Ti Xu Memorial Lecture: Enhancing Power System Innovation Through the Use of Synthetic Electric Grids

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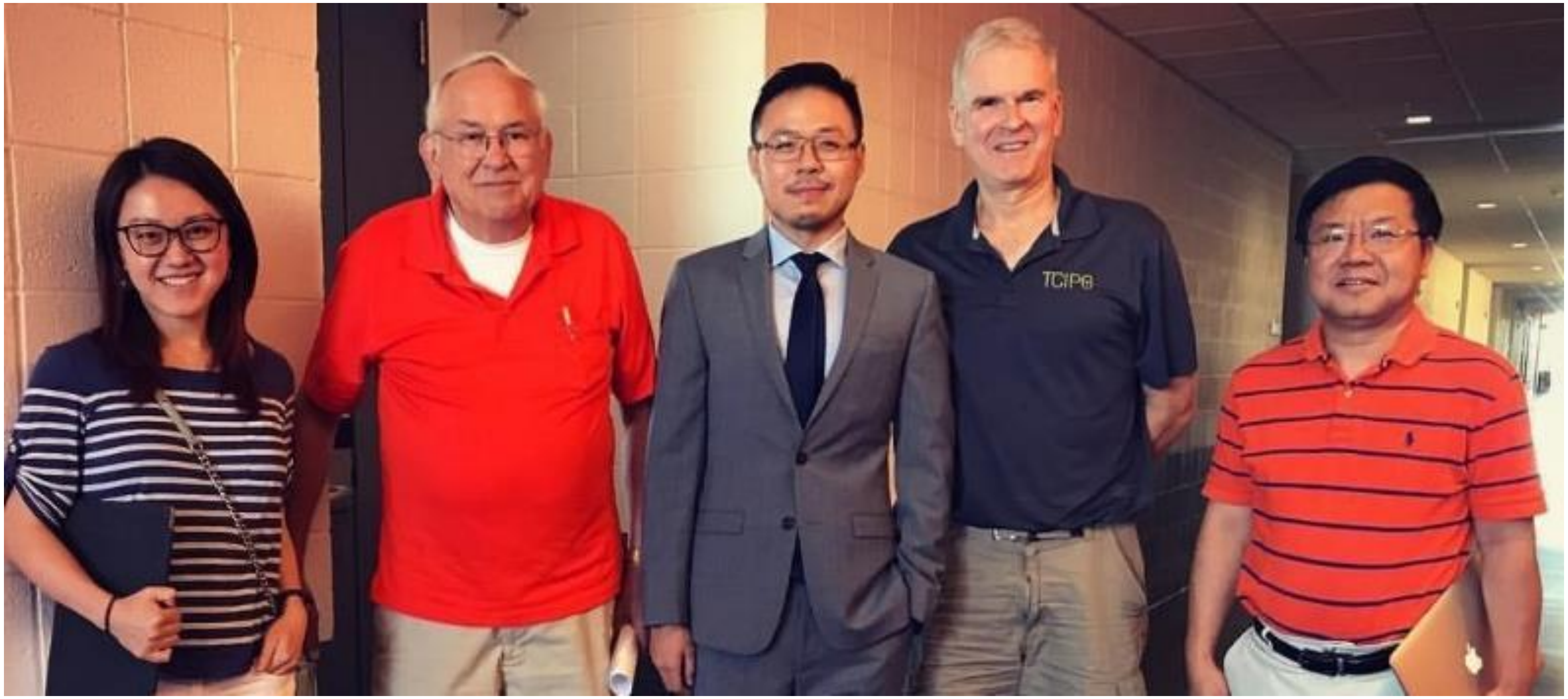
TEXAS A&M UNIVERSITY

Tribute to Ti Xu, 1988 - 9/14/2018



UIUC PhD: “Valuing of Inertia and Fast-Acting Storage Devices in Interconnected Power Grids,” (July 14, 2017)

Ti very much wanted to be a professor, was starting his second year as a TAMU postdoc and teaching a class in Fall 2018

Tribute to Ti Xu, 1988 - 2018

Ti and PECI

- PECI Treasurer, 2014-2015
- PECI Co-Director 2015-2016
- Two 2016 Papers (plus several others)

A Methodology for the Creation of Geographically Realistic Synthetic Power Flow Models

Kathleen M. Gegner, *Student Member, IEEE*, Adam B. Birchfield, *Student Member, IEEE*,
Ti Xu, *Student Member, IEEE*, Komal S. Shetye, *Member, IEEE*, Thomas J. Overbye, *Fellow, IEEE*
Department of Electrical and Computer Engineering

Application of Set-theoretic Method to Assess the Locational Impacts of Virtual Inertia Services on the Primary Frequency Responses

Ti Xu, Wonhyeok Jang, and Thomas Overbye
Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, IL, 61820
{txu20, wjang7, overbye}@illinois.edu

Some of Ti's Papers, 2017-8

Metric development for evaluating inertia's locational impacts on system primary frequency response
T Xu, Y Liu, TJ Overbye
2018 IEEE Texas Power and Energy Conference (TPEC), 1-6

Load modeling in synthetic electric grids
H Li, AL Bornsheuer, T Xu, AB Birchfield, TJ Overbye
2018 IEEE Texas Power and Energy Conference (TPEC), 1-6

Location-dependent impacts of resource inertia on power system oscillations
T Xu, W Jang, TJ Overbye
Proceedings of the 51st Hawaii International Conference on System Sciences

Building synthetic power transmission networks of many voltage levels, spanning multiple areas
AB Birchfield, T Xu, K Shetye, T Overbye

Real-time detection of malicious PMU data
Z Mao, T Xu, TJ Overbye
2017 19th International Conference on Intelligent System Application to ...

Creation of synthetic electric grid models for transient stability studies
T Xu, AB Birchfield, KS Shetye, TJ Overbye
Bulk Power Systems Dynamics and Control Symposium (IREP 2017)

PGLib OPF Case 200 PSERC
AB Birchfield, T Xu, KM Gegner, KS Shetye, TJ Overbye
IEEE PES Task Force

A metric-based validation process to assess the realism of synthetic power grids
A Birchfield, E Schweitzer, M Athari, T Xu, T Overbye, A Scaglione, ...
Energies 10 (8), 1233

Ti at HICSS January, 2018

Some of Ti's Papers: 2018

Power flow convergence and reactive power planning in the creation of large synthetic grids
AB Birchfield, T Xu, TJ Overbye
IEEE Transactions on Power Systems 33 (6), 6667-6674

Modeling, tuning, and validating system dynamics in synthetic electric grids
T Xu, AB Birchfield, TJ Overbye
IEEE Transactions on Power Systems 33 (6), 6501-6509

Locational Dependence of Inertia's Impacts on Critical Clearing Time
Y Liu, T Xu, TJ Overbye
2018 North American Power Symposium (NAPS), 1-6

ACTIVSg2000: A 2000-bus synthetic grid geolocated in Texas
A Birchfield, T Xu, K Shetye, T Overbye
Texas A&M University

Towards operational validation: Mapping power system inputs to operating conditions
E Schweitzer, T Xu, AB Birchfield, A Scaglione, TJ Overbye, RJ Thomas, ...
2018 Power Systems Computation Conference (PSCC), 1-7

ACTIVSg25K: A 25,000-bus synthetic grid geolocated in the Mid Atlantic USA
A Birchfield, T Xu, K Shetye, T Overbye
Texas A&M University

Commitment of fast-responding storage devices to mimic inertia for the enhancement of primary frequency response
T Xu, W Jang, T Overbye
IEEE Transactions on Power Systems 33 (2), 1219-1230

Synthetic Electric Grids Intro

- Our modern society depends on reliable electricity; large blackouts can be catastrophic
- Interconnected electric grids world-wide are in a period of rapid transition. Examples include
  – Integration of large amounts of renewable generation
  – Changing load, including more electric vehicles
  – Customers having more choice in their electric service
  – Inclusion of new technologies for sensing and control, such as phasor measurement units with "big data"
- There are lots of opportunities for innovation!

Data and Model Access Barriers

- In many places worldwide access to data about the actual power grid is restricted because of needs for confidentiality (e.g., in US critical energy infrastructure [CEII])
  - Data and models are sometimes available through NDAs, but ability to publish and distributed is limited
- To do effective research, and to drive innovation, researchers need access to common, realistic grid models and data sets
  - Scientific principle of reproducibility of results

Solution: Synthetic Electric Grids

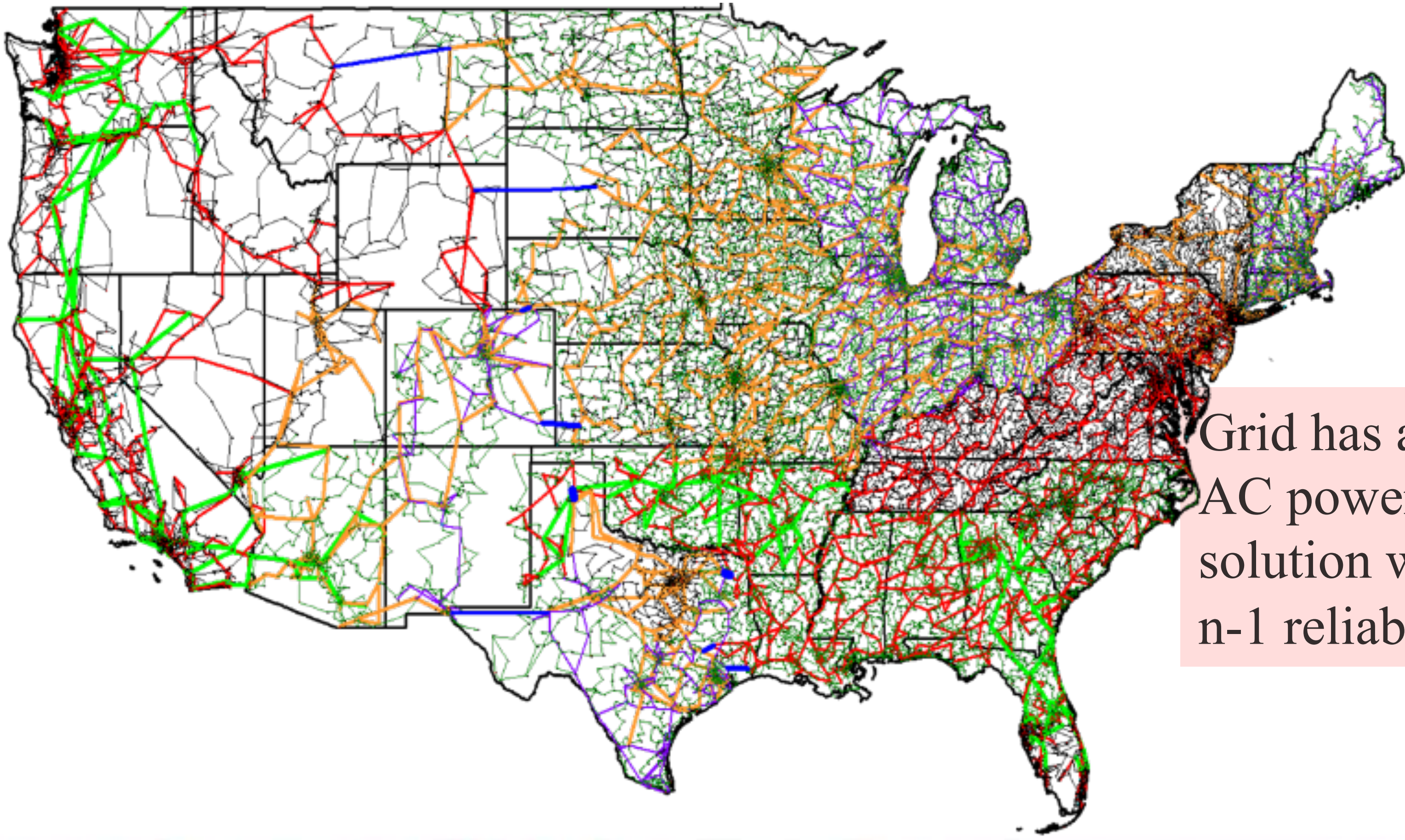
- Synthetic electric grids are fictional representations that are free from confidential information and hence can be freely shared
- Over the last three years tremendous progress has been made through the U.S. ARPA-E Grid Data Program in creating large-scale, high quality, realistic synthetic grids
- Validation with actual electric grids and data sets has been a crucial component of this research
- Goal is that innovation done with these grids can be directly applied to the actual grid

Our Synthetic Grid Approach

- Make grids that look real and familiar by siting them geographically (North America for us) and serving a population density the mimics actual
- Goal is to leverage widely available public data
  - Geography
  - Population density (easily available by post office)
  - Load by utility (US FERC 714), state-wide averages
  - Existing and planned generation (Form US EIA-860, which contains lots of generator information)
- Substation locations and transmission system is entirely fictional (but hopefully good fiction!)

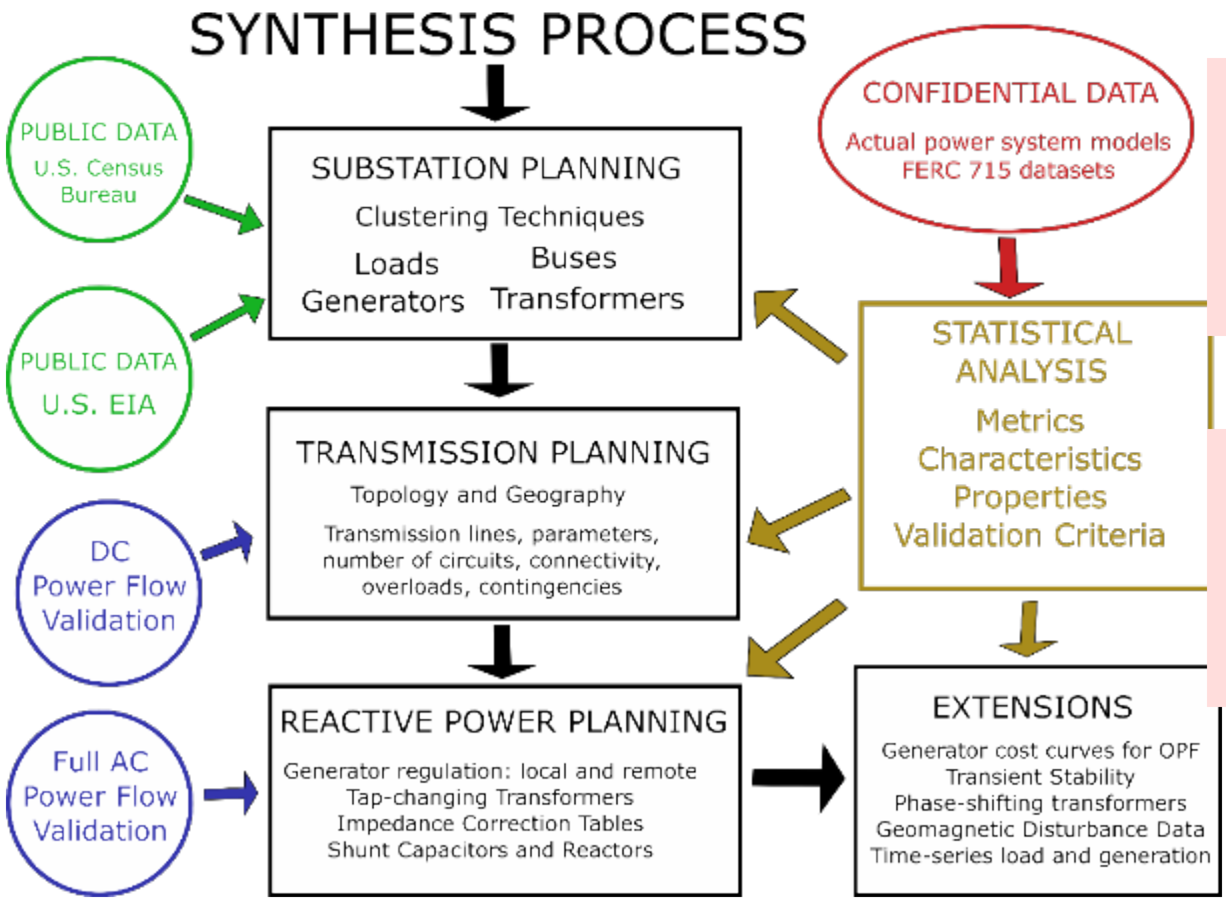
Current Status: Large-Scale Grids are Now Available

This is an 82,000 bus synthetic model that we publicly released in summer 2018 at **electricgrids.engr.tamu.edu**



Grid has an AC power flow solution with n-1 reliability

Synthetic Model Design Process



The assumed peak load is based on population, scaled by geographic values

Much of this is automated, but there is still some manual adjustment

Ti's work was focused on including electric grid dynamics

Outlier Characteristics are Key

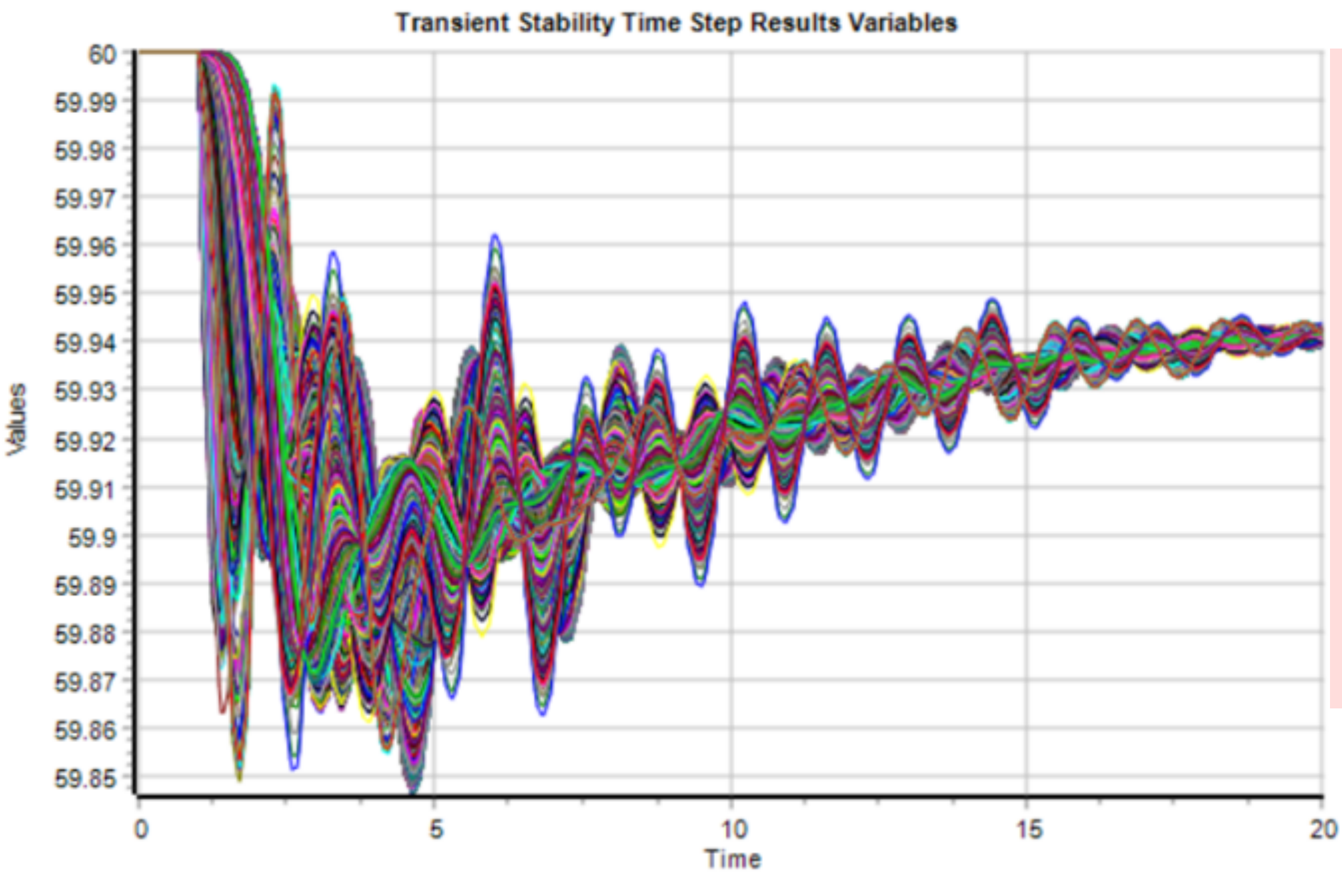
- A 76,000 bus North American power flow model has 27,622 transformers with 98 phase shifters
  - Impedance correction tables are used for 351, including about 2/3 of the phase shifters; tables can change the impedance by more than two times
- The voltage magnitude is controlled at about 19,000 buses (by Gens, LTCs, switched shunts)
  - 94% regulate their own terminals with about 1100 doing remote regulation. Of this 277 are regulated by three or more devices
- Reactive power control interaction is a issue

More Details on Design Process

- Substation planning: cluster actual population and energy data into correctly-sized substations and assign load, generation, bus voltage levels, and internal branches, along with parameters.
- Transmission planning: use iterative penalty-based dc power flow algorithm to place transmission lines, with the Delaunay triangulation and neighborhood as base
- Reactive power planning: iterative ac power flow starting from known solution to place capacitors and adjust generator set points.

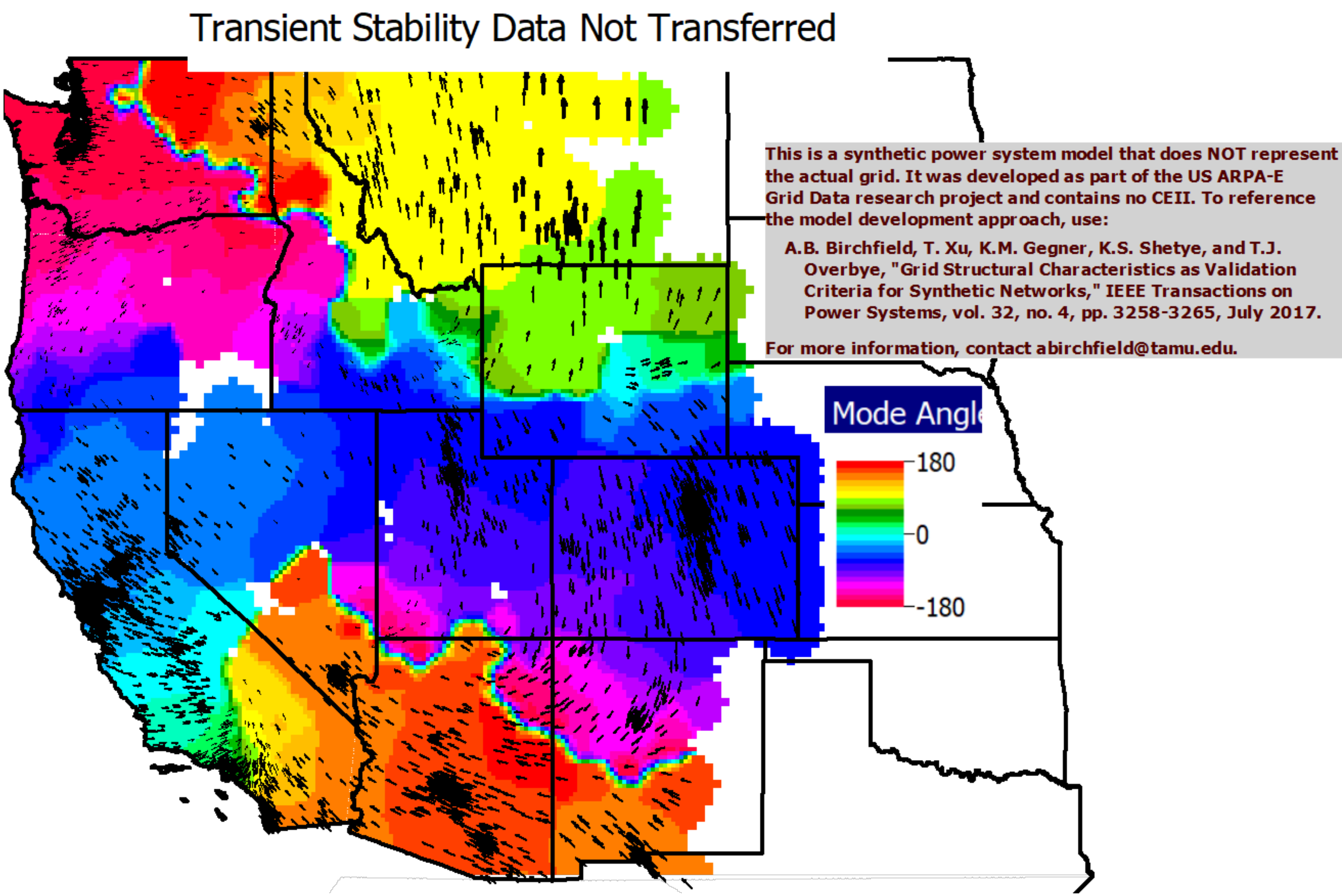
10K Example Transient Stability Results: Double Generator Outage

Substation Frequency Results for All Substations



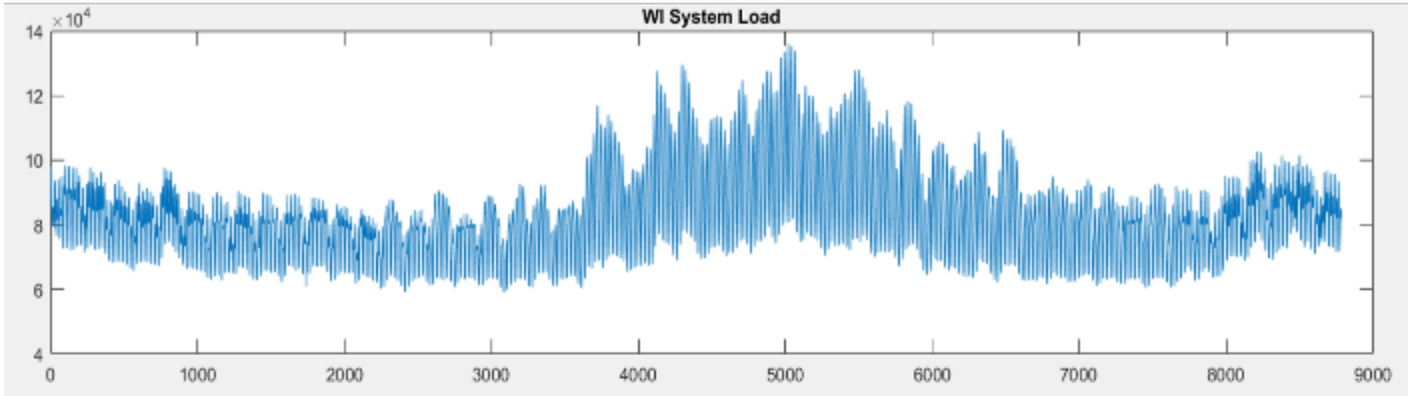
The dynamic models were developed by Ti. He was looking at the modes and their damping as a validation criteria.

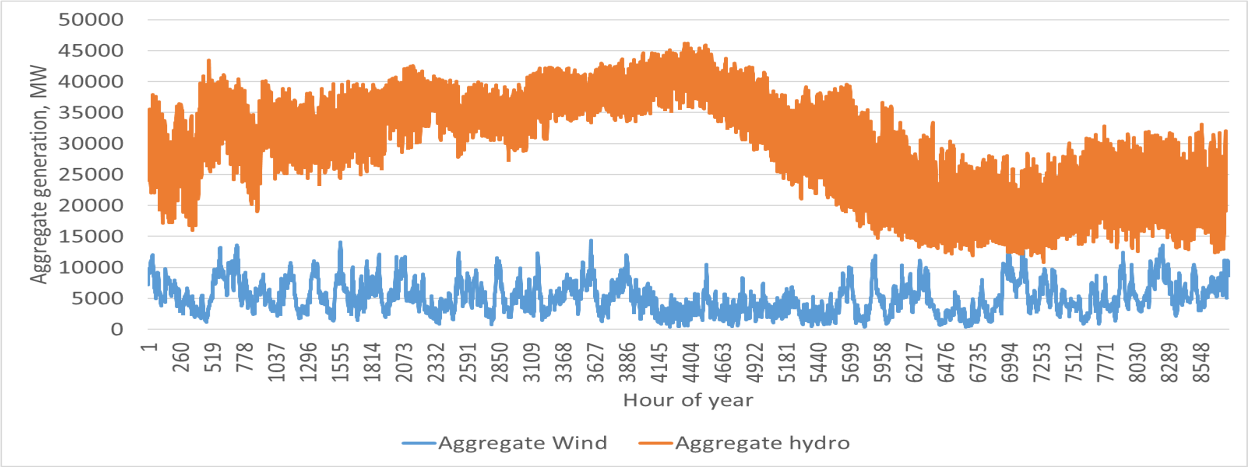
Synthetic Grid Modal Analysis: 0.73 Hz Lightly Damped Mode



Synthetic Electric Grid Scenarios

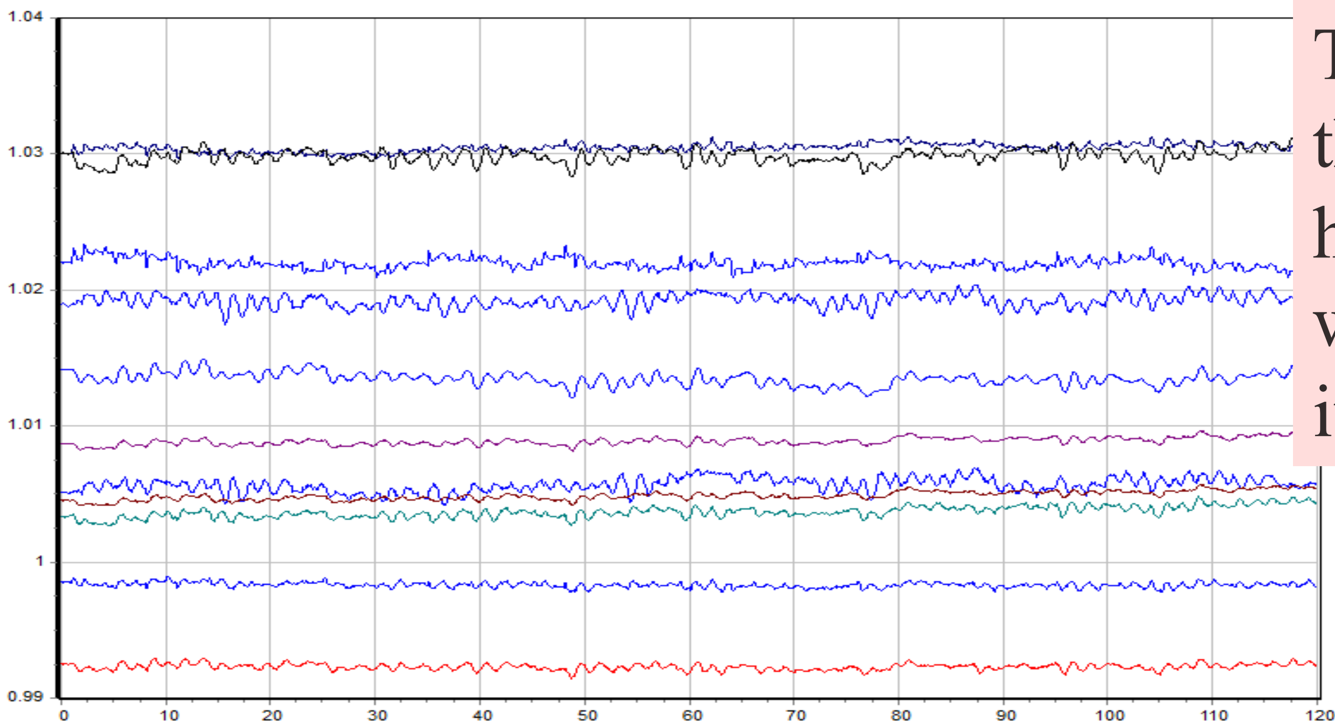
- We have developed detailed, yearly scenarios with variation of both bus level load and





Synthetic PMU Data

- To create synthetic PMU data we need dynamic simulations with realistic variation in the load and generation; validation will be crucial!



Ti produced this data, and had been working on its validation

Validation is Key!

- To-date we've developed about 20 metrics that cover the proportions, size, and structure of actual power grids models, with more coming!
- For example:
  - Buses/substation, Voltage levels, Load at each bus
  - Generator commitment, dispatch
  - Transformer reactance, MVA limit, X/R ratio
  - Percent of lines on minimum spanning tree and various neighbors of the Delaunay triangulation

Example Validation Metrics

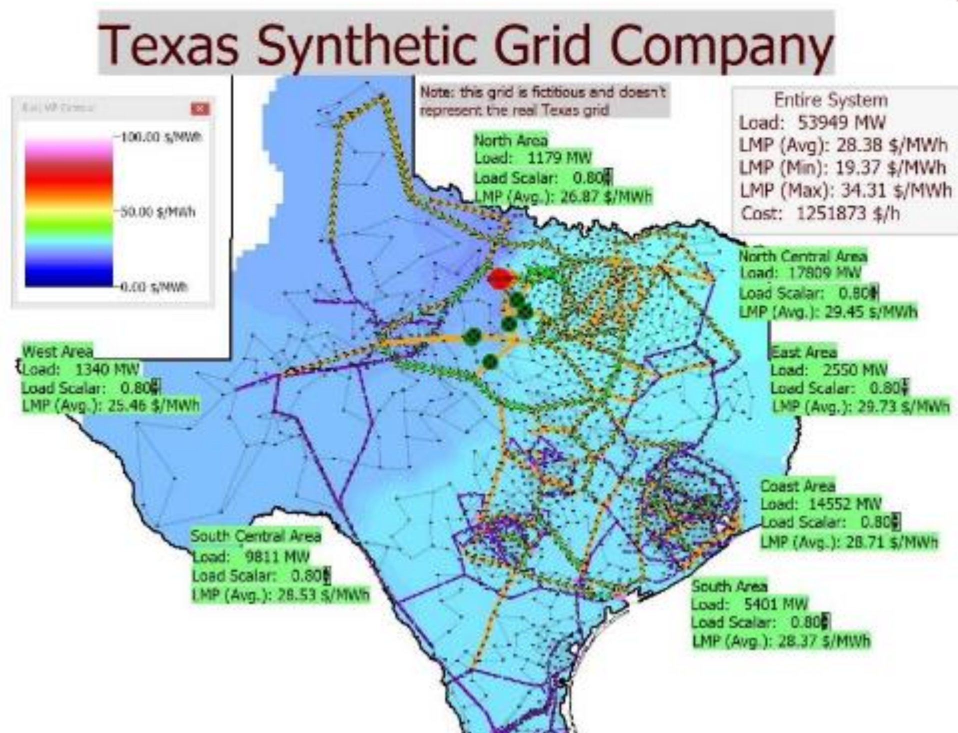
Validation Metric	Criteria	ACTIVSg25k
Voltage control and reactive power		
Shunt capacitors and reactors	10-25% of subs shunts 30-50% above 200 kV	9.1% 35.1%
Off-nominal network transformer taps	60-75% off-nominal 30-50% control voltage	67.2% 44.1%
Grid proportions, generators, load, and substations		
Buses per substation	Mean 1.7-3.5 Exponential decay	2.7 Next slide
Substations containing buses in kV range	<200 kV, 85-100% >201 kV, 7-25%	99.5% 12.9%
Substations with load	75-90%	85.0%
Load per bus	Mean 6-18 MW Exponential decay	9.4 MW Next slide
Load power factor	Mean 0.93-0.95 Decreasing distribution	0.959 Next slide
Generation capacity / load	1.2-1.6	1.30
Substations with generators	5-25%	17.6%
Generator MW maximum capacities	25-200 MW, 40+% 200+ MW, 2-20%	24.7% 9.2%
Generator MW minimum	Coal average 0.37-0.47 Gas average 0.27-0.37	0.3 0.31
Committed Generators	60-80%	78%
Generators dispatched > 80%	50+%	76%
Cycle distribution	Decreasing distribution	Next slide

Example Validation Metrics, cont.

Network topology / branch params.	765	500	345	230	161	138	115	100	69
XF p.u. X, own base	98	98	98	98	95	98	96	98	98
XF X/R ratio and MVA lim	51/58 49/42 100/98	56/53 44/47 100/99	49/47 51/53 99/91	48/37 52/62 100/99	48/50 52/50 99/89	51/34 50/66 100/99	54/62 46/38 100/88	47/66 54/35 100/90	47/66 54/35 100/90
Line X	79	94	99	98	97	100	98	98	98
Line X/R and MVA	100/99	100/99	100/96	100/99	100/ 100	100/98	100/ 100	100/ 100	100/ 100
Lines/subs	1.19	1.20	1.33	1.15	1.16	1.24	1.16	1.21	1.21
Lines MST	53.5	53.5	51.7	53.0	50.8	53.3	54.8	53.7	53.7
Delaunay distance	80.6 15.9 3.5	80.8 15.9 3.3	79.8 16.4 3.7	80.2 16.6 3.2	75.9 20.0 4.1	79.6 16.6 3.8	80.3 16.0 3.7	80.5 16.1 3.4	80.5 16.1 3.4
length / MST	1.38	1.55	1.74	1.46	1.46	1.64	1.57	1.42	1.42

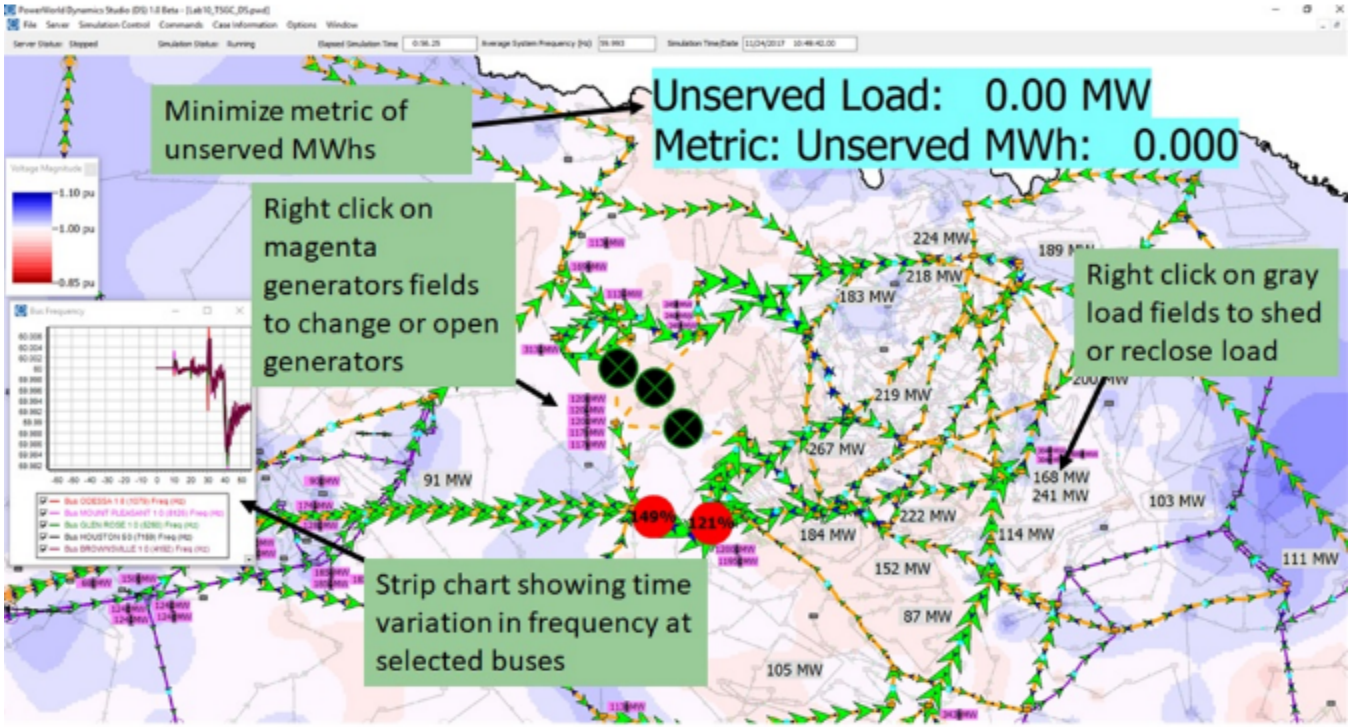
Innovative Electric Power Education

- Lab assignments involving a 2000 bus case have been integrated into Texas A&M's power classes
- Class includes large-system exercises for power flow, economic dispatch, contingency analysis, SCOPF, and transient stability



Innovative Electric Power Education

- One lab challenges students to save the synthetic Texas grid from voltage collapse following a simulated tornado!

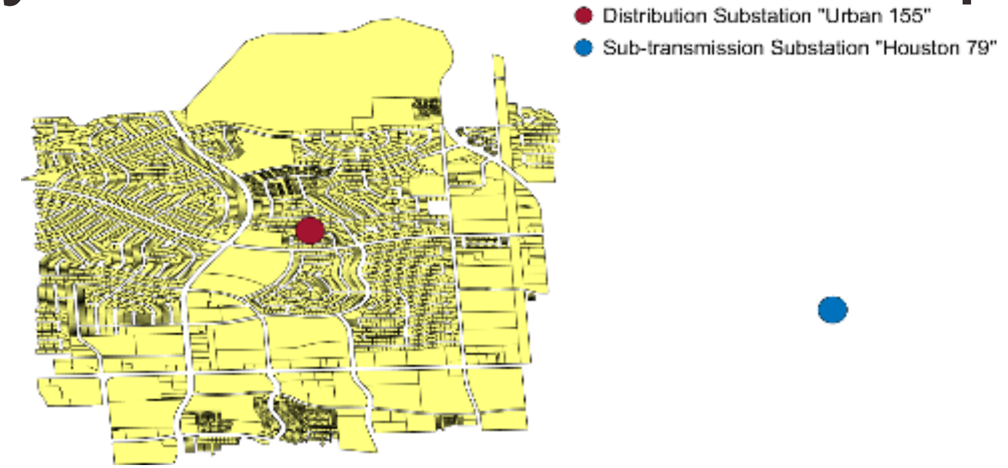


Development of Electric Control System of the Future

Moving Forward: Highly Detailed Synthetic Grids

- We are continuing to build on Ti's work in the area of dynamics, now adding much more detailed protection system models
- We're also partnering with NREL to build highly detailed synthetic grids that go down to the parcel level to represent individual electric meters
  - Since we're using actual parcel information (which is public data), we're able to couple in with other infrastructures such as transportation and water

Detailed Synthetic Distribution Power Systems of Texas Example



- Parcels are clustered to be connected to substations in an existing 2000 bus synthetic transmission system
- Co-simulation between synthetic transmission and distribution system will be established

Conclusions

- CEII concerns have limited the availability of actual grids to researchers, and most existing public test grids do not match the complexity of actual grids
- As a result of Ti's work (and others) synthetic grids, scenarios and data sets are now available to close this gap
  - Freely available at **electricgrids.engr.tamu.edu**
- We are building on Ti's work to move forward while honoring the legacy of our colleague!

Thank You!