ECEN 615
Methods of Electric Power Systems Analysis

Lecture 19: EMSs, Synthetic Grids, Voltage Stability

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TEXAS A&M UNIVERSITY

Announcements

- Starting reading Chapter 8
- Homework 6 is now due on Thursday Nov 17 but it counts as two regular homeworks.

Grid Equivalent Examples

- A 2016 EI case had about 350 lines with a circuit ID of ’99’ and about 60 with ‘EQ’ (out of a total of 102,000)
  - Both WECC and the EI use ’99’ or ‘EQ’ circuit IDs to indicate equivalent lines
  - One would expect few equivalent lines in interconnect wide models
- A 12 year old EI case had about 1633 lines with a circuit ID of ’99’ and 400 with ‘EQ’ (out of a total of 65673)
- A 12 year old case with about 5000 buses and 5000 lines had 600 equivalent lines

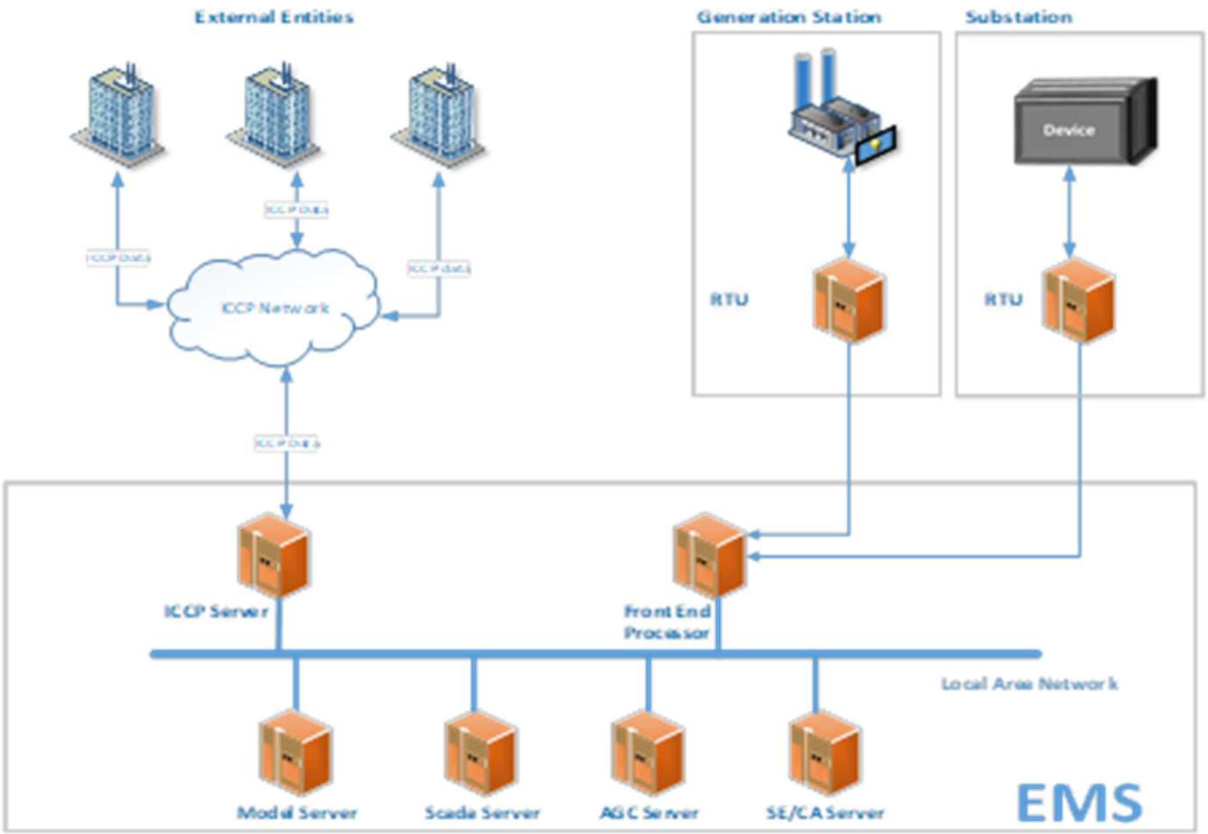
Energy Management Systems (EMSs)

- EMSs are now used to control most large scale electric grids
- EMSs developed in the 1970's and 1980's out of SCADA systems
  - An EMS usually includes a SCADA system; sometimes called a SCADA/EMS
- Having a SE is almost the definition of an EMS. The SE then feeds data to the more advanced functions
- EMSs have evolved as the industry has evolved, with functionality customized for the application (e.g., a reliability coordinator or a vertically integrated utility)

ERCOT Control Center with EMS

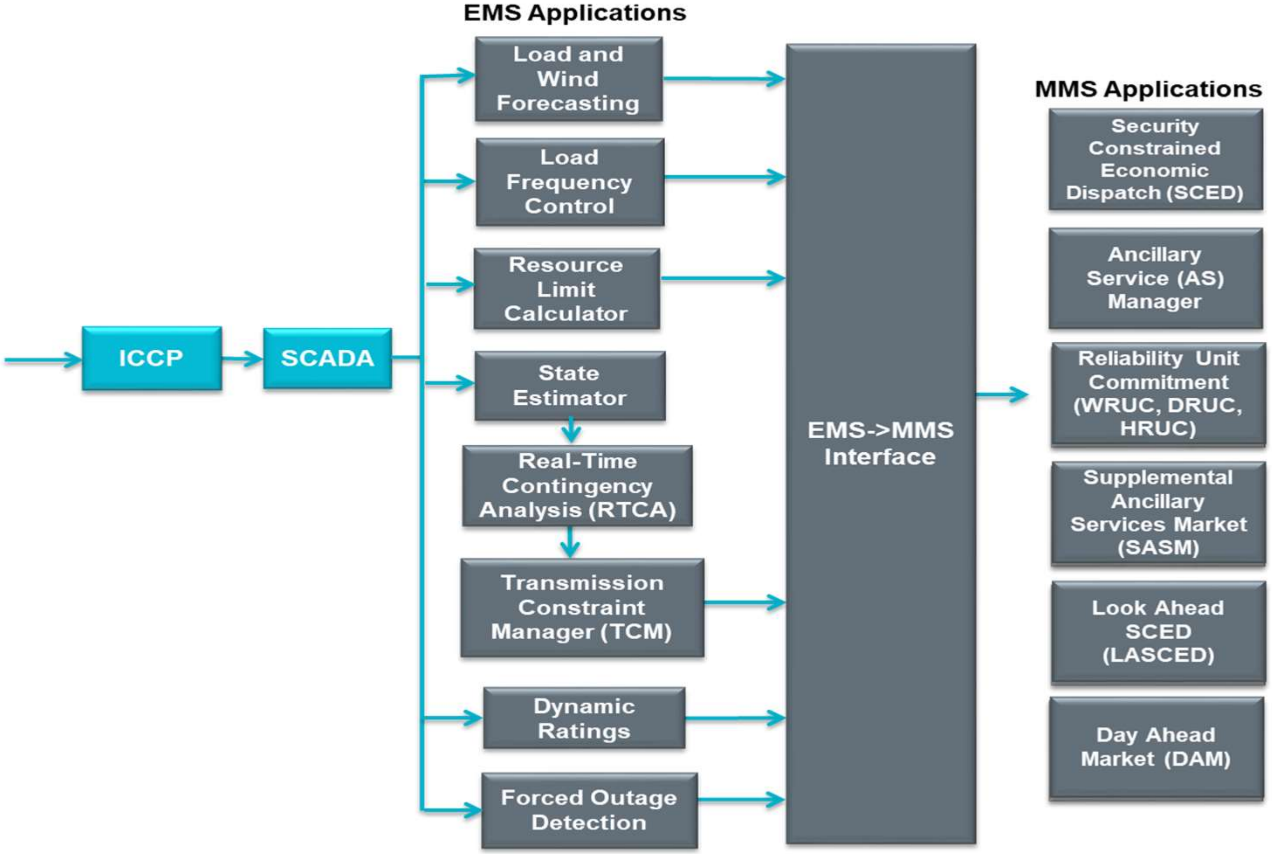
Source: www.texastribune.org/2016/05/17/texas-market-forces-driving-shift-coal-study-says/

ERCOT EMS



Slide source: ERCOT, D. Penney, J. Mandavilli, M. Henry, “Loss of SCADA, EMS or LCC”

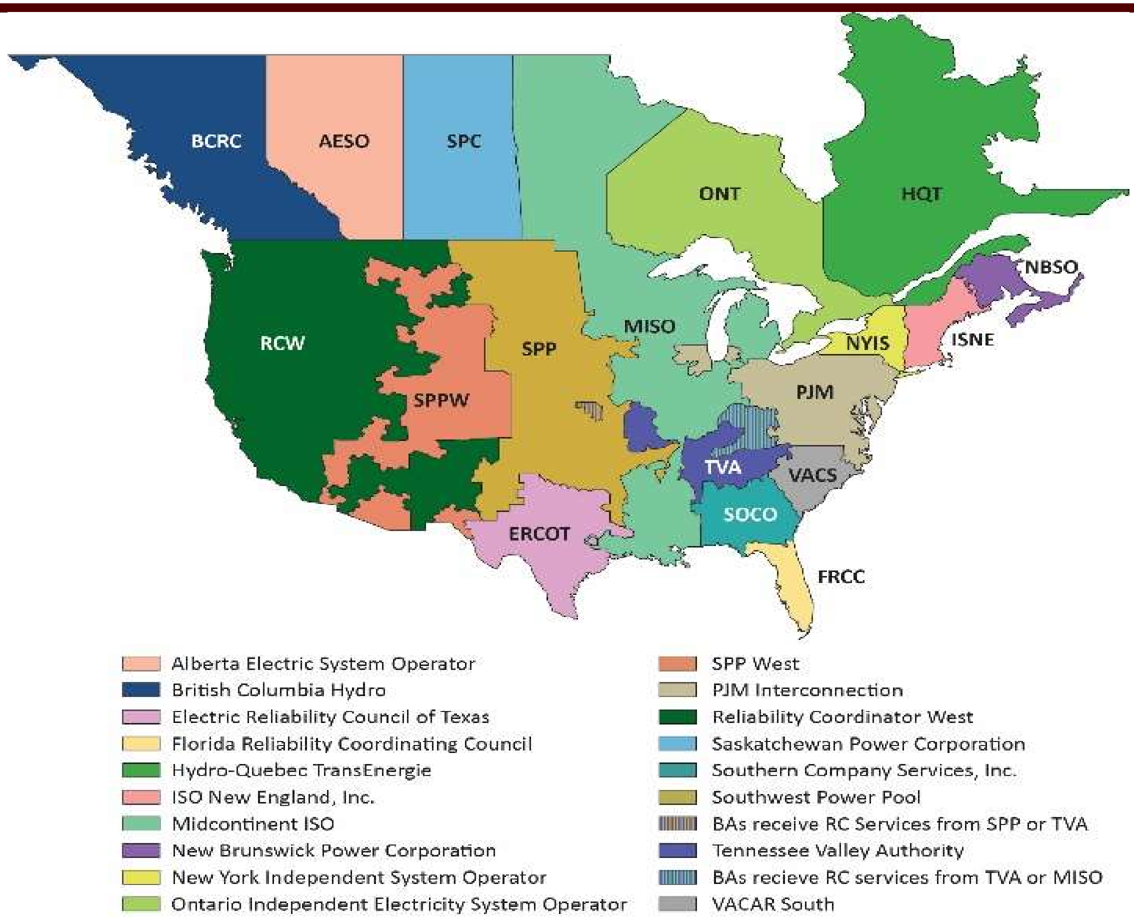
ERCOT EMS, cont.



In 2021 Anjan Bose and I wrote a white paper for DOE on new research needs in grid operations. This paper also provides a summary of the development of EMSs. The paper is Bose, Anjan, and T. J. Overbye "*Electricity Transmission System Research and Development: Grid Operations*" In Transmission Innovation Symposium: Modernizing the U.S. Electrical Grid, U.S. Department of Energy 2021 (a link is on my website at **overbye.engr.tamu.edu/publications)**

Slide source: ERCOT, D. Penney, J. Mandavilli, M. Henry, "Loss of SCADA, EMS or LCC"

NERC Reliability Coordinators

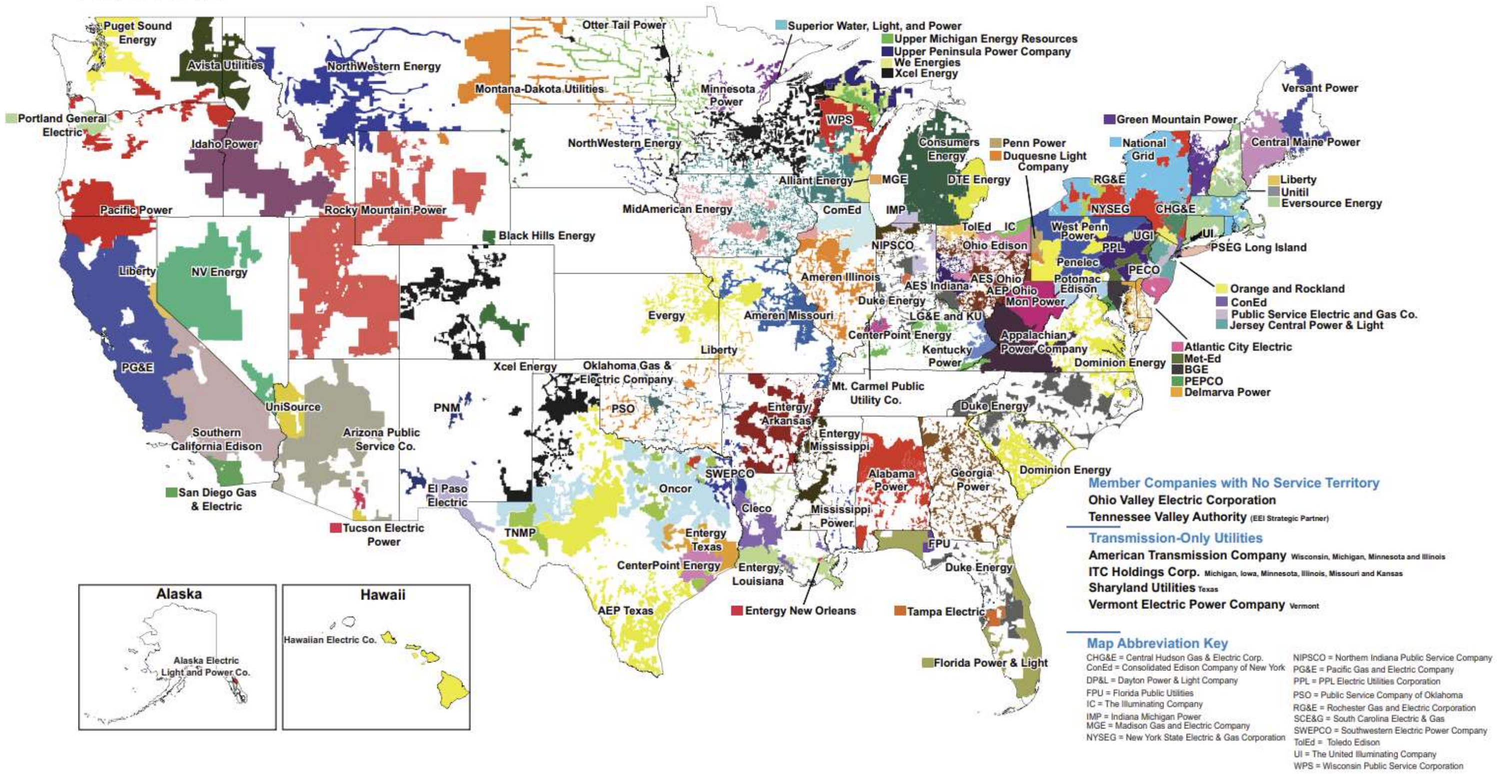


Source: www.nerc.com/pa/rrm/TLR/Pages/Reliability-Coordinators.aspx

EEI Member Companies

EEI
Edison Electric
INSTITUTE

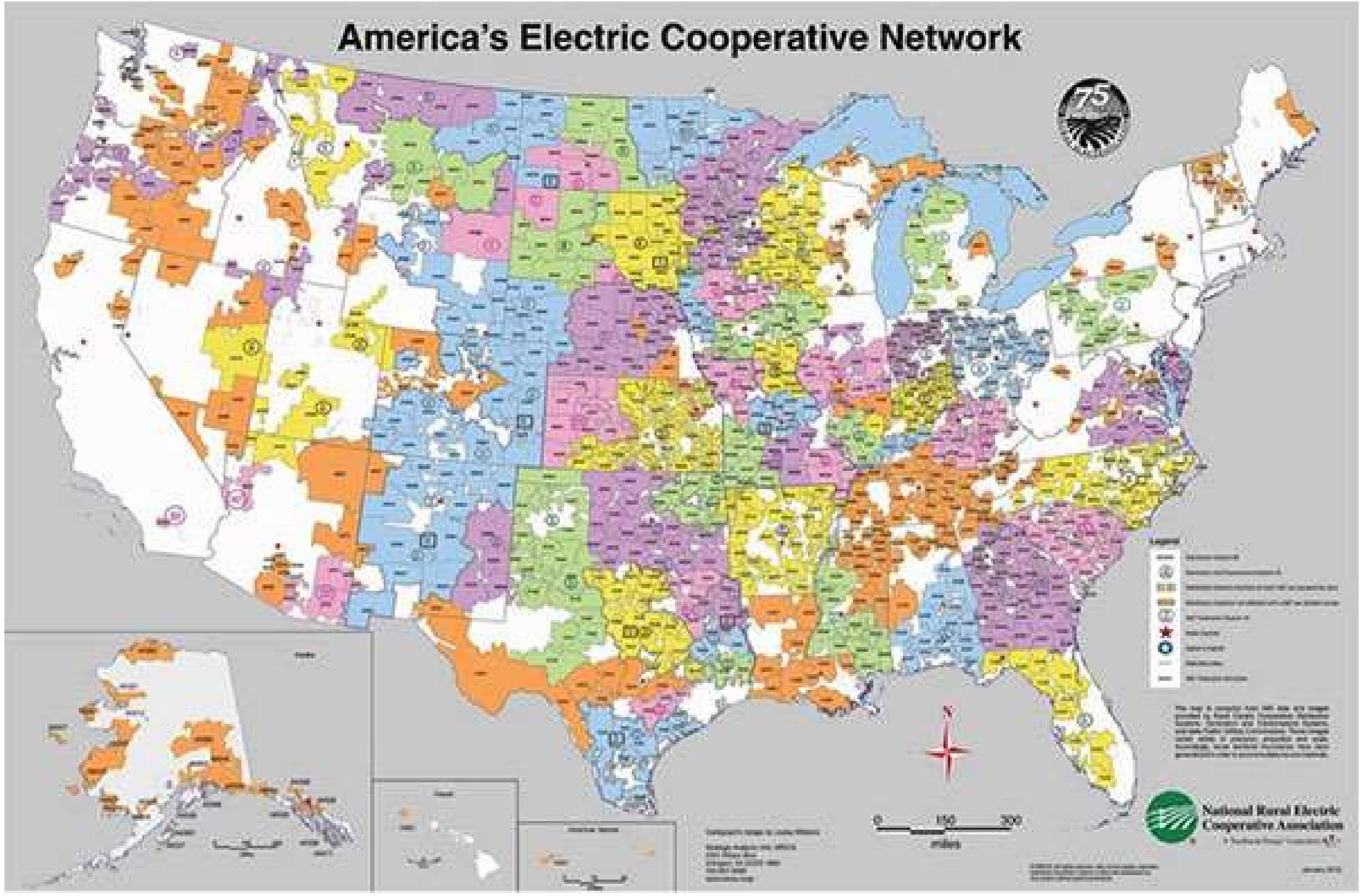
EEI U.S. Member Company Service Territories



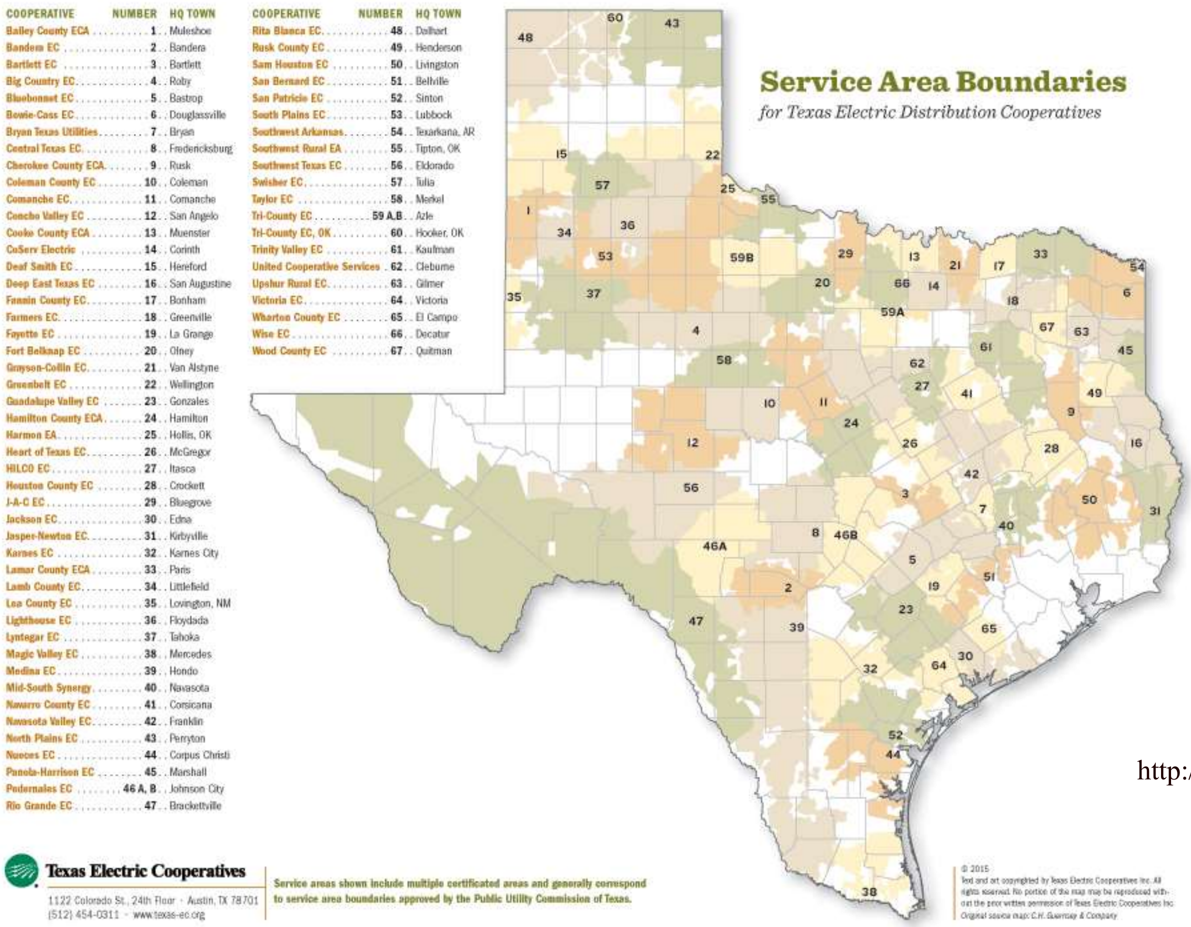
Produced by Edison Electric Institute. Data Source: ABB, Velocity Suite. September 2022

Geographically the map is somewhat sparse because EEI represents investor owned utilities

Electric Coops



Texas Electric Coops



COOPERATIVE	NUMBER	HQ TOWN
Bailey County ECA	1	Muleshoe
Bandera EC	2	Bandera
Bartlett EC	3	Bartlett
Big Country EC	4	Roby
Bluebonnet EC	5	Bastrop
Bowie-Cass EC	6	Douglassville
Bryan Texas Utilities	7	Bryan
Central Texas EC	8	Fredericksburg
Cherokee County ECA	9	Rusk
Coleman County EC	10	Coleman
Comanche EC	11	Comanche
Concho Valley EC	12	San Angelo
Cooke County ECA	13	Muenster
CoServ Electric	14	Corinth
Deaf Smith EC	15	Hereford
Deep East Texas EC	16	San Augustine
Fannin County EC	17	Bonham
Farmers EC	18	Greenville
Fayette EC	19	La Grange
Fort Belknap EC	20	Olney
Grayson-Collin EC	21	Van Alstyne
Greenbelt EC	22	Wellington
Guadalupe Valley EC	23	Gonzales
Hamilton County ECA	24	Hamilton
Harmon EA	25	Hollis, OK
Heart of Texas EC	26	McGregor
HILCO EC	27	Itasca
Houston County EC	28	Crockett
J-A-C EC	29	Bluegrove
Jackson EC	30	Edna
Jasper-Newton EC	31	Kirbyville
Karnes EC	32	Karnes City
Lamar County ECA	33	Paris
Lamb County EC	34	Littlefield
Lea County EC	35	Lovington, NM
Lighthouse EC	36	Floydada
Lyntegar EC	37	Tahoka
Magic Valley EC	38	Mercedes
Medina EC	39	Hondo
Mid-South Synergy	40	Navasota
Navarro County EC	41	Corsicana
Navasota Valley EC	42	Franklin
North Plains EC	43	Perryton
Nueces EC	44	Corpus Christi
Panola-Harrison EC	45	Marshall
Pedernales EC	46 A, B	Johnson City
Rio Grande EC	47	Brackettville
Rita Blanca EC	48	Dalhart
Rusk County EC	49	Henderson
Sam Houston EC	50	Livingston
San Bernard EC	51	Bellville
San Patricio EC	52	Sinton
South Plains EC	53	Lubbock
Southwest Arkansas	54	Texarkana, AR
Southwest Rural EA	55	Tipton, OK
Southwest Texas EC	56	Eldorado
Swisher EC	57	Tulia
Taylor EC	58	Merkel
Tri-County EC	59 A,B	Azle
Tri-County EC, OK	60	Hooker, OK
Trinity Valley EC	61	Kaufman
United Cooperative Services	62	Cleburne
Upshur Rural EC	63	Gilmer
Victoria EC	64	Victoria
Wharton County EC	65	El Campo
Wise EC	66	Decatur
Wood County EC	67	Quitman

http://www.tecutility.org/about/member-directory

Synthetic Electric Grids

- Synthetic electric grids are models of electric grids that were not created to represent any actual electric grid
- The below image shows the five bus synthetic grid I used as an undergraduate

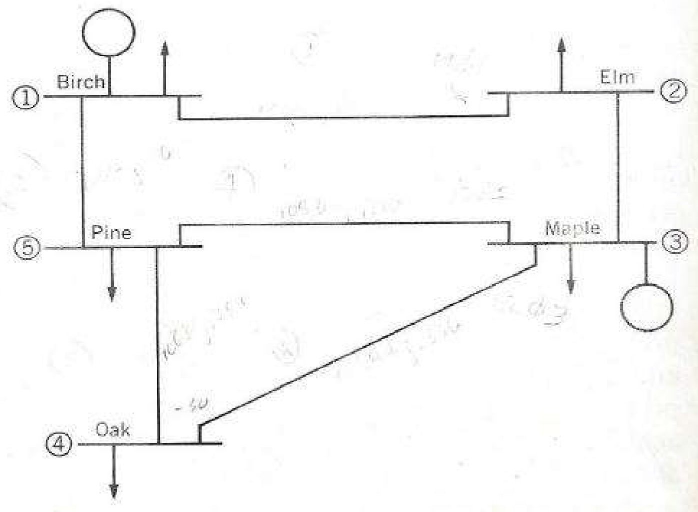


Figure 8.1 One-line diagram for Example 8.1.

Image Source: W.D. Stevenson, *Elements of Power Systems*, Fourth Edition, McGraw-Hill Book Company New York, 1982 (the first edition was in 1955)

Geographically-Based Synthetic Electric Grids

- Synthetic electric grids can be created with or without reference to actual geography
- The image shows an early geographically-based synthetic electric grid
- This grid was designed to show concepts to regulators

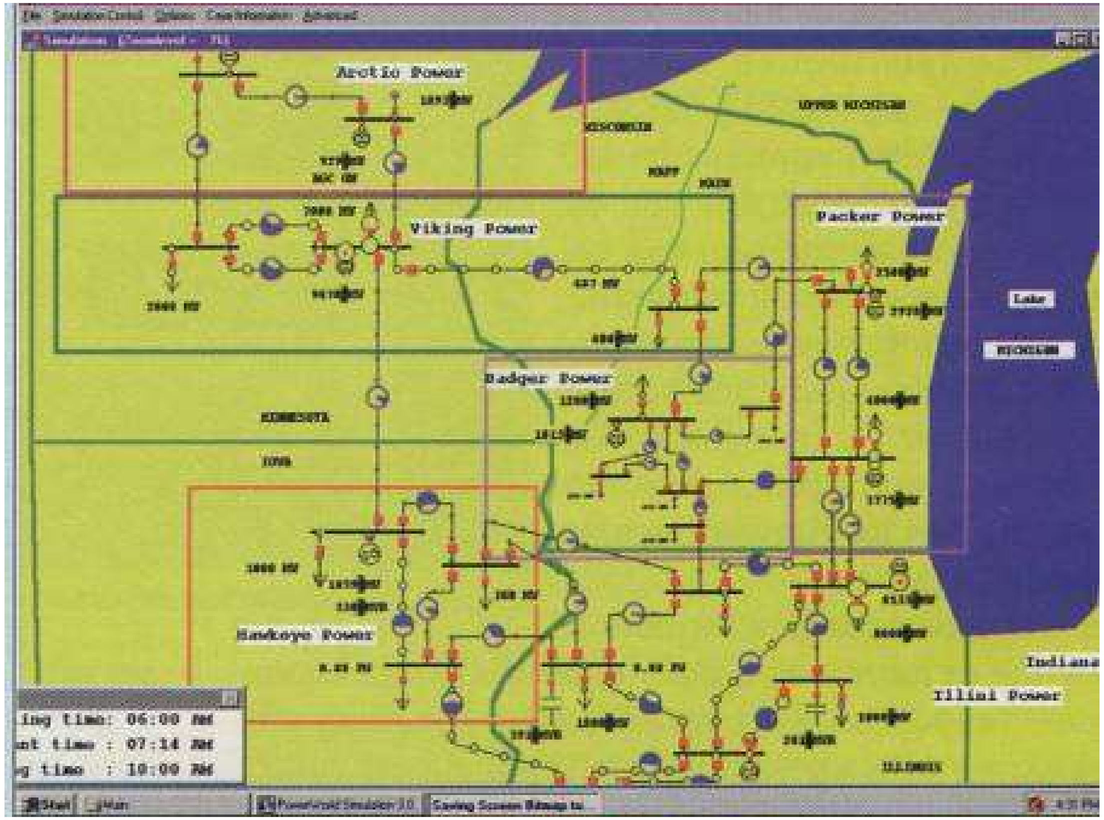


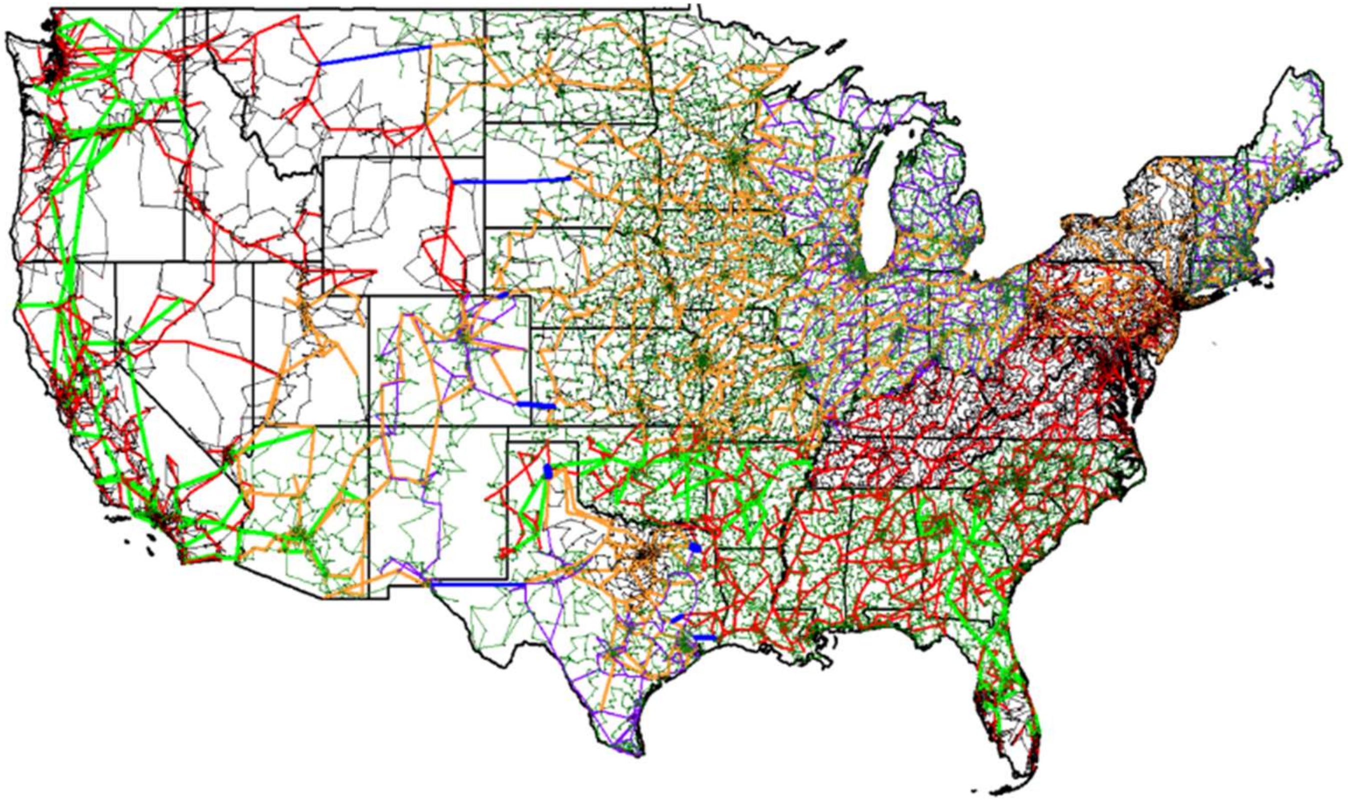
Image Source: PowerWorld Corporation, 1995

High-Quality, Geographically-Based Synthetic Electric Grids

- High-quality synthetic electric grids are designed to have a wide range of characteristics that are similar to those found in actual electric grids
  - "Realistic but not real" to quote Wisconsin colleagues
  - Fictional, but hopefully good fiction
  - **Developed techniques can be applied to real grids**
- However, importantly these grids are not designed to try to duplicate any actual grid
- Over the last five years tremendous progress has been made through ARPA-E at both the transmission and distribution levels

Current Status: Large-Scale Grids are Now Available

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



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

The Need for Synthetic Grids

- Prior to 9/11/01, a lot of grid information was publically available
- Now access to data and models about the actual power grid in the US is quite restricted (e.g., critical energy/electricity infrastructure [CEII])
  - What is available is often partial, and can't be shared
- 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
- Synthetic grids and datasets are, of course, designed to augment, not replace actual grids

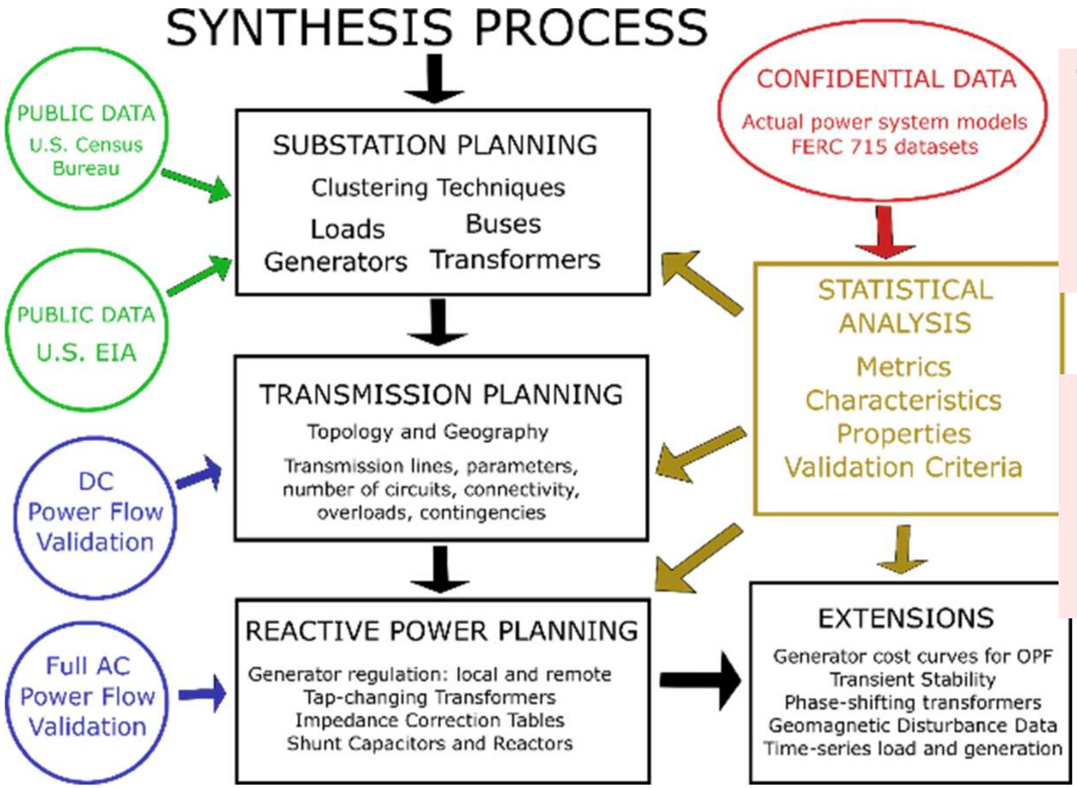
The Need for Synthetic Grids, cont.

- But the synthetic grids offer some significant advantages, both to industry and researchers
  - Since there are no CEII or privacy concerns, full models and their associated datasets can be freely shared; this is particularly helpful for interdisciplinary research
  - Synthetic grids can allow future grid scenarios to be considered in-depth (i.e., high renewables or high impact, low frequency events) yet still be potentially public
  - Synthetic grids can be customized to represent particular grid idiosyncrasies; utilities can provide this to researchers or potential vendors
    - We've deliberately designed ours using different voltage levels than those used in the actual grid (e.g., 500/230 versus 345/138 in Texas) to emphasis they are synthetic
  - They can be coupled with actual data, like weather
  - Synthetic grids can be used for education, including vendor training and short courses

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!)

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

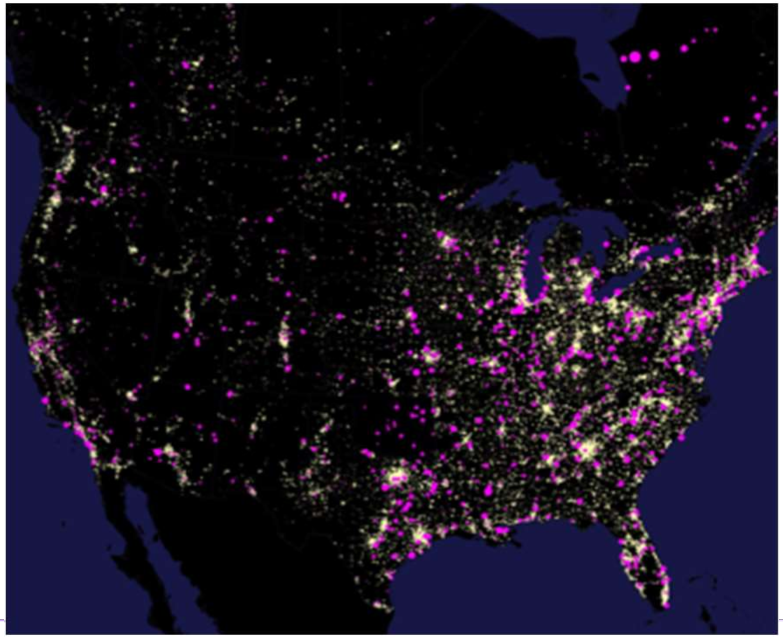
This process can be augmented to couple with detailed distribution grids

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.

Understanding Actual Electric Grid Topology

- To make realistic synthetic grids it is important to understand the geographic of actual grids
- Actual power grids are geographically consistent
  - This is an inherent characteristic that has profound modeling implications
  - Examples include line impedance, and constraints such as lakes, rivers, and mountains
- Traditionally power system planning models did not include geographic coordinates but this has now changed

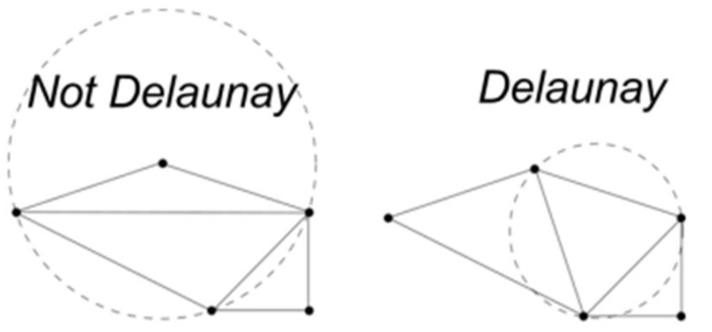


Understanding Actual Electric Grid Topology

- Assuming the substation geographic locations are known, the topology of the grid can be discovered, voltage level by voltage level
  - Transformers are within substations
- At a particular voltage level think of each substation as a node; the minimum spanning tree (MST) is the shortest set of lines to connect all the nodes
- The Delaunay triangulation is a triangulation of these points such that no point is inside the circumcircle of any triangle.
- The Delaunay triangulation contains the MST

Use of Delaunay Triangulation

- Helps to capture geometric constraints of grids, i.e. substations generally connect to nearby neighbors.
- Considering only Delaunay triangulation and 2-3 neighbors cuts potential lines from n^2 to $21n$, but captures about 98% of actual lines

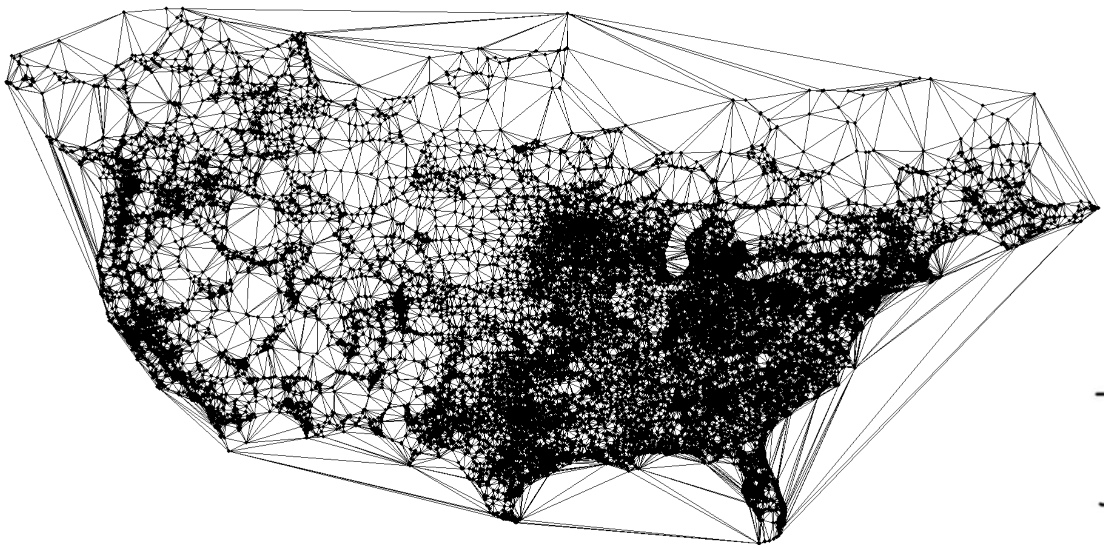


Transmission Line Category	Average percentage for Eastern Interconnect	Average percentage for Western Interconnect
Min. Span. Tree	47.8%	44.3%
Delaunay	75.6%	71.1%
2 neighbor	18.3%	21.5%
3 neighbor	4.6%	5.3%
4 neighbor	1.1%	1.4%
5+ neighbor	0.4%	0.7%

Actual Grid Delaunay Triangulation and Minimum Spanning Tree

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))

MST for the EI 500 kV grid black is actual on MST; red is MST without a line; green is other



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

Validation: Ensuring High Quality

- Based upon data from actual grids we've developed a large number of metrics that cover many aspects of both transmission and distribution grids
- 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
  - Bus phase angle differences, flow distribution

Example Validation Metrics

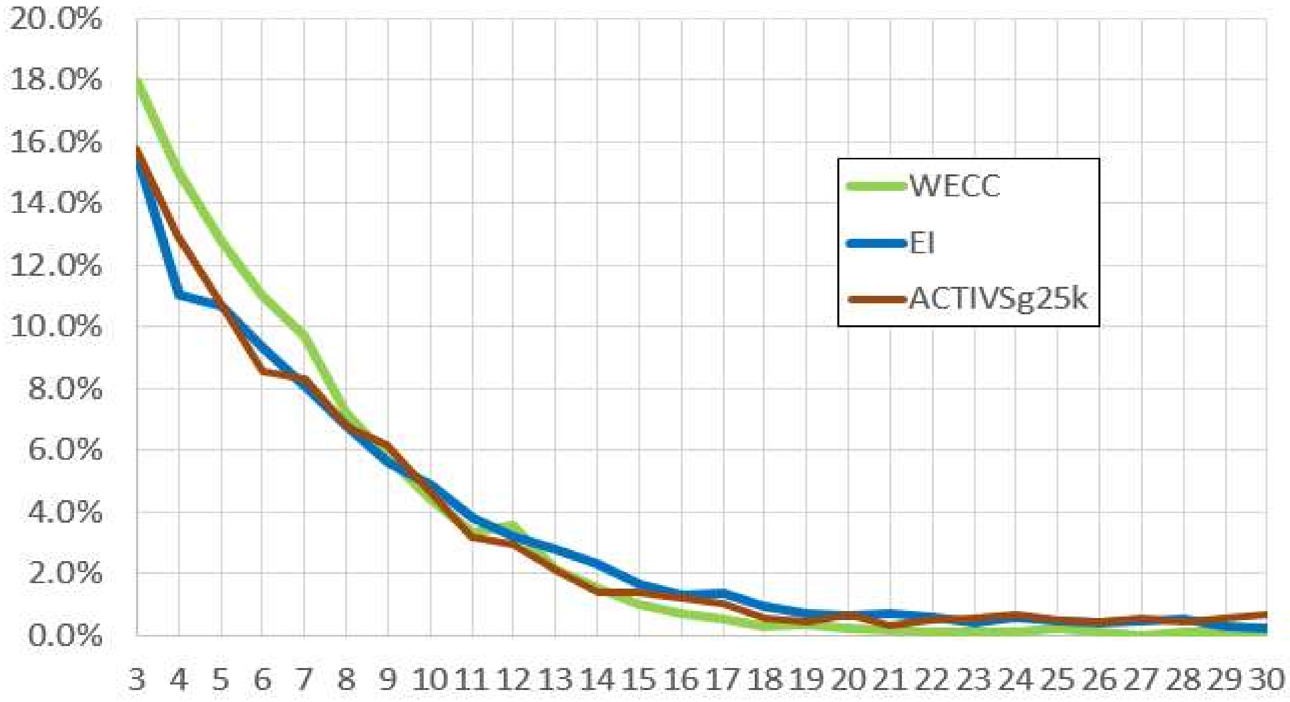
Validation Metric	Criteria	ACTIVSg25k
Voltage control and reactive power		
Shunt capacitors and reactors	10-25% of subs shunts 30-50% above 200 kV	9.1% 35.1%
Off-nominal network transformer taps	60-75% off-nominal 30-50% control voltage	67.2% 44.1%
Grid proportions, generators, load, and substations		
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

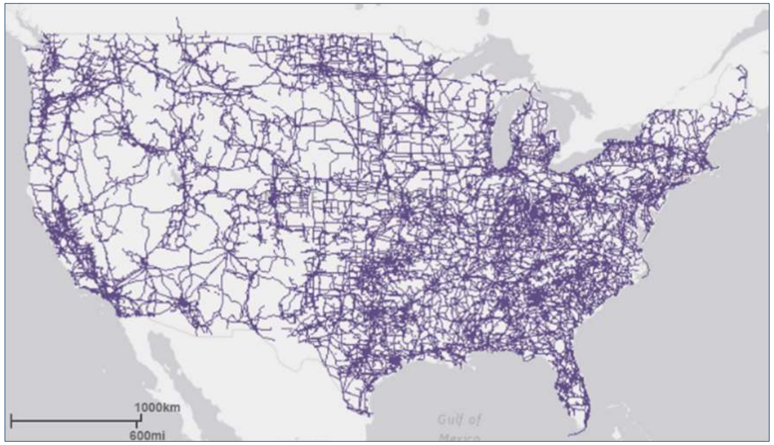
Validation Example: Cycle Sizes

- Cycles are loops of connected buses. Power systems have many cycles and an important metric to match is to have a similar cycle basis



Intersections (Transmission Line Crossings)

- We've found it is important to match properties of electric grids that depend on their physical layout; for example transmission line crossings
  - Transmission line right-of-ways are available in EIA datasets; hence line crossings can be analyzed



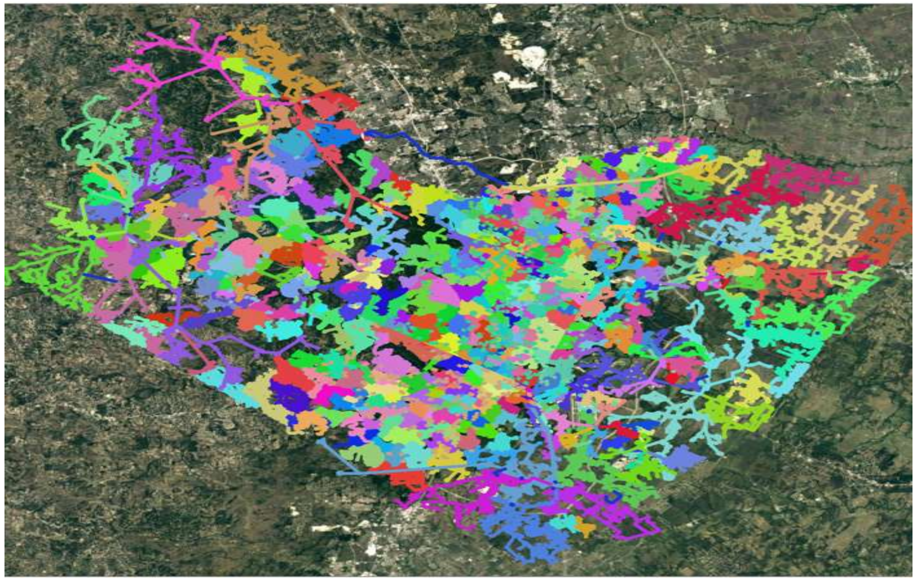
GEOGRAPHIC CROSSINGS FOR EIA DATASET VOLTAGE NETWORKS

Voltage class	Number of substations	Number of lines	Crossings, straight-line Number	Crossings, straight-line % of lines
765 kV	40	42	1	2.4
500 kV	529	732	67	9.2
345 kV	1526	2171	297	13.7
230 kV	4648	6233	935	15.1
161 kV	2633	3172	405	13.0
138 kV	8611	10684	1617	15.3
115 kV	12826	15031	1485	10.2
100 kV	894	1595	118	7.5
69 kV	8022	8022	289	3.7

A paper discussing this is A. Birchfield, T. J. Overbye, "*Graph Crossings in Electric Transmission Grids,*" 2021 North American Power Symposium, College Station, TX, November 2021. (it is on my website at https://overbye.engr.tamu.edu/publications/)

Detailed Transmission and Distribution Testing

- Full transmission and distribution system studies are being done using a co-simulation framework
  - PowerWorld Simulator is used to solve the transmission system and OpenDSS is used to solve each of the distribution circuits
  - The simulations are coupled together using the national lab developed HELICS package; one year of simulations took about 3 hours



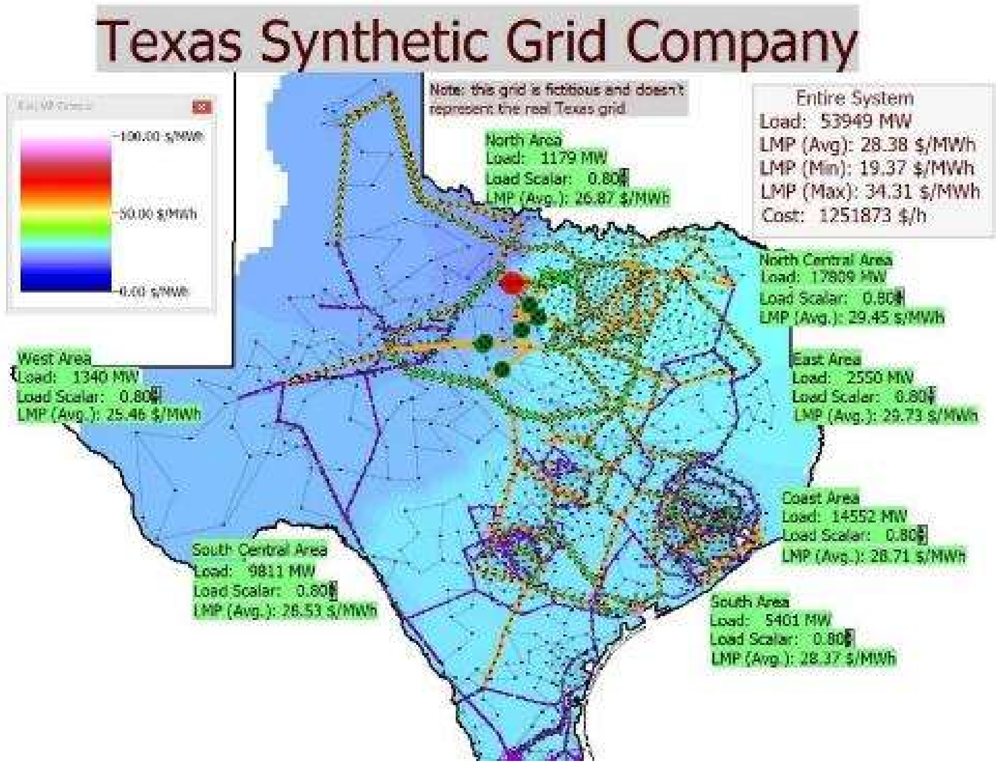
For Travis County (population 1.2 million) 307,236 meters are served by 488 distribution circuits

Different Levels of Modeling

- Just because we have detailed grids, doesn't mean we always simulate the coupled transmission and distribution models. Other options are
  - Transmission only
  - Distribution only
  - Full transmission with distribution topology; this can be quite useful for doing multi-infrastructure simulation in which we just need to know what parts of the distribution system are out-of-service

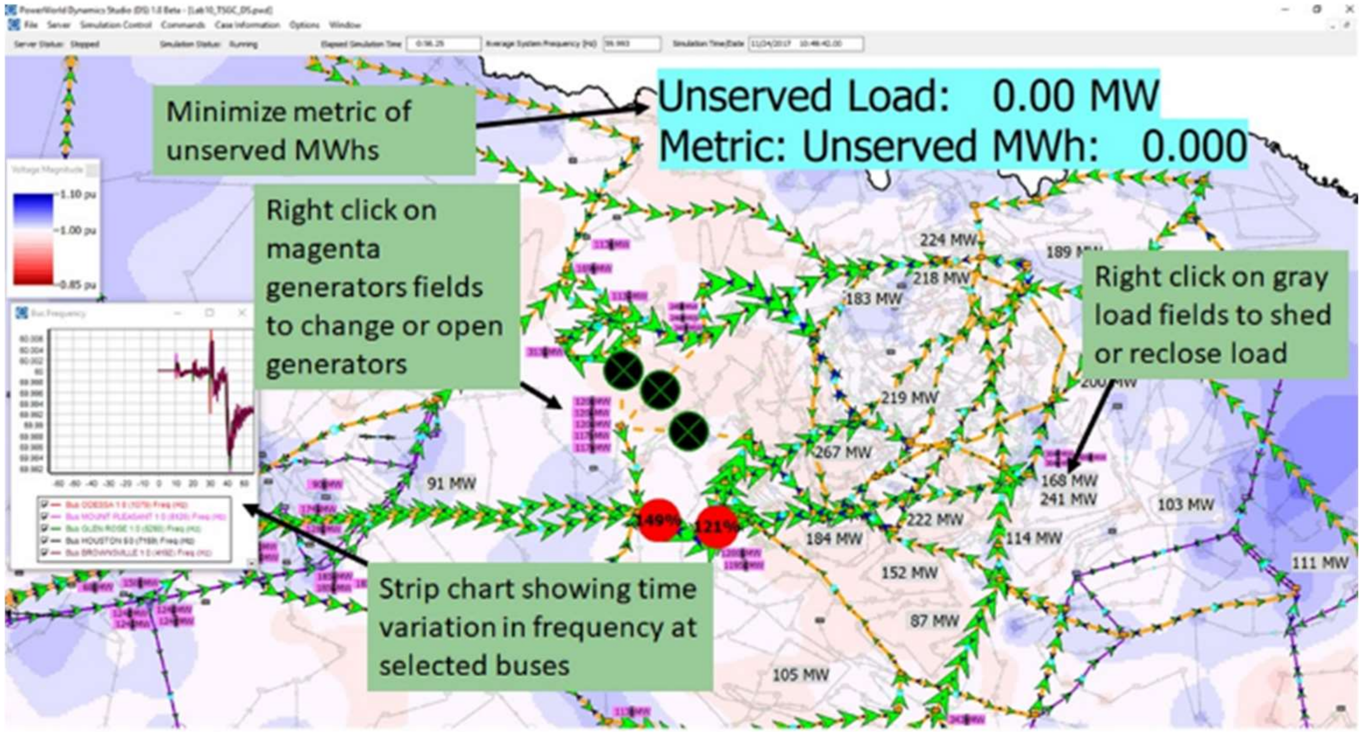
Synthetic Grid Applications: Innovative Electric Power Education

- 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 in real-time!



The lab was introduced in Fall 2017; in Fall 2018 it was expanded to be a multi-user simulation. However it did not involve integrated analysis.

Giving Students (and Others) Experience In Grid Operations

- Most electric power students have little or no experience in actually operating an electric grid (real or simulated)
- One of our goals is to provide such an experience both in an individually and as part of a team
- Developing this involves a combination of the electric grid, the scenario, and the associated simulation environment, and the path to give the users experience with the environment
- This also generates data

The Simulation Environment

Power System Voltage Stability

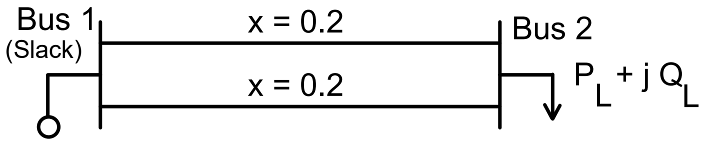
- **Voltage Stability**: The ability to maintain system voltage so that both power and voltage are controllable. System voltage responds as expected (i.e., an increase in load causes proportional decrease in voltage).
- **Voltage Instability**: Inability to maintain system voltage. System voltage and/or power become uncontrollable. System voltage does not respond as expected.
- **Voltage Collapse**: Process by which voltage instability leads to unacceptably low voltages in a significant portion of the system; typically results in loss of system load.

Voltage Stability

- Two good references are
  - P. Kundur, et. al., "Definitions and Classification of Power System Stability," *IEEE Trans. on Power Systems*, pp. 1387-1401, August 2004.
  - T. Van Cutsem, "Voltage Instability: Phenomena, Countermeasures, and Analysis Methods," *Proc. IEEE*, February 2000, pp. 208-227.
- Classified by either size of disturbance or duration
  - Small or large disturbance: small disturbance is just perturbations about an equilibrium point (power flow)
  - Short-term (several seconds) or long-term (many seconds to minutes) (covered in ECEN 667)

Small Disturbance Voltage Stability

- Small disturbance voltage stability can be assessed using a power flow (maximum loadability)
- Depending on the assumed load model, the power flow can have multiple (or no) solutions
- PV curve is created by plotting power versus voltage



Assume V_{slack}=1.0

$$P_L - BV\sin\theta = 0$$

$$Q_L + BV\cos\theta - BV^2 = 0$$

Where B is the line susceptance =-10,
V∠θ is the load voltage

Small Disturbance Voltage Stability

- Question: how do the power flow solutions vary as the load is changed?
- A Solution: Calculate a series of power flow solutions for various load levels and see how they change
- Power flow Jacobian

$$\mathbf{J}(\theta, V) = \begin{bmatrix} -BV\cos\theta & -B\sin\theta \\ -BV\sin\theta & B\cos\theta - 2BV \end{bmatrix}$$

$$\det \mathbf{J}(\theta, V) = VB^2\left(2V\cos\theta - \cos^2\theta - \sin^2\theta\right)$$

Singular when $\left(2V\cos\theta - 1\right) = 0$

Maximum Loadability When Power Flow Jacobian is Singular

- An important paper considering this was by Sauer and Pai from *IEEE Trans. Power Systems* in Nov 1990, “Power system steady-state stability and the load-flow Jacobian”
- Other earlier papers were looking at the characteristics of multiple power flow solutions
- The power flow Jacobian depends on the assumed load model (we’ll see the impact in a few slides)

Relationship Between Stability and Power Flow Jacobian

- The Sauer/Pai paper related system stability to the power flow Jacobian by noting that the system dynamics could be written as a set of differential algebraic equations

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{y}, \mathbf{p})$$

$$\mathbf{0} = \mathbf{g}(\mathbf{x}, \mathbf{y}, \mathbf{p})$$

Linearing about and equilibrium gives

$$\begin{bmatrix} \Delta\dot{\mathbf{x}} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial \mathbf{f}}{\partial \mathbf{x}} & \dfrac{\partial \mathbf{f}}{\partial \mathbf{y}} \\ \dfrac{\partial \mathbf{g}}{\partial \mathbf{x}} & \dfrac{\partial \mathbf{g}}{\partial \mathbf{y}} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{x} \\ \Delta\mathbf{y} \end{bmatrix}$$

Relationship Between Stability and Power Flow Jacobian

- Then assuming $\frac{\partial \mathbf{g}}{\partial \mathbf{y}}$ is nonsingular then

$$\Delta\dot{\mathbf{x}} = \left[\frac{\partial \mathbf{f}}{\partial \mathbf{x}} - \frac{\partial \mathbf{f}}{\partial \mathbf{y}} \left[\frac{\partial \mathbf{g}}{\partial \mathbf{y}} \right]^{-1} \frac{\partial \mathbf{g}}{\partial \mathbf{x}} \right] \Delta\mathbf{x}$$

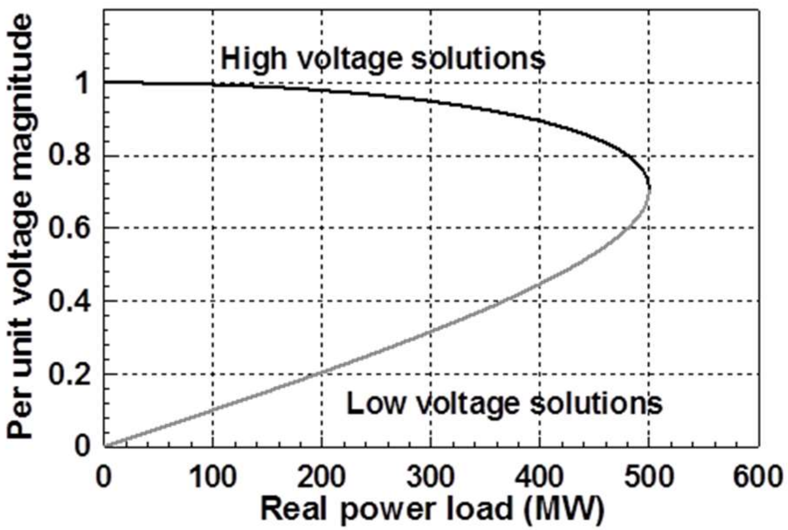
- What Sauer and Pai show is if $\partial\mathbf{g}/\partial\,\mathbf{y}$ is singular then the system is unstable; if $\partial\mathbf{g}/\partial\,\mathbf{y}$ is nonsingular then the system may or may not be stable
- Hence it provides an upper bound on stability

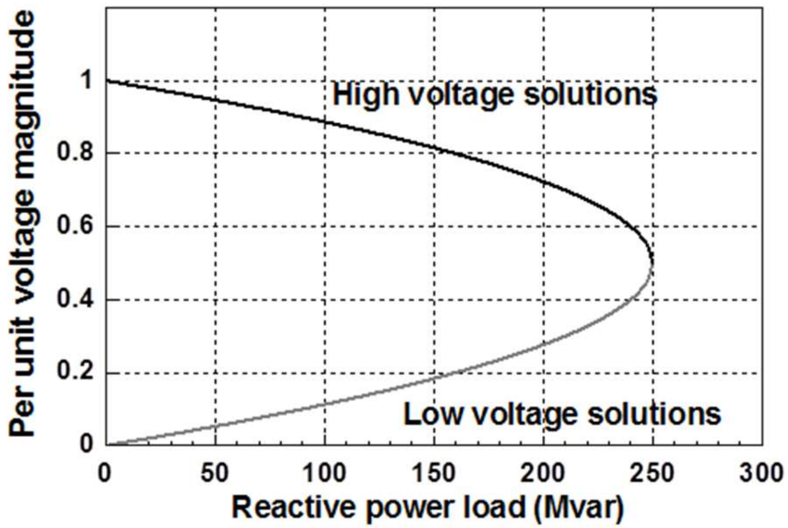
Bifurcations

- In general, bifurcation is the division of something into two branches or parts
- For a dynamic system, a bifurcation occurs when small changes in a parameter cause a new quality of motion of the dynamic system
- Two types of bifurcation are considered for voltage stability
  - Saddle node bifurcation is the disappearance of an equilibrium point for parameter variation; for voltage stability it is two power flow solutions coalescing with parameter variation
  - Hopf bifurcation is cause by two eigenvalues crossing into the right-half plane

PV and QV Curves

- PV curves can be traced by plotting the voltage as the real power is increased; QV curves as reactive power is increased
  - At least for the upper portion of the curve
- Two bus example PV and QV curves





Small Disturbance Voltage Collapse

- At constant frequency (e.g., 60 Hz) the complex power transferred down a transmission line is $S=VI^*$
  - V is phasor voltage, I is phasor current
  - This is the reason for using a high voltage grid
- Line real power losses are given by RI^2 and reactive power losses by XI^2
  - R is the line's resistance, and X its reactance; for a high voltage line X >> R
- Increased reactive power tends to drive down the voltage, which increases the current, which further increases the reactive power losses