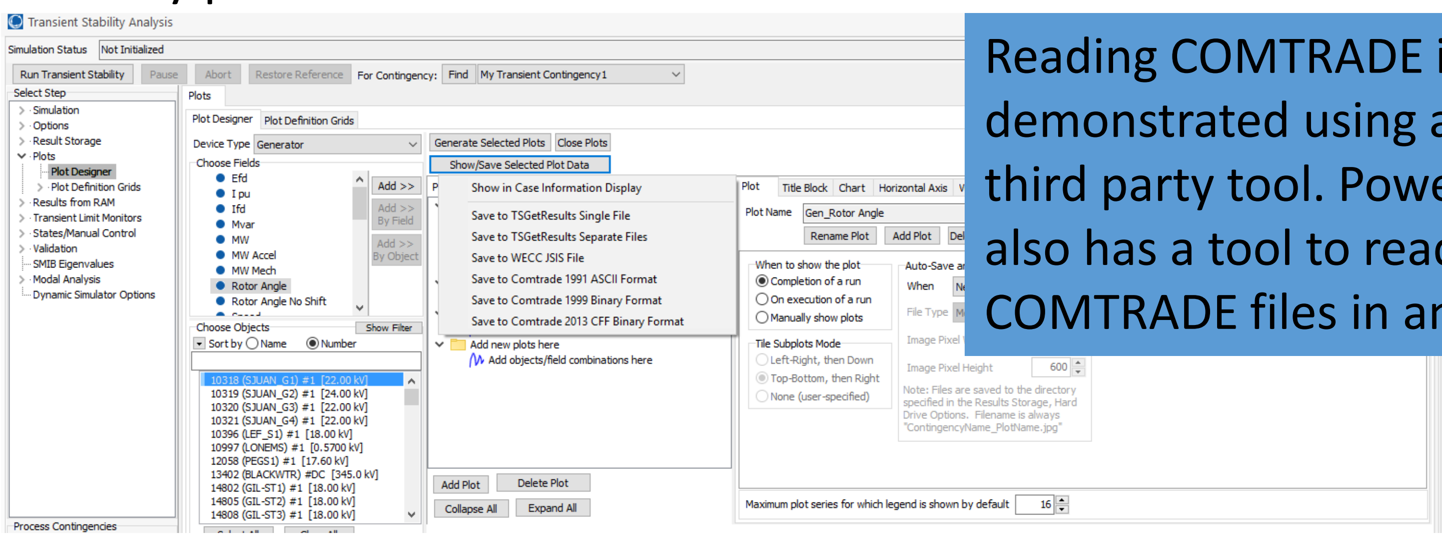
Saving Synthetic PMU Data in COMTRADE format (C37.111)

- PowerWorld Simulator allows transient stability results to be quickly saved in COMTRADE Format, which is given by IEEE Std. C37.111
  - Both the 1991, 1999 and 2013 formats are supported; data can be exported in 1991 ASCII (for compatibility), 1999 BINARY (for small size) or 2013 FLOAT32 single file format (*.cff)
- Exported data is determined is specified by defining transient stability plots



Reading COMTRADE is demonstrated using a third party tool. PowerWorld also has a tool to read/write COMTRADE files in any format.

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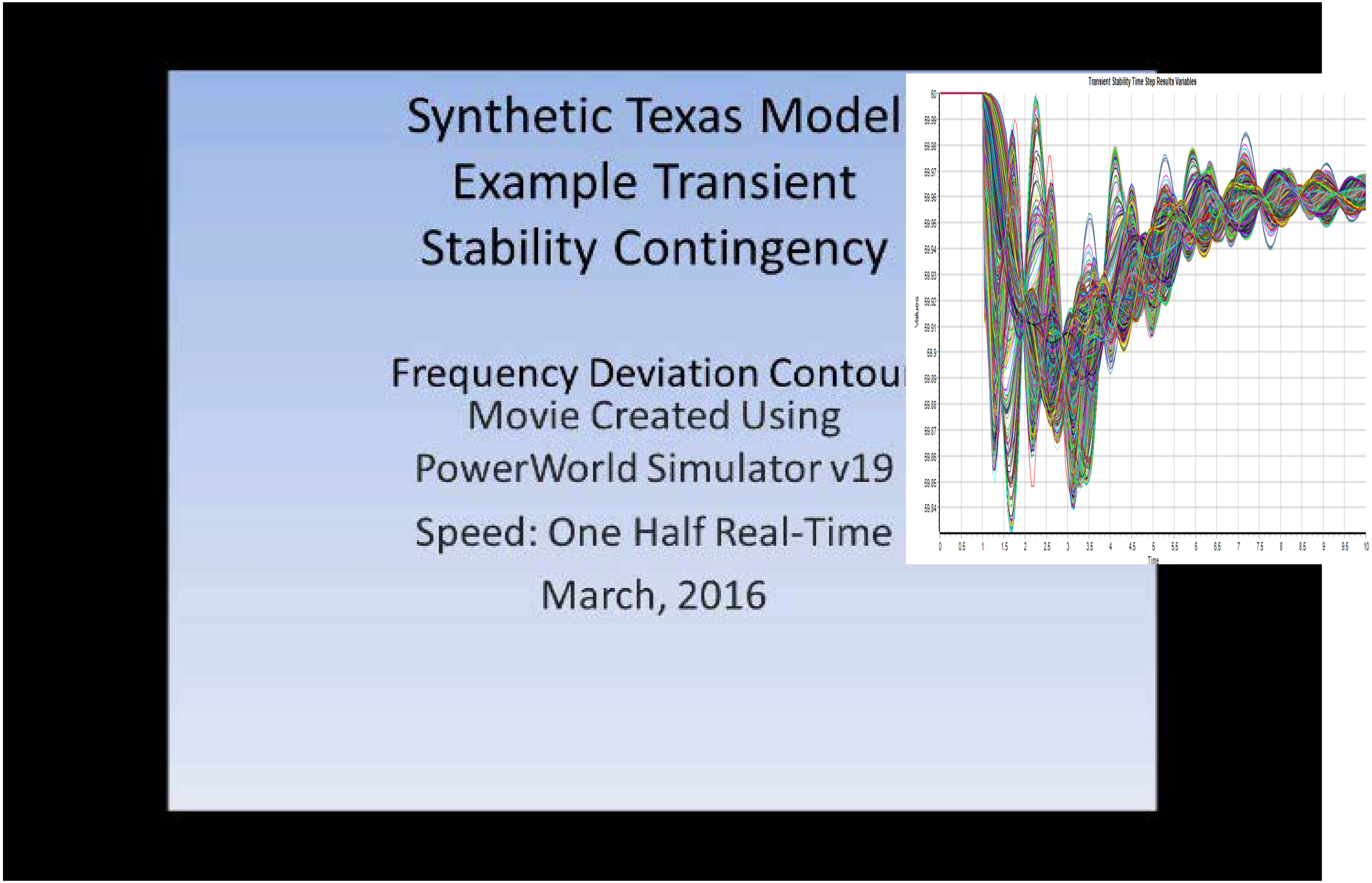
Example: 2100 Bus Texas Case Frequency Response



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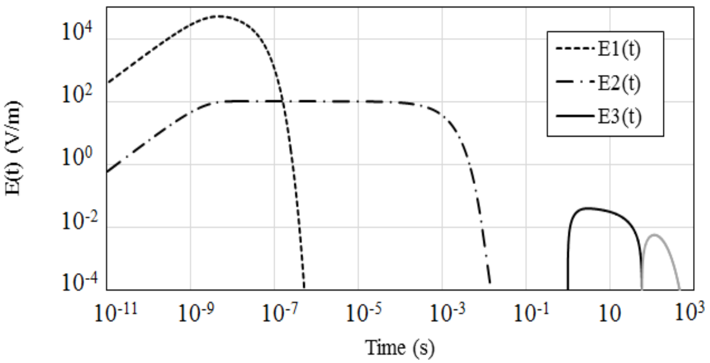
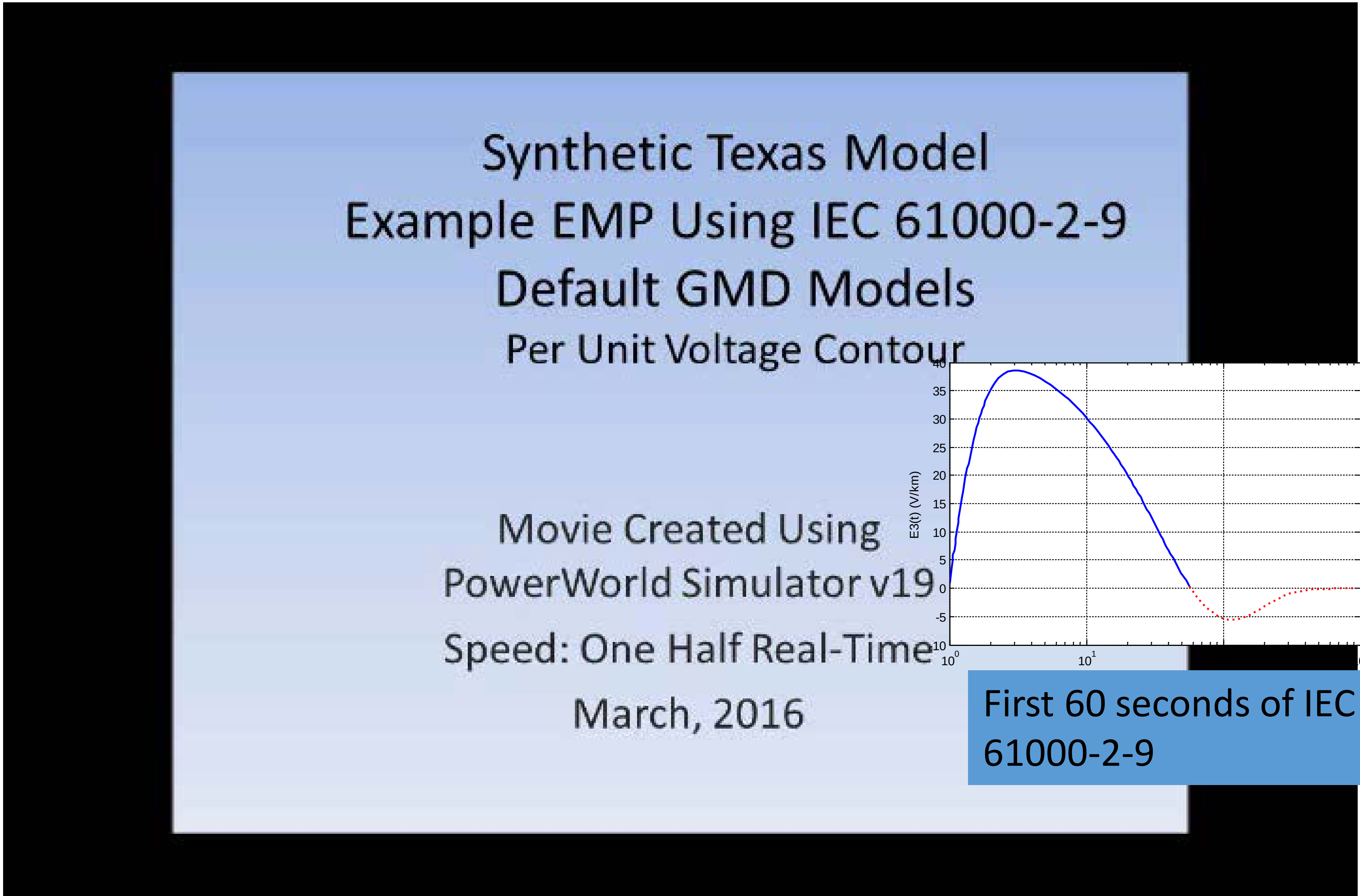
EMP Background

- Electromagnetic pulses caused by high-altitude detonation of nuclear devices
    - Causes fast time-varying electric fields E1, E2, E3 of different frequencies
    - E3 has time frame of milliseconds to seconds
- E3 can be studied using geomagnetically induced currents (GIC) modeling, but in the transient stability time frame
- GICs can cause transformer half-cycle saturation leading to reactive power losses, and low voltages in the system
- PMU's can potentially capture the fast changes in voltages in the event of an EMP
- Synthetic networks can allow simulation of such high-impact low-frequency events



Electric field waveforms generated by a benchmark HEMP from IEC 61000-2-9

Simulating High Impact, Low Frequency Events



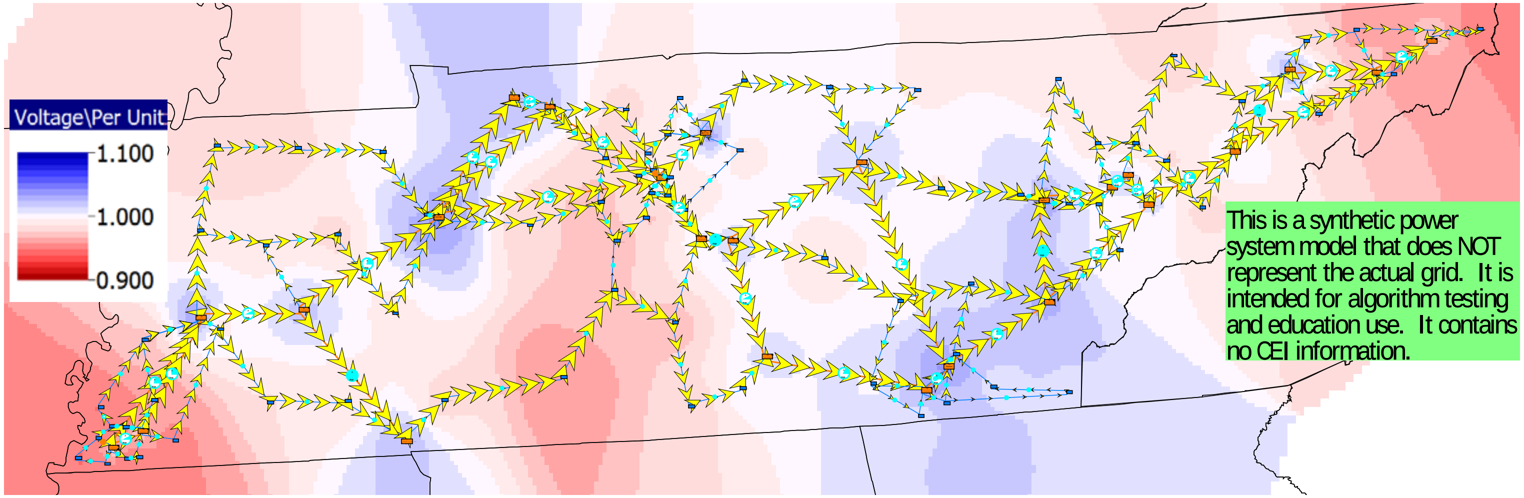
First 60 seconds of IEC 61000-2-9

Future Work

- Advance synthetic network creation algorithms
  - Reactive power control
  - Adding more realistic dynamic model parameters
- Generate statistics from actual PMU data
- Develop clients to add noise and other anomalies to synthetic PMU data to make it more realistic
- Work on more visualization applications of PMU data

Thank You! Questions?

- Synthetic cases website
  - http://icseg.iti.illinois.edu/synthetic-power-cases/
  - Contact: shetye1@Illinois.edu
- UIUC 150 bus test case (available in different formats)
  - Placed geographically in Tennessee
  - Contains GMD parameters
  - Figure shows response to an assumed GMD

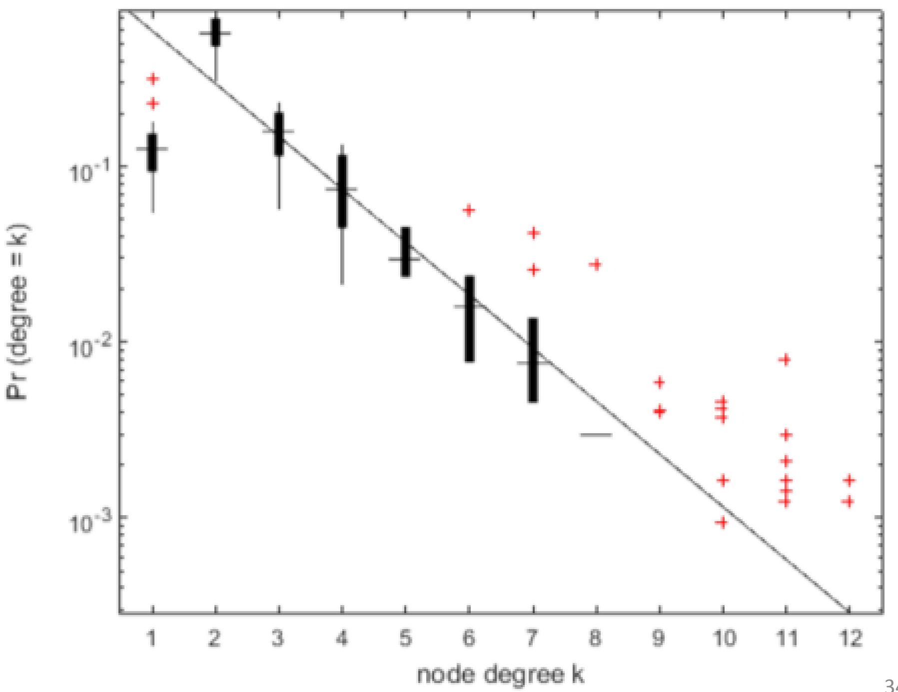


Backup slides

Creation Methodology: 3. Transmission Lines

- Substations are connected together by transmission lines
- Need to match statistics for number of connected substations at each voltage level
- Average nodal degree $\langle k \rangle = 2.43$, nearly constant with n for single-voltage networks in EI
- Number of lines $m = \frac{\langle k \rangle n}{2} = 1.22n$
- Node degree distribution appears to be exponential. $\Pr(k) = 1.19e^{-0.69k}$

(except for k=1 and 2)



Creation Methodology: 3. Transmission Lines

- In general, transmission line topologies are totally connected, and remain so with one node removed
- Typical actual power system contains 60% of its substations' minimum spanning tree (MST) at each nominal voltage level (percent varies by voltage level)
- Approach is to match the MST percentage
- Then other lines are added to match the typical average ($1.22n$ edges per bus)
- Delaunay triangulation
  - No triangle's circumcircle contains another point
  - Nearest few neighbors are connected
  - Statistics $\langle c \rangle$ and $\langle l \rangle$ match regular lattice and actual grid
- Contains 70% of real lines on average, and 98% separated by 3 hops or less
- We select subset out of Delaunay's $3n$ segments