Synthetic Power Grid Models: What are They, How They’re Made, and Why They Matter

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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)
  • ARPA-E Grid Data Synthetic Data for Power Grid R&D
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Presentation Overview

• Access to data about the actual power grid is often restricted because of requirements for data confidentiality (e.g., critical energy infrastructure)
  • Focus here is on high voltage power flow, optimal power flow, transient stability models, SCADA, PMUs
  • Some data is public, some is available by NDAs, and some is essentially unavailable to those outside of power system control centers

• Focus of talk is on the creation of synthetic (fictional) models that mimic the complexity of the actual grid cases but will contain no confidential data and can be publicly available
A Few Initial Thoughts

- The reason why this matters is to help spur innovation in the electric grid software
  - Algorithms tested on synthetic models applied to actual
- In 2000 the NAE named Electrification (the vast networks of electricity that power the developed world) as the top engineering technology of the 20th century
  - automobiles (2), airplanes (3), water (4), electronics (5)
- Our challenge in this century is to develop a sustainable and resilient electric infrastructure for the entire world
A Few Initial Thoughts

• "All models are wrong but some are useful,“

• “The use of nondisclosure agreements or NDA’s to obtain data, while useful in many instances, is not useful if the world community is to engage in research that adheres to the scientific principle of reproducibility of results by other qualified researchers and to use important findings to advance their own work“
  PSERC Founding Director Bob Thomas, 2015
Overall Goals

• The development of entirely synthetic transmission system models and scenarios that match the complexity and variety of the actual grid
  • 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
  • Scenarios will be SCOPF validated
• We want to partner with industry!
The Need

- 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 the Eastern Interconnect models now more than 70,000 buses, and also model complexity
  - Public models also lack extra data like transient stability
- 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/
What Makes a Model Real?

• The challenge is to capture the essence of what makes actual grid models different
  • Actual grid models are quite diverse

• Statistics can be used to quantify some of the characteristics
  • topology, parameters for buses, generators, loads, transmission lines, transformers, switched shunts, transient stability and GMD parameters

• System-wide metrics are also needed
Complexity Examples

• A recent 76,000 bus Eastern Interconnect (EI) power flow model has 27,622 transformers including 98 phase shifters
  • Impedance correction tables are used for 351, including about 2/3 of the phase shifters; tables can change the impedance by more than two times over the tap range

• The 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!
How to Make Realistic, Geographically-Based, Synthetic Models

• Our approach 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 widely available public data:
  • Geography
  • Population density (easily available by post office)
  • Load by utility (FERC 714) and state-wide averages
  • Existing and planned generation: Form EIA-860 contains information about generators 1 MW and larger; data includes location, capacity and fuel type
Example: 2100 Bus Texas Case
Frequency Response

Synthetic Texas Model
Example Transient
Stability Contingency

Frequency Deviation Contour
Movie Created Using
PowerWorld Simulator v19
Speed: One Half Real-Time
March, 2016
Since our goal is to make entirely synthetic models, no existing company names will be used. We may be changing the actual generator capacity values as well.
How to Make Realistic Synthetic Models

• 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
How to Make Realistic Synthetic Models: 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)
How to Make Realistic Synthetic Models: Substation Selection

• In our approach substations are placed geographically at post offices
• 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
Generator Substation Placement

- 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

<table>
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<tr>
<th>Governor Type</th>
<th>Max Mvar as fraction of MW capacity</th>
<th>Mvar range as fraction of MW capacity</th>
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<td>Steam</td>
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<td>0.588</td>
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<tr>
<td>Gas</td>
<td>0.509</td>
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<td>Nuclear</td>
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<tr>
<td>Wind</td>
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</table>
Substation 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
Adding Transmission Lines

- Substations are connected together by transmission lines, matching characteristics of actual models
  - Builds on pioneering work done by PSERC researchers Thomas, Wang and Scaglione
Substation Node Degree  
(Number of Neighbors)

• 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 $2$)
Adding Transmission Lines

- Graph theory considerations are used to determine which substations are connected
  - An approach is to do Delaunay triangulation along with minimum spanning tree (MST) analysis

Image shows Delaunay triangulation of 42,000 North America substations; statistics only consider single voltage levels; computationally fast (order $n \ln(n)$)
Adding 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).
Using Delaunay Triangulation to Add Additional Lines

- 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
Transmission Line Parameters

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

<table>
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<tr>
<th>Conductor</th>
<th>Tower Type</th>
<th>X, pu, per 100 miles</th>
<th>X/R ratio</th>
<th>B, pu, per 100 miles</th>
<th>MVA limit</th>
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<tr>
<td></td>
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<td>14.52</td>
<td>0.855</td>
<td>1494</td>
</tr>
</tbody>
</table>

These parameters are validated against real transmission lines.
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
- Place total of $1.22n$ lines per voltage level
- 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
Example: Transmission Line Placement

• Based on voltage angle gradient, this might be a good location for a transmission line
Reactive Compensation and Additional Model Complexity

- The next step is the specification of the generator PV bus setpoints, the inclusion of additional reactive power control devices such as switched shunts and LTC control, and the inclusion of additional complexities such as tap dependent impedances (XF correction tables)
  - Realistic remote generator PV control will be modeled, including reactive power sharing among a number of generator
  - A hypothesis we are considering is that the difficulties encountered with actual models compared to public models, such as the IEEE 118 bus case, are due to these complexities
Model Creation Methodology: Inclusion of Additional Parameters

- The final step in the creation of the models themselves will be the inclusion of the models necessary to do transient stability and GMD analysis.
- As with the other models, parameters will be set to match the statistics of the actual grid.

Images show example transient stability models and parameters.
Example: 150 Bus Network for GMD Analysis

Images show a synthetic 150 bus model placed geographically in Tennessee; bottom image shows response to an assumed GMD.
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
Example Case: Initial Generation Dispatch

- System divided into 8 areas
- Two areas have more load than generation capacity
- Transactions set up from other areas
- Generators dispatched proportionally to meet load + transaction commitments
- This is done before lines are placed, so that the algorithm’s dc power flow reflects realistic generation dispatch
Example Case: Voltage Phase Angle Contour

- Gradual voltage angle gradient
- All branches less than 90% loaded
- Average branch is 28% loaded, matching real cases
- These properties are direct result of automatic line placement without manual intervention
Example Case: Voltage Control

• All voltages within 0.97-1.05 pu in base case
• After line placement algorithm voltages were within 0.9 to 1.1 pu
• Adjustment of generator set points and insertion of 33 shunt capacitor banks in urban areas
Simulating High Impact, Low Frequency Events: Results can be Exchanged!

Synthetic Texas Model
Example EMP Using IEC 61000-2-9
Default GMD Models
Per Unit Voltage Contour

Movie Created Using
PowerWorld Simulator v19
Speed: One Half Real-Time
March, 2016

First 60 seconds of
IEC 61000-2-9
Synthetic Model Validation

• Key to this research is to demonstrate synthetic models have similar properties of actual grids
• Synthetic models are not meant to represent the actual grid, so direct comparison is not appropriate
• Useful metrics are
  • Topological properties, which we meet by design
  • Individual model parameters, which we meet by design
  • Solution algorithm properties, such as power flow convergence
  • Solution results, such as LMPs, amount of congestion, transient stability damping, etc.
Driving Innovation!

• Goal is to publicly release synthetic models of various sizes and complexities
  • Algorithm results from synthetic models can be published without restriction; algorithms can be used confidentially on real models
  • Fully public, anyone can make derivative models; some models will be standardized for comparisons purposes

• Large-scale models can be used to compare software packages
  • Customers and researchers can compare results
  • Visualization research not hindered by confidentiality
Thank You!

Questions?

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