DOE/OE Transmission Reliability Program

Random Topology Power Grid Modeling and Automated Simulation Platform

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ELECTRIC RELIABILITY
TECHNOLOGY SOLUTIONS

Overall Project Objectives

I. **A Comprehensive Study** of grid topology and parameters

- Using statistical approaches
- Topology metrics vs. Electric parameters
- Probabilistic distribution, scaling properties, interdependences

II. **Automated Simulation Platform**

- Generative models of power grid test cases
- Enabling sufficient testing and verification of new concepts, methods, and approaches.

Motivation of the Project

- Data access to actual power grids (**critical energy infrastructure**) is restricted.
- Power system engineers and researchers need grid test cases of varying size/complexity and appropriate properties for the "**sufficient**" testing and verification of new concepts, methods, and approaches.

Special case study ⇒ **Genuine Monte Carlo Experiments**

- To address the grid data challenge ⇒ Automatic generative model of power grid test cases (**AutoSynGrid**)
  - Fictional, i.e., without revealing sensitive information
  - Truly representative, i.e. with the same kind of electric topology, parameters, and properties found in real power grids.

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Major Accomplishments in Past Year - I

- Scaling properties of power grid
- Statistical analysis on transformer/transmission line parameters: R, X, ratios, capacities
- Statistical analysis on the generation, load settings: siting, size, dispatch, power flow
- Interdependence between different topo and electrical parameters, e.g.
  - Voltage levels vs. grid parameters
  - Generation/load settings vs. node degree

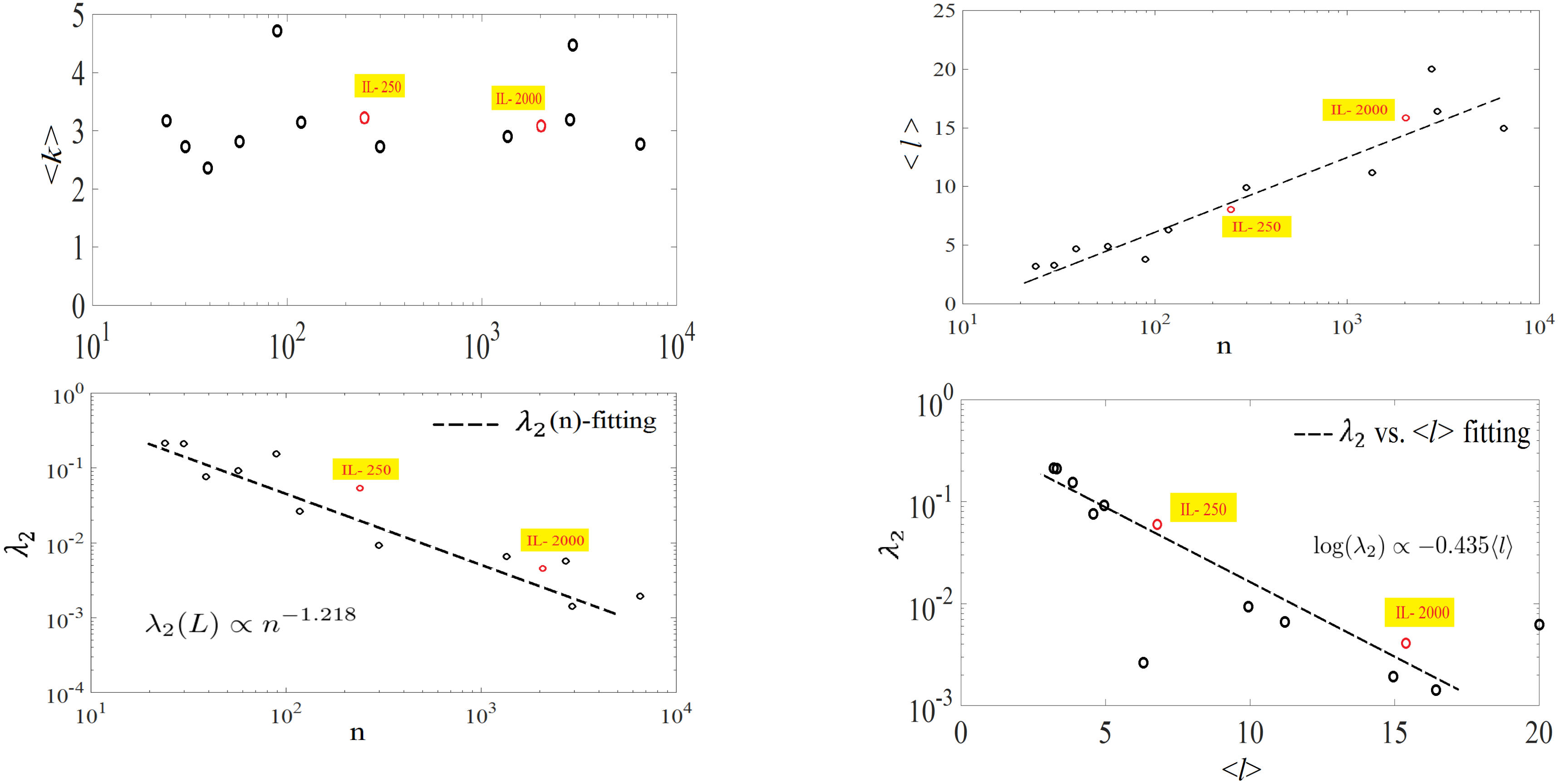
Major Accomplishments in Past Year - II

- Algorithm development to statistically determine:
  - Siting and sizing of generation and loads
  - Generation dispatch, flow distribution
  - Capacity of transmission branches
- Grid vulnerability analysis (started, ongoing)
  - Modeling uncertainties in renewable generation and smart grid Load
  - Grid vulnerability to cascading failures
    - Line overload modeling
    - Tripping mechanism, relay model
    - Island detection and power rebalance

Publications:

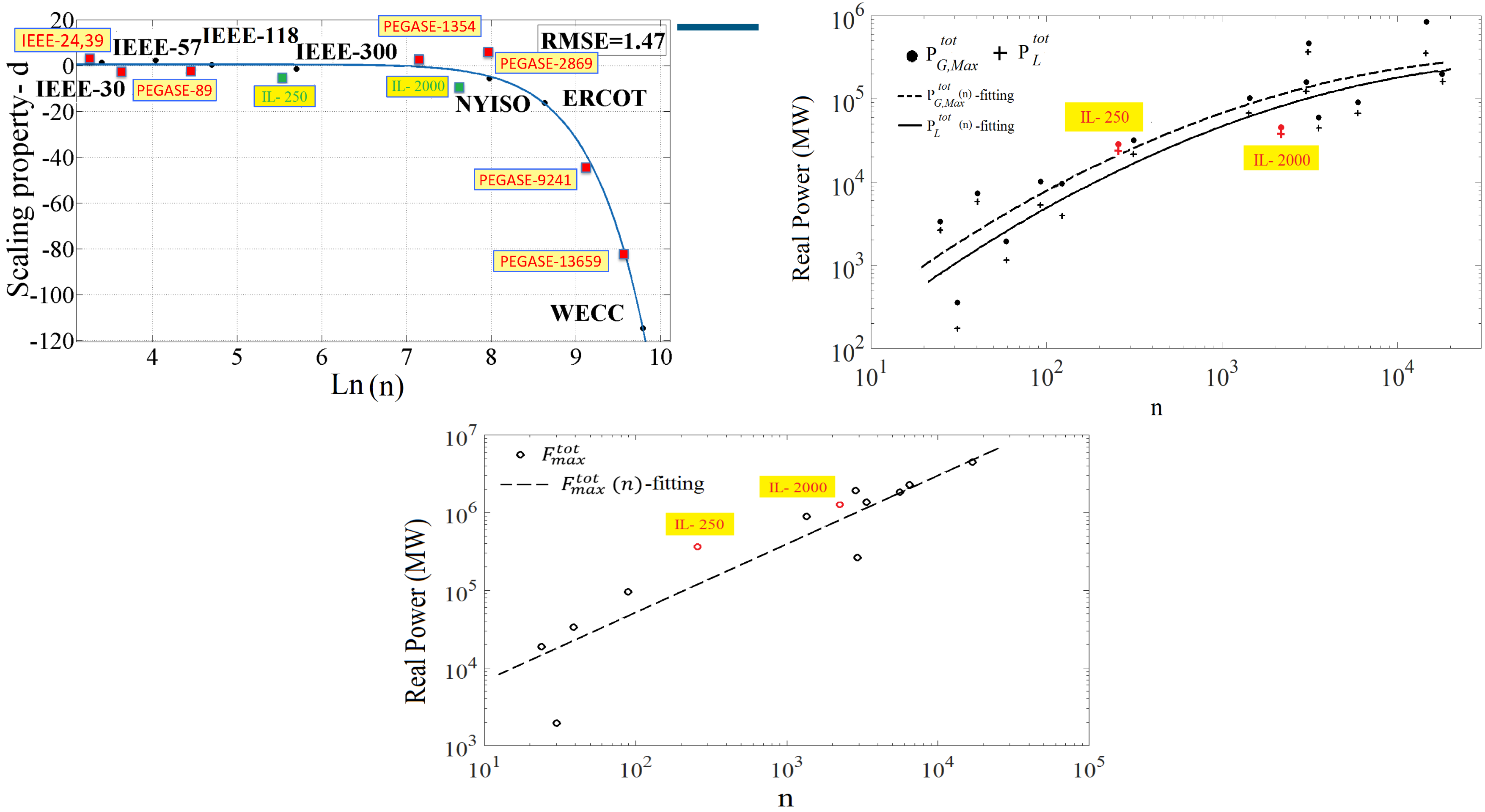
- IEEE Journals:
  - ✓ "Improved Synthetic Power Grid Modeling with Correlated Bus Type Assignments", Elyas, Wang. (accepted by IEEE trans.on PS in Dec 2016, available in IEEE explorer)
  - ✓ "Impacts of Wind Power Uncertainty on Grid Vulnerabilty to Cascading Overload Failures", Athari, Wang. (submitted to IEEE trans on Sustainable Energy)
- IREP 2017:
  - ✓ "Statistical Study on Transformer Parameters for the Validation of Synthetic Grid Modeling", Athari, Wang.
  - ✓ "On Statistical Size and Placement of Generation and Load for Synthetic Grid Modeling", Elyas, Wang, Thomas.
- IEEE PES GM 2017
  - ✓ "Study Cascading Overload Failures under High Penetration of Wind Generation", Athari, Wang.
- HICSS 2017
  - ✓ "On the Scaling Property of Power Grids", Elyas, Wang.
- IEEE PES ISGT 2016:
  - ✓ "Statistical Analysis of Transmission Line Capacities for the Random Topology Power Grid Modeling", Elyas, Wang.
  - ✓ "Modeling the Uncertainties in Renewable Generation and Smart Grid Loads", Athari, Wang.
- UPEC 2016:
  - ✓ "Generating Synthetic Power System Data with Accurate Electric Topology and Parameters", Wang, Elyas, Thomas.

Scaling Properties of Power Grid - I



node-degree, path length, algebraic connectivity vs. network size

Scaling Properties of Power Grid - II



Bus type entropy, aggregate generation capacity and load, backbone transmission capacity, vs. network size

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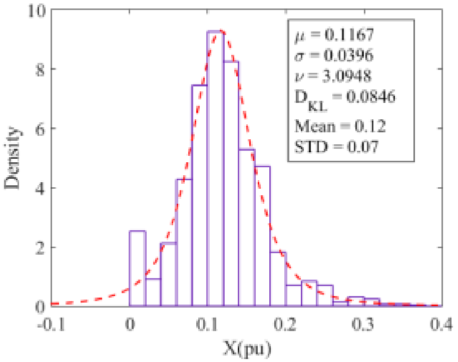
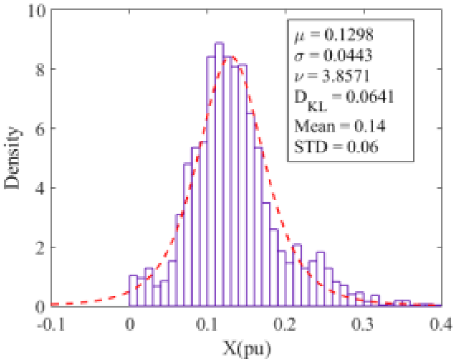
Transmission Branch Parameters

- **Transformers**
  - Per unit reactance
  - MVA limit
  - X/R ratio
- **Transmission lines**
  - Number of lines (m_{V_B})
  - Line length (l_{V_B})
  - Distributed reactance (X_d)
  - Distributed resistance (R_d)
  - X/R ratio
  - Real power loss (P_{loss})
  - Voltage difference ($|\Delta V|$)

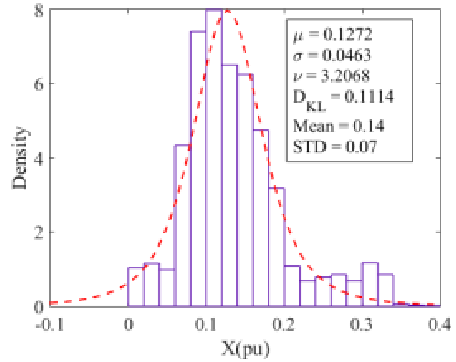
Transformer per unit Reactance



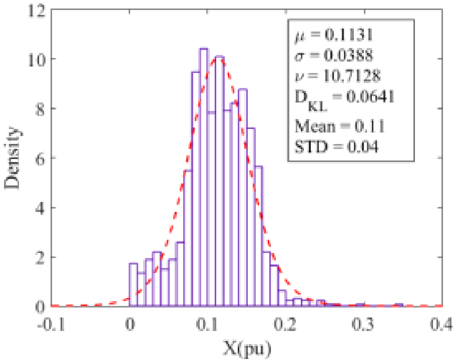
69 kV



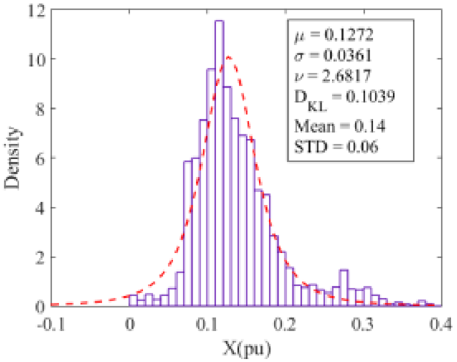
115 kV



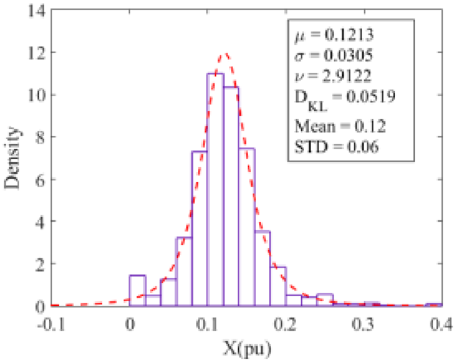
138 kV



161 kV



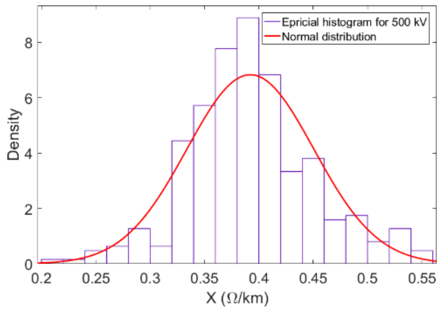
230 kV



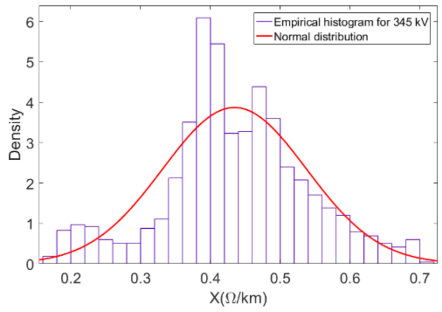
345 kV

Stable TLS distribution obtained after converting X_e using the transformer's S_B instead of system S_B

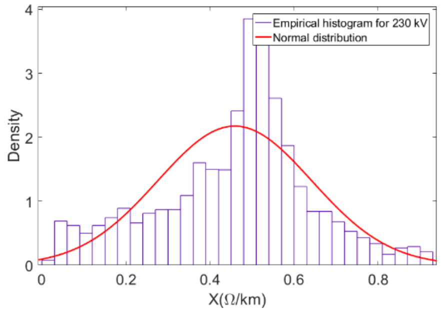
Transmission Line Distributed Reactance



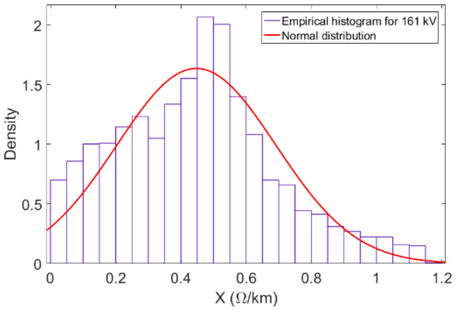
500 kV



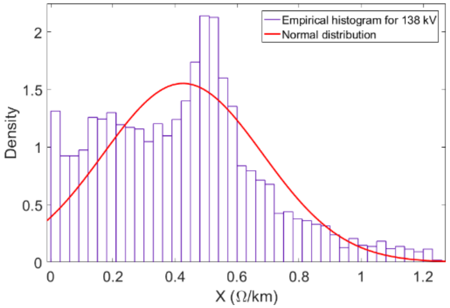
345 kV



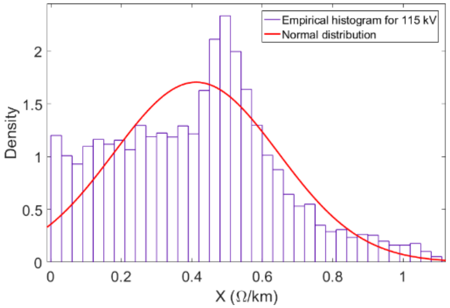
230 kV



161 kV



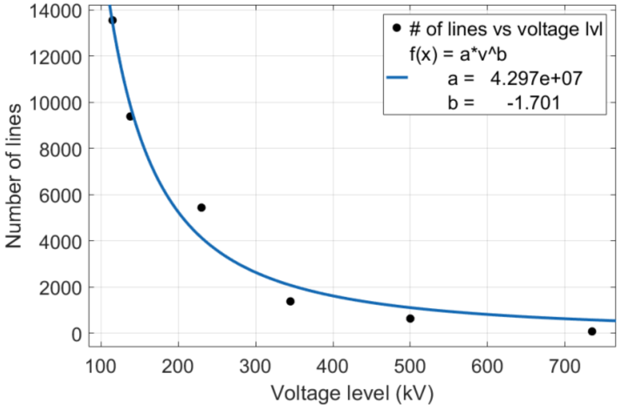
138 kV



115 kV

Stable distribution obtained for the Line Distributed Reactance (Ω/km) regardless of voltage levels

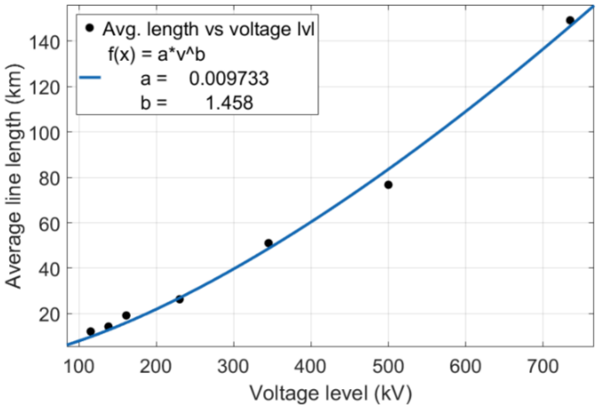
Interdependence on V_B



$$m_{V_B} \propto V_B^{-1.70}$$

Number of lines at each voltage level

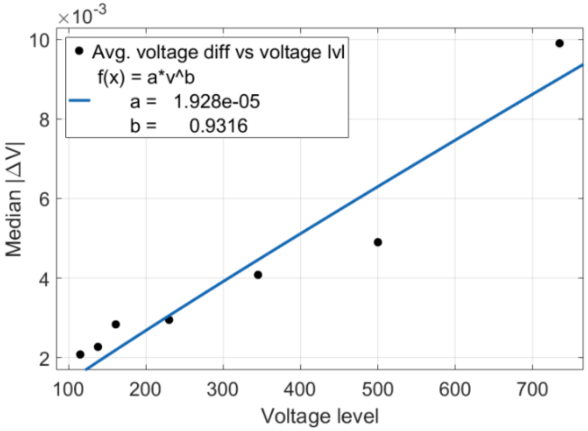
✓ More lines at lower voltage levels



$$l_{V_B} \propto V_B^{1.45}$$

Average line length (km) vs voltage level

✓ Longer lines at higher voltage levels

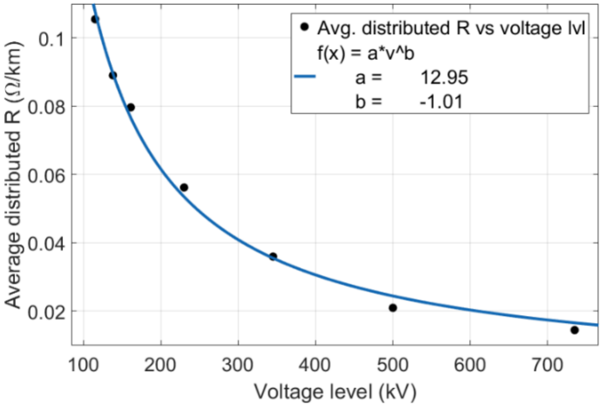


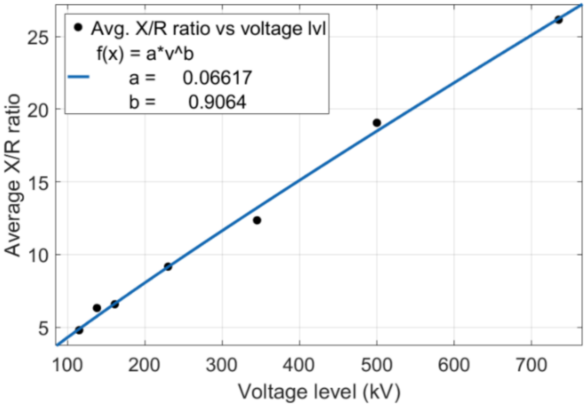
$$|\Delta V| \propto V_B^{0.93}$$

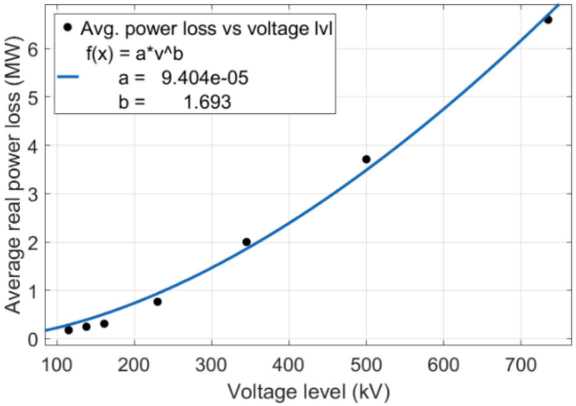
Voltage difference median (P.U.) vs voltage level

✓ Larger voltage difference in higher voltage levels

Interdependence on V_B







$R_d \propto V_B^{-1.01}$

Average distributed R (Ω/km) vs voltage level

✓ Larger R_d for lower voltage levels

$X/R \propto V_B^{0.90}$

Average X/R ratio vs voltage level

✓ Larger X/R ratio for higher voltage levels

$P_{loss} \propto V_B^{1.70}$

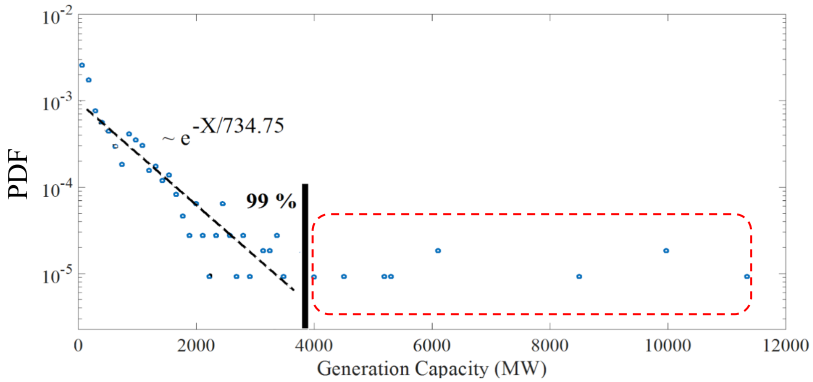
Average real power loss (MW) vs voltage level

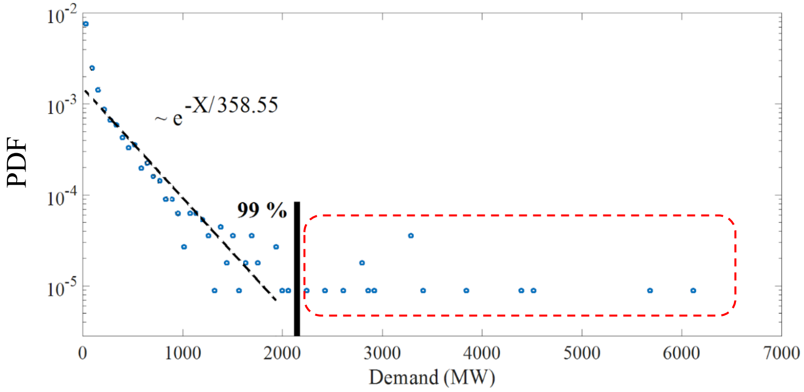
✓ Larger power loss for higher voltage levels

Curve fitting using power equation $f(x) = a.x^b$ for parameters to find their dependence on voltage level

Empirical distribution of generation capacity and load

NYISO-2935





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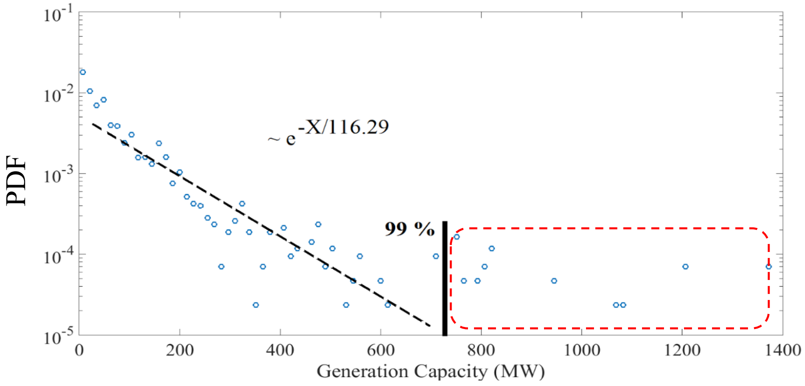
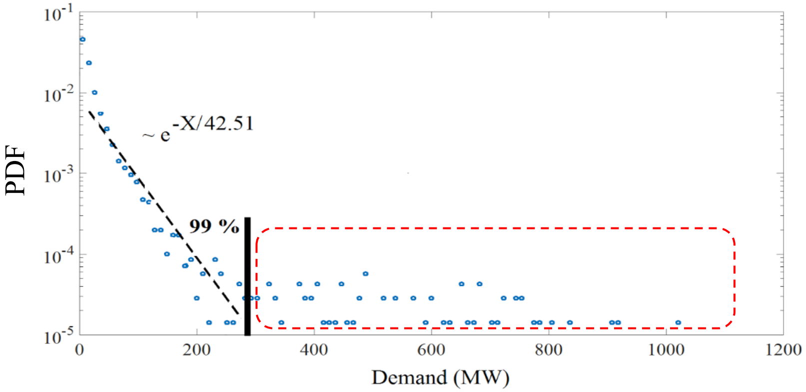
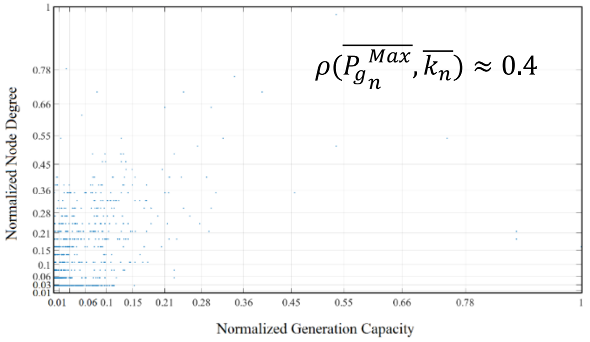




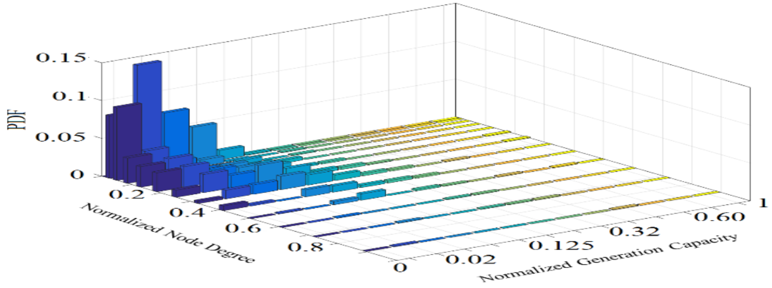
Generation capacity vs node degree

Scatter plot for $\overline{P_{g_n}^{Max}}$vs $\overline{k_n}$



$\rho(\overline{P_{g_n}^{Max}}, \overline{k_n}) \approx 0.4$

2-D empirical PDF of normalized node degree versus normalized generation capacity

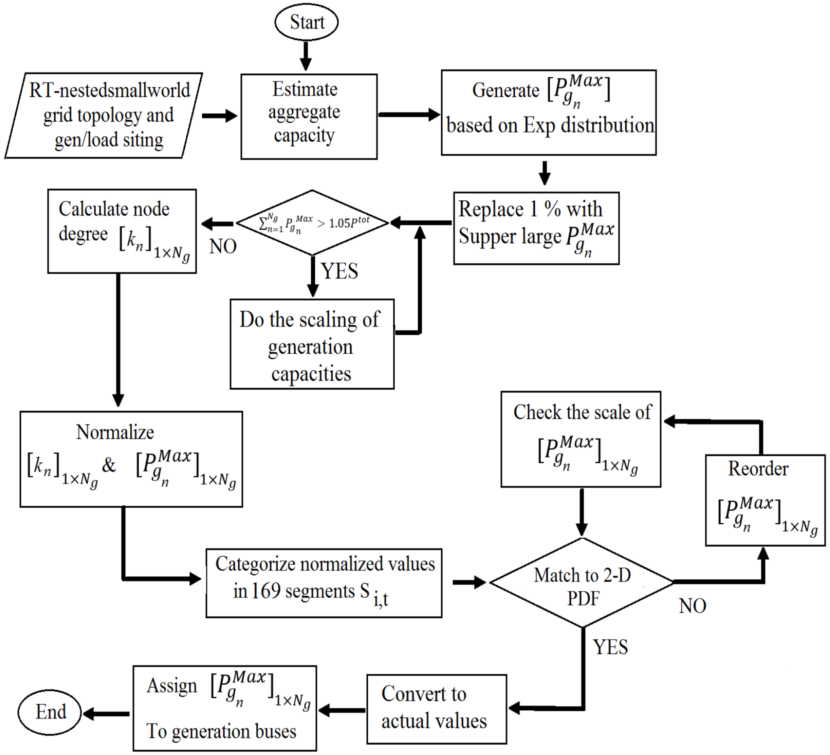


Two-dimensional variables $\overline{P_{g_n}^{Max}}$ and $\overline{k_n}$ are considered mainly by their density function $f(\overline{P_{g_n}^{Max}}, \overline{k_n})$, which integrated on a set A gives the probability of the event that the value of $(\overline{P_{g_n}^{Max}}, \overline{k_n})$ is in the set A:

$$\Pr(A) = \Pr\left(\left(\overline{P_{g_n}^{Max}}, \overline{k_n}\right) \in \mathrm{A}\right)$$

		$\overline{k_n}$													Marginal Prob
		0.00–0.01	0.01–0.03	0.03–0.06	0.06–0.1	0.1–0.15	0.15–0.21	0.21–0.28	0.28–0.36	0.36–0.45	0.45–0.55	0.55–0.66	0.66–0.78	0.78–1.00	
$\overline{P_{g_n}^{Max}}$	0.78–1.00	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.002
	0.66–0.78	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.004
	0.55–0.66	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.003
	0.45–0.55	0.000	0.001	0.000	0.004	0.008	0.000	0.002	0.001	0.000	0.001	0.000	0.001	0.000	0.018
	0.36–0.45	0.006	0.002	0.000	0.009	0.008	0.003	0.003	0.002	0.000	0.000	0.000	0.000	0.000	0.034
	0.28–0.36	0.003	0.011	0.012	0.017	0.013	0.007	0.003	0.002	0.000	0.001	0.000	0.000	0.000	0.072
	0.21–0.28	0.009	0.024	0.016	0.024	0.013	0.004	0.003	0.001	0.000	0.000	0.000	0.000	0.001	0.097
	0.15–0.21	0.025	0.027	0.016	0.013	0.009	0.002	0.002	0.000	0.000	0.000	0.000	0.000	0.001	0.097
	0.1–0.15	0.027	0.031	0.010	0.010	0.005	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.088
	0.06–0.1	0.033	0.017	0.003	0.003	0.005	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.063
	0.03–0.06	0.090	0.030	0.01	0.008	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.151
	0.01–0.03	0.082	0.140	0.070	0.04	0.010	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.360
	0.00–0.01	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
Marginal Prob		0.283	0.291	0.147	0.141	0.077	0.022	0.017	0.008	0.001	0.003	0.000	0.001	0.002	1.000

Proposed algorithm for generation and load setting



Start

RT-nestedsmallworld grid topology and gen/load siting

Estimate aggregate capacity

Generate $[P_{g_n}^{Max}]$ based on Exp distribution

Replace 1 % with Supper large $P_{g_n}^{Max}$

$\sum_{n=1}^{N_g} P_{g_n}^{Max} > 1.05P^{tot}$

YES

Do the scaling of generation capacities

NO

Calculate node degree $[k_n]_{1\times N_g}$

Normalize $[k_n]_{1\times N_g}$ & $[P_{g_n}^{Max}]_{1\times N_g}$

Categorize normalized values in 169 segments $S_{i,t}$

Check the scale of $[P_{g_n}^{Max}]_{1\times N_g}$

Match to 2-D PDF

NO

Reorder $[P_{g_n}^{Max}]_{1\times N_g}$

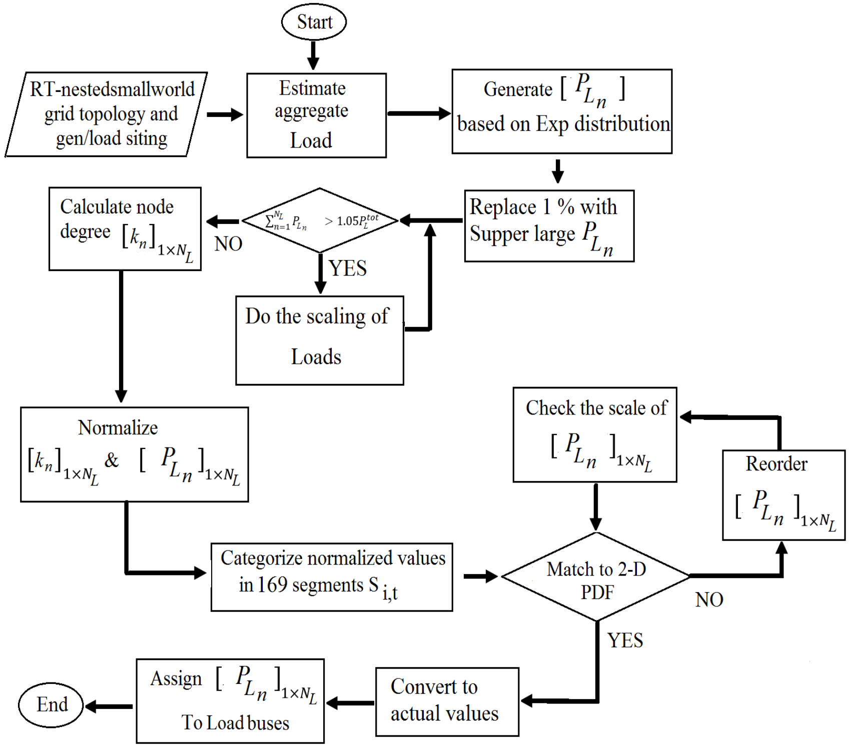
YES

Convert to actual values

Assign $[P_{g_n}^{Max}]_{1\times N_g}$ To generation buses

End

Generation Setting



Start

RT-nestedsmallworld grid topology and gen/load siting

Estimate aggregate Load

Generate $[\,P_{L_n}\,]$ based on Exp distribution

Replace 1 % with Supper large P_{L_n}

$\sum_{n=1}^{N_L} P_{L_n} > 1.05P_L^{tot}$

YES

Do the scaling of Loads

NO

Calculate node degree $[k_n]_{1\times N_L}$

Normalize $[k_n]_{1\times N_L}$ & $[\,P_{L_n}\,]_{1\times N_L}$

Categorize normalized values in 169 segments $S_{i,t}$

Check the scale of $[\,P_{L_n}\,]_{1\times N_L}$

Match to 2-D PDF

NO

Reorder $[\,P_{L_n}\,]_{1\times N_L}$

YES

Convert to actual values

Assign $[\,P_{L_n}\,]_{1\times N_L}$ To Load buses

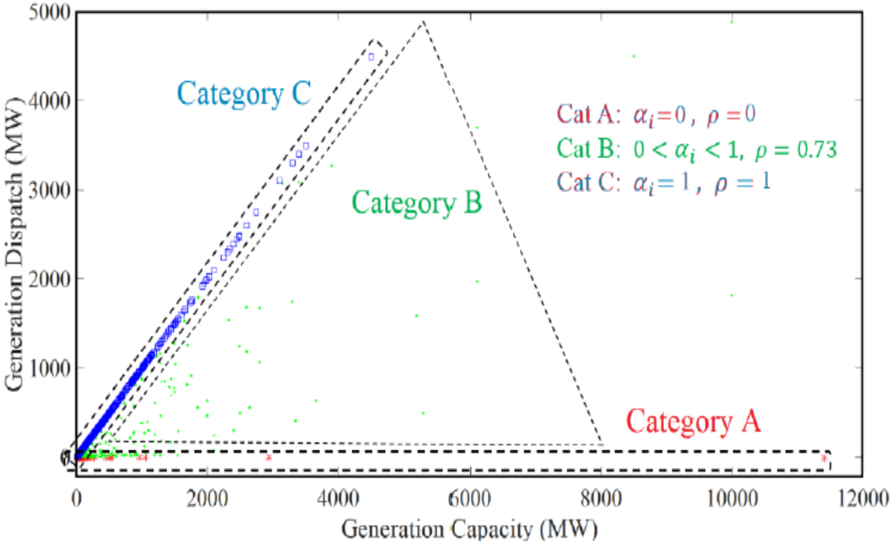
End

Load Setting

Generation Dispatch vs Generation Capacity

Approach:

By studying the possible correlation between generation capacities $P_{G,i}^{Max}$ and power dispatch $P_{G,i}(t_0)$ in realistic power grids an appropriate method can be constructed to estimate the power output of generating units



Observations:

1- Strong correlation between $P_{G,i}^{Max}$ and $P_{G,i}(t_0)$ as:

$$\rho\{P_{G,i}^{Max}, P_{G,i}(t_0)\} = 0.9563$$

2- 0 ~ 20 % of generators are uncommitted units.

3- Small number of uncommitted units belong to the super large power units

4- 50 % of committed power units are operated very closed to their maximum generation capacities.

5- 50 % of committed power units are operated between minimum and maximum generation capacity

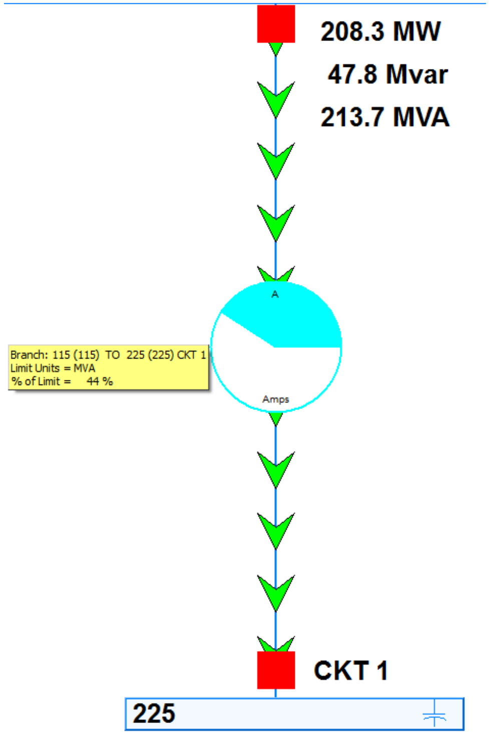
Dispatch Factor $\alpha_i = P_{G,i}(t_0)/P_{G,i}^{Max}, i = 1, \ldots, N_G$

Category A: $\alpha_i = 0, \ \ \rho = 0$

Category B: $0 < \alpha_i < 1, \ \ \rho = 0.73$

Category C: $\alpha_i = 1, \ \ \rho = 1$

Transmission Line capacity: $F_l^{\max}$ vs. F_l



Transmission line capacity margin

$$\beta_l = \frac{F_l^{max} - F_l}{F_l^{max}}, \qquad l = 1, \dots, M$$

where F_l^{max} and F_l are maximum capacity and short-term power flow of l^{th} transmission line, respectively.

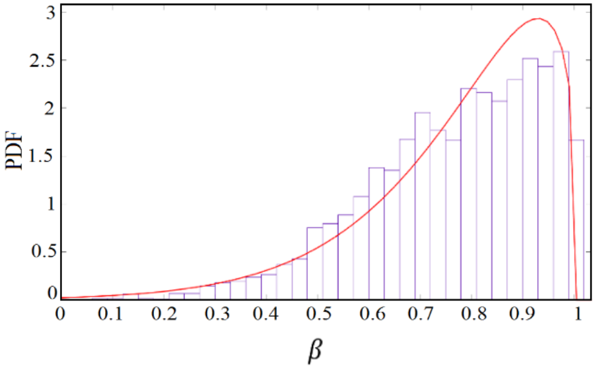
Observation:

1- Transmission lines tend to have a big capacity margin

2- The fitted curve follows the generalized extreme value distribution.

3- The maximum transmission capacity of each line can be calculated with respect to the assigned marginal capacity and the real-time power flow resulted from DC power flow calculation:

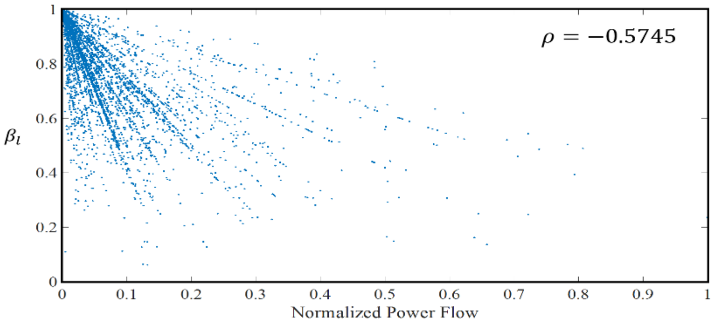
$$F_l^{Max} = \frac{F_l}{1 - \beta_l}$$



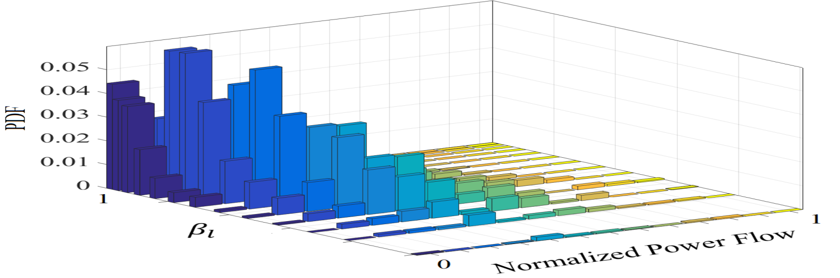
The Empirical PDF of capacity margin in realistic power grid

Transmission Line Capacities

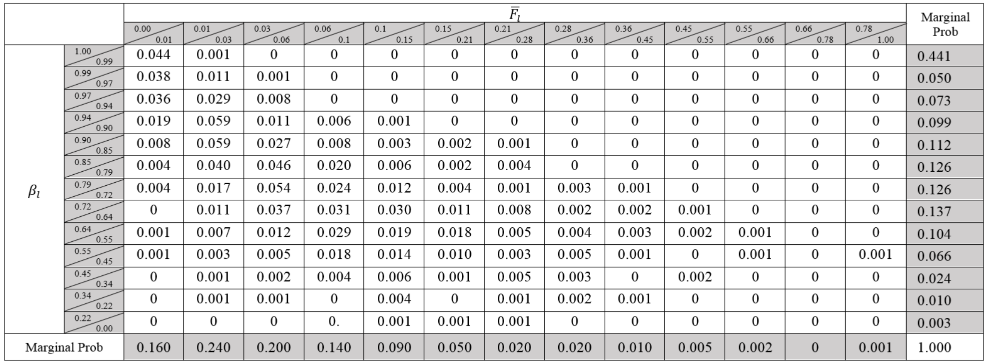
Capacity margin β versus normalized short-term power flow



The 2-D empirical PDF of capacity margin versus normalized short term power flow



Probability analysis of generation dispatch and normalized generation capacity



		$\overline{F}_l$													Marginal Prob
		0.00 0.01	0.01 0.03	0.03 0.06	0.06 0.1	0.1 0.15	0.15 0.21	0.21 0.28	0.28 0.36	0.36 0.45	0.45 0.55	0.55 0.66	0.66 0.78	0.78 1.00	
β_l	1.00 0.99	0.044	0.001	0	0	0	0	0	0	0	0	0	0	0	0.441
	0.99 0.97	0.038	0.011	0.001	0	0	0	0	0	0	0	0	0	0	0.050
	0.97 0.94	0.036	0.029	0.008	0	0	0	0	0	0	0	0	0	0	0.073
	0.94 0.90	0.019	0.059	0.011	0.006	0.001	0	0	0	0	0	0	0	0	0.099
	0.90 0.85	0.008	0.059	0.027	0.008	0.003	0.002	0.001	0	0	0	0	0	0	0.112
	0.85 0.79	0.004	0.040	0.046	0.020	0.006	0.002	0.004	0	0	0	0	0	0	0.126
	0.79 0.72	0.004	0.017	0.054	0.024	0.012	0.004	0.001	0.003	0.001	0	0	0	0	0.126
	0.72 0.64	0	0.011	0.037	0.031	0.030	0.011	0.008	0.002	0.002	0.001	0	0	0	0.137
	0.64 0.55	0.001	0.007	0.012	0.029	0.019	0.018	0.005	0.004	0.003	0.002	0.001	0	0	0.104
	0.55 0.45	0.001	0.003	0.005	0.018	0.014	0.010	0.003	0.005	0.001	0	0.001	0	0.001	0.066
	0.45 0.34	0	0.001	0.002	0.004	0.006	0.001	0.005	0.003	0	0.002	0	0	0	0.024
	0.34 0.22	0	0.001	0.001	0	0.004	0	0.001	0.002	0.001	0	0	0	0	0.010
	0.22 0.00	0	0	0	0.	0.001	0.001	0.001	0	0	0	0	0	0	0.003
Marginal Prob		0.160	0.240	0.200	0.140	0.090	0.050	0.020	0.020	0.010	0.005	0.002	0	0.001	1.000

$$F_l^{Max} = \frac{F_l}{1-\beta_l}$$

Conclusions

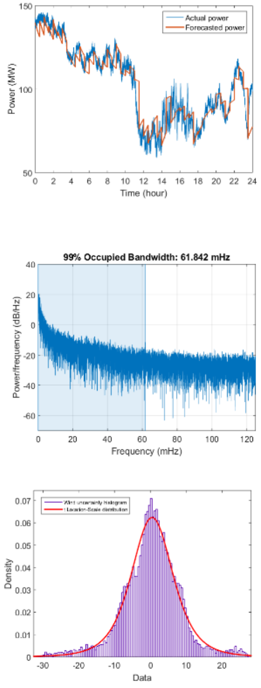
- The scaling properties of power grid parameters, such as the node degree, connectivity, path length, siting and size of generation and loads, transmission capacities, with regard to network size have been examined.
- The electric parameters of transformer and transmission lines have been statistically studied and interdependence of these parameters versus voltage levels derived. These results may be useful to enhance and improve the AutoSynGrid model.
- Statistics–based approaches have been developed:
  - to determine the generation and load settings taking into account their non-trivial correlation with bus nodal degree.
  - to determine the real power dispatch of generation units with respect to their estimated generation capacities.
- With the results from the generation and load setting, a statistical approach is proposed to estimate power flow $F_l(t_0)$ in a synthetic grid network, hence to determine the statistical assignment of the flow capacities F_l^{Max} for each transmission branch.

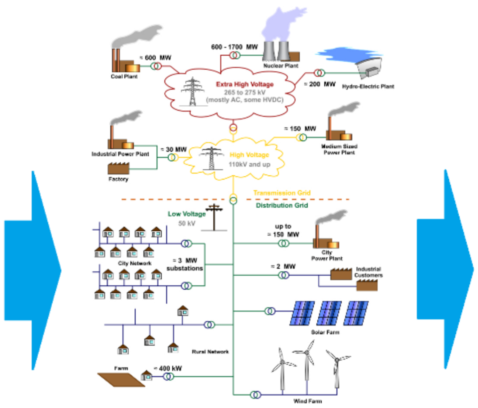
What to Do Next (need further funding)

- Complete the development of MATLAB Toolkits
- Release two Matlab Toolkits using GNU license:
  - **GridStatAnalysis** - Statistical Analysis of Grid e-topology
  - **AutoSynGrid** - Automated Simulation Platform to generate synthetic grid test cases
  - Make available free downloads from: www.epeslab.vcu.edu/downloads

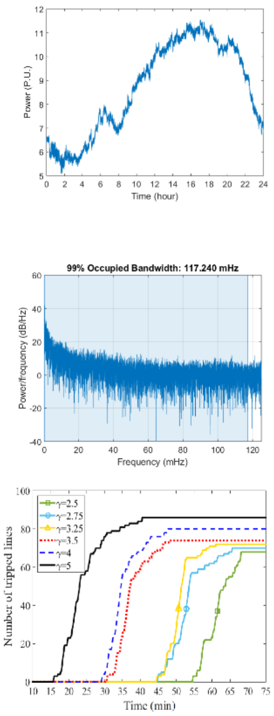
What to Do Next (need further funding)

- Grid Vulnerability and the Renewables:
  - Statistical modeling + time series modeling of uncertainties from generation, load, protective relays, and interdependences.
  - Grid Vulnerability Analysis in terms of overload outages, voltage collapse.
  - Mitigation approaches.





The power grid comprehensive



What to Do Next (need further funding)

- Articles in preparation or submitted:
  - HICSS 2018,
    - 1 paper submitted, on the interdependence of transmission branches vs voltage levels.
  - IEEE PES GM 2018,
    - 1 paper in preparation, on the AutoSynGrid model
  - IEEE trans on. Power Delivery
    - 1 submitted, on the grid vulnerability
  - IEEE trans on. Power System
    - 1 in preparation, on the GridStatAnalysis toolkit

Questions?

Thank you!

VCU

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