ECEN 615
Methods of Electric Power Systems Analysis

Lecture 17:EMSs, SVD, Pseudo Inverse, Equivalents

Prof. Tom Overbye

Dept. of Electrical and Computer Engineering

Texas A&M University

overbye@tamu.edu

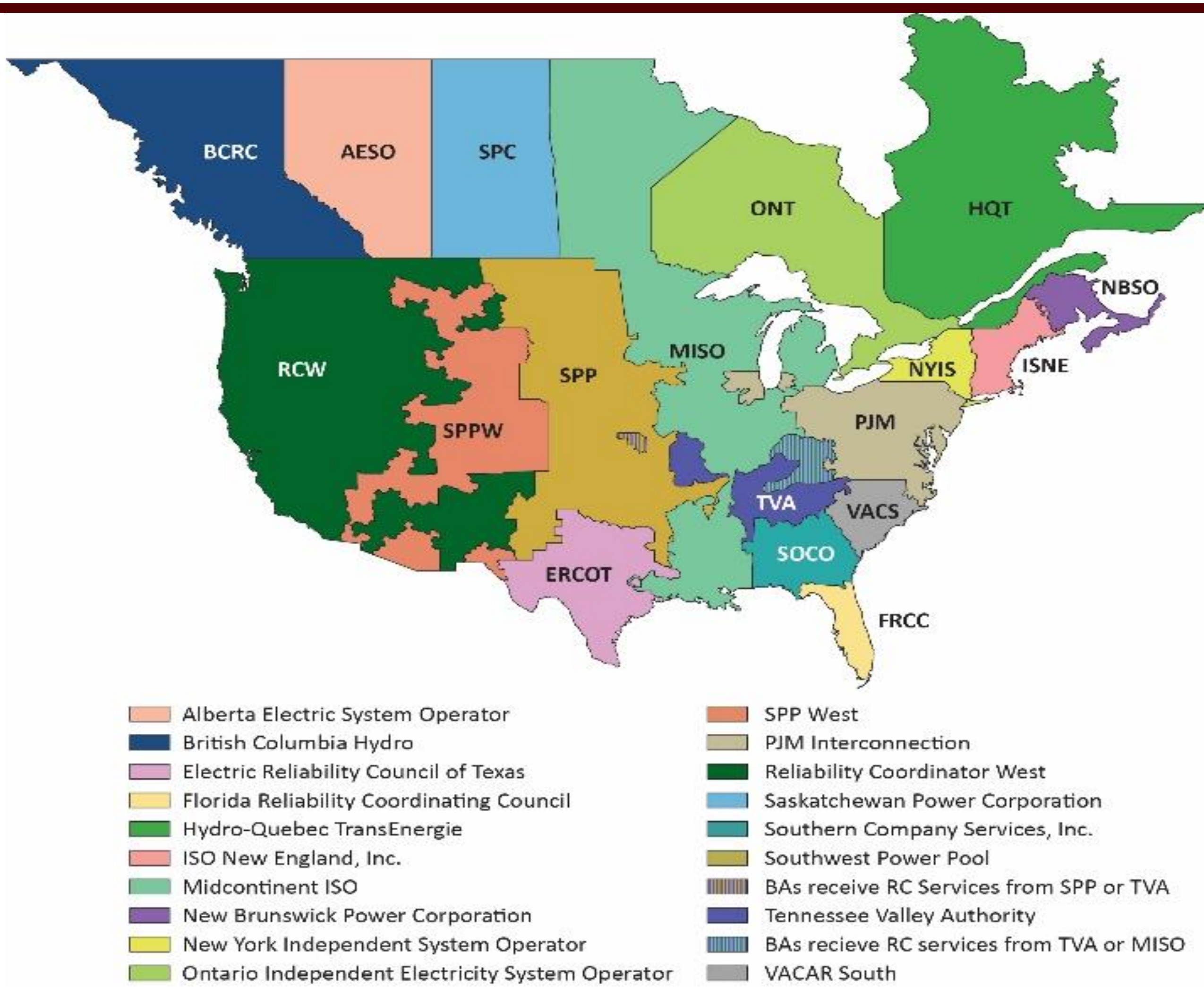
Announcements

- Skim Chapters 3, 4 and 5
- Starting reading Chapter 8
- Homework 5 is due on Thursday Oct 29

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 as evolved as the industry has evolved, with functionality customized for the application (e.g., a reliability coordinator or a vertically integrated utility)

NERC Reliability Coordinators

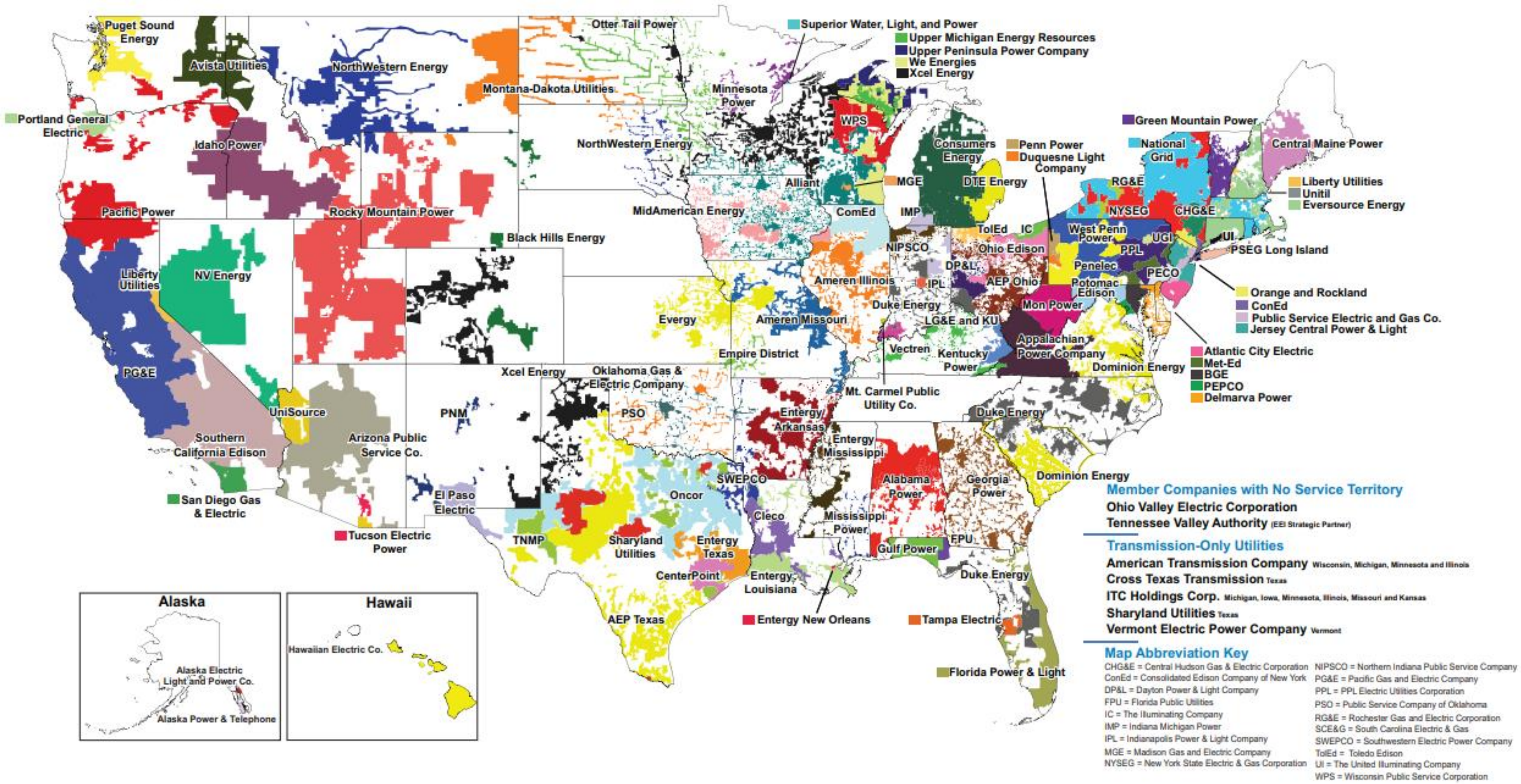


Source: www.nerc.com/pa/rrm/TLR/Pages/Reliability-Coordinators.aspx

EEI Member Companies

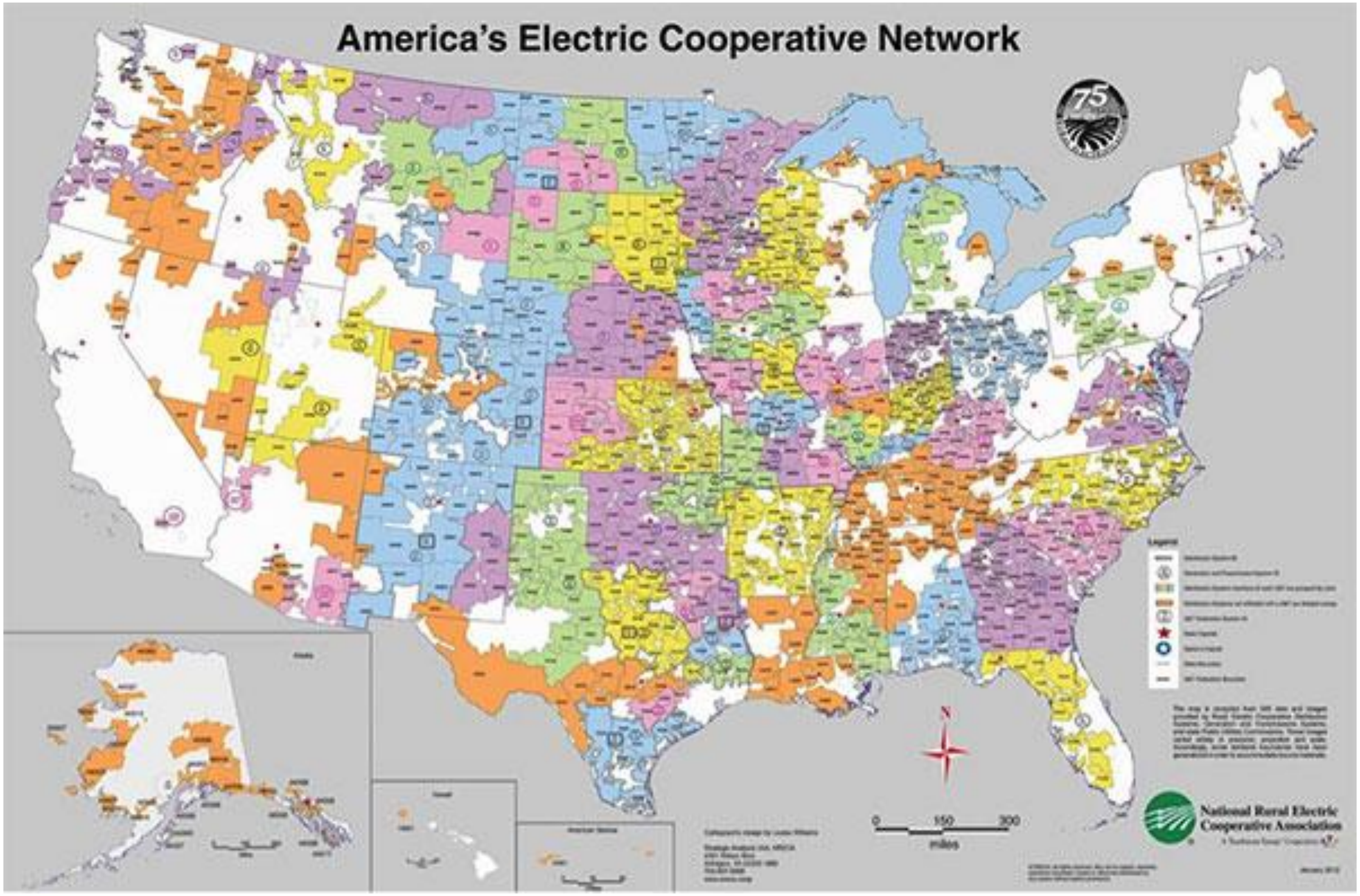
Edison Electric INSTITUTE

EEI U.S. Member Company Service Territories



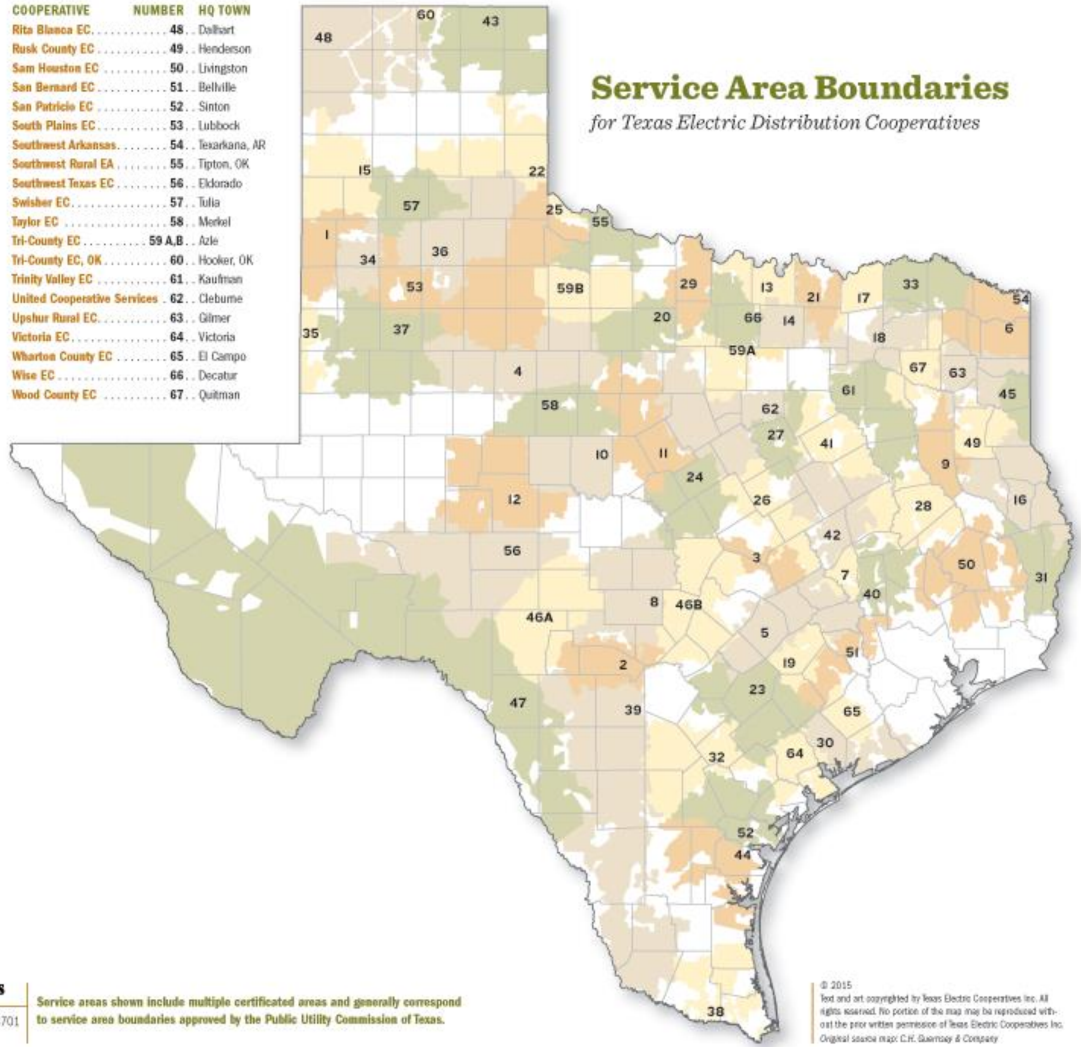
Produced by Edison Electric Institute. Data Source: ABB, Velocity Suite. June 2020

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



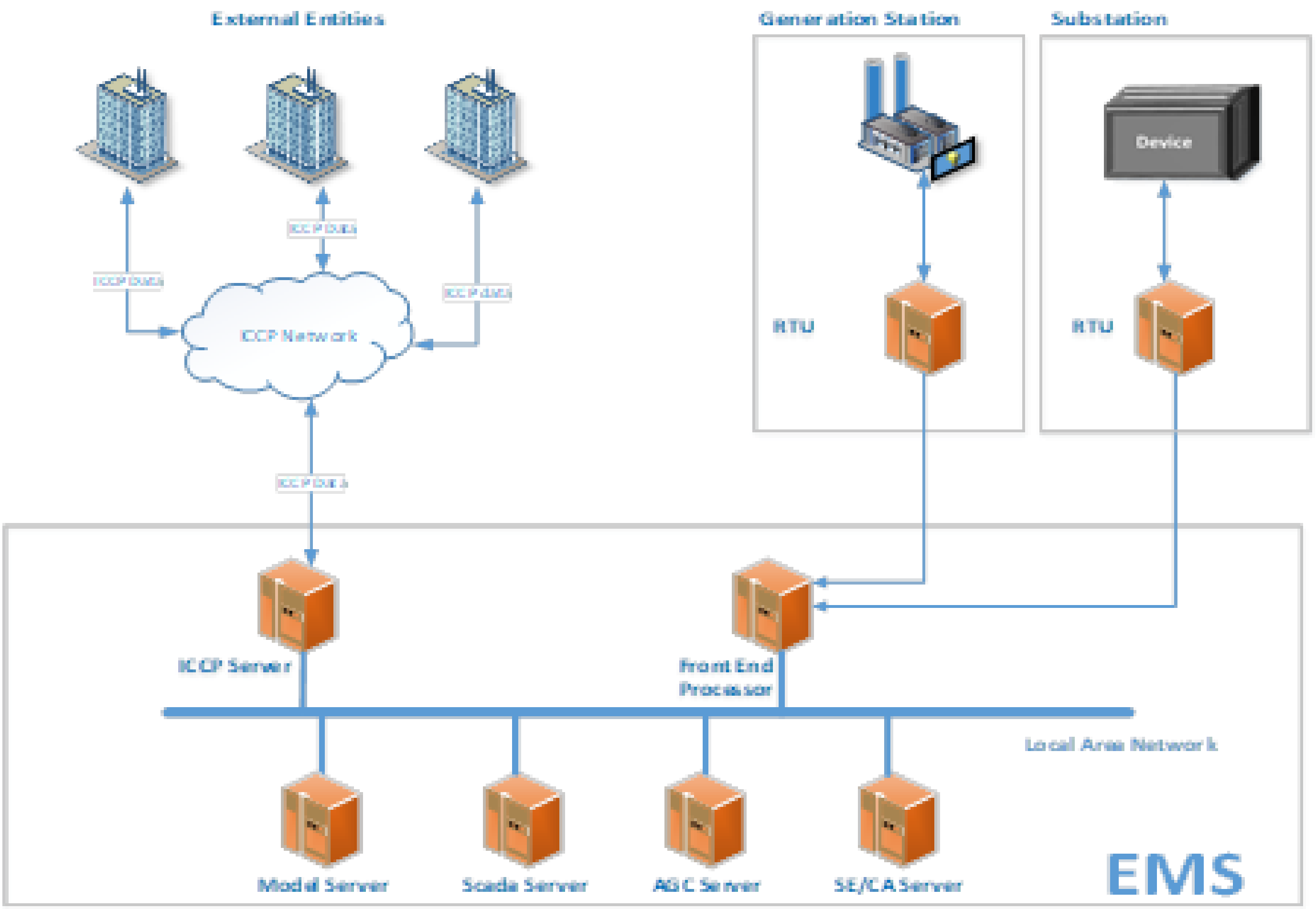
Texas Electric Cooperatives
1122 Colorado St., 24th Floor · Austin, TX 78701
(512) 454-0311 · www.texas-ec.org

Service areas shown include multiple certificated areas and generally correspond to service area boundaries approved by the Public Utility Commission of Texas.

ERCOT Control Center with EMS

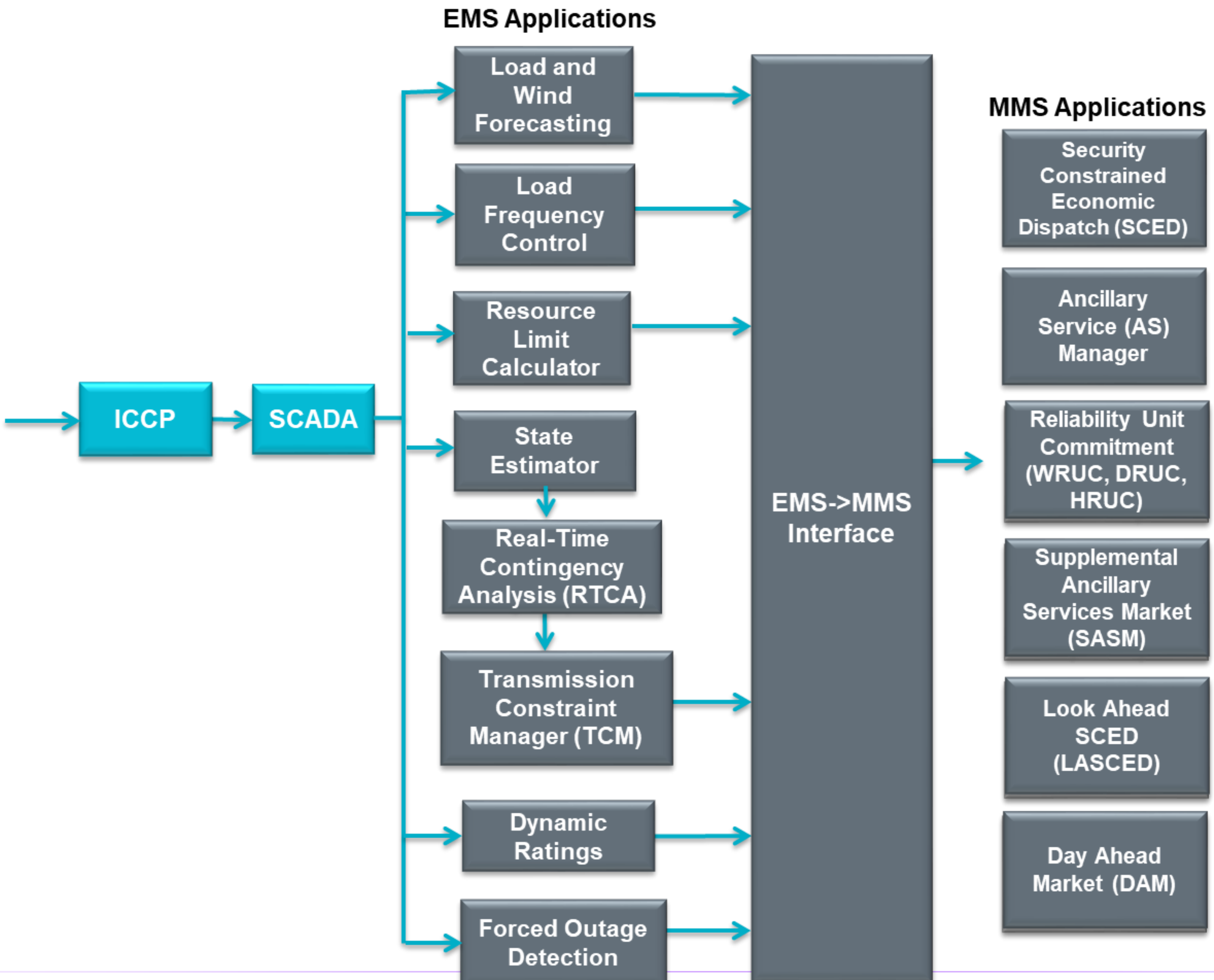
Source: www.texastribune.org/2016/05/17/texas-market-forces-driving-shift-coal-study-says/

ERCOT EMS



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

ERCOT EMS


EMS Applications
Load and Wind Forecasting
Load Frequency Control
Resource Limit Calculator
State Estimator
Real-Time Contingency Analysis (RTCA)
Transmission Constraint Manager (TCM)
Dynamic Ratings
Forced Outage Detection
ICCP
SCADA
EMS->MMS Interface
MMS Applications
Security Constrained Economic Dispatch (SCED)
Ancillary Service (AS) Manager
Reliability Unit Commitment (WRUC, DRUC, HRUC)
Supplemental Ancillary Services Market (SASM)
Look Ahead SCED (LASCED)
Day Ahead Market (DAM)

Aside: Singular Value Decomposition

- Traditionally power system analysis has mostly been focused on the sparse matrices associated with the electric grid; there was not much signal analysis
- This is rapidly changing as the power industry get more signals and need to extract information from them, with PMUs one example
- This data is often presented in the form of a matrix, for example with the rows being sample points
- A key technique for extracting information from matrices is known as the singular value decomposition

Aside: Matrix Singular Value Decomposition (SVD)

- The SVD is a factorization of a matrix that generalizes the eigendecomposition to any m by n matrix to produce

$$\mathbf{Y} = \mathbf{U\Sigma V}^{\mathbf{T}}$$

The original concept is more than 100 years old, but has founds lots of recent applications

where S is a diagonal matrix of the singular values, and U and V are orthogonal matrices

- The singular values are non-negative real numbers that can be used to indicate the major components of a matrix (the gist is they provide a way to decrease the rank of a matrix
- A key application is image compression

Aside: SVD Image Compression Example

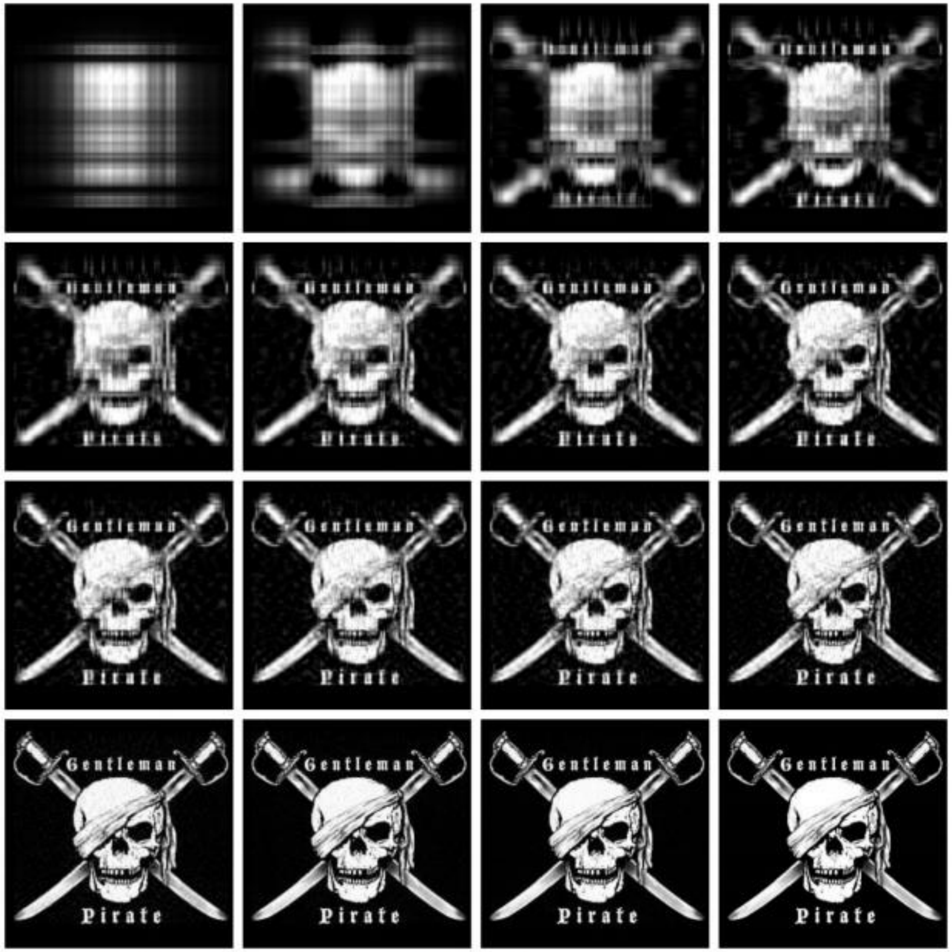


Figure 3.1: Image size 250x236 – modes used {{1,2,4,6},{8,10,12,14},{16,18,20,25},{50,75,100,original image}}

Images can be represented with matrices. When an SVD is applied and only the largest singular values are retained the image is compressed.

Image Source: www.math.utah.edu/~goller/F15_M2270/BradyMathews_SVDImage.pdf

Aside: SVD and Principle Component Analysis (PCA)

- The previous image compression example demonstrates PCA, which reduces dimensionality
  - Extracting the principle components
- The principle components are associated with the largest singular values
  - This helps to extract the key features of the data and removes redundancy
- PCA can be used to do facial recognition
- PCA is starting to be more widely used in power system analysis, particularly when doing signal analysis

Aside: An SVD Application, the Pseudoinverse of a Matrix

- The pseudoinverse of a matrix generalizes concept of a matrix inverse to an m by n matrix, m >= n
  - Specifically this is a Moore-Penrose Matrix Inverse
- Notation for the pseudoinverse of **A** is $\mathbf{A}^{+}$
- Satisfies $\mathbf{A}\mathbf{A}^{+}\mathbf{A} = \mathbf{A}$
- If **A** is a square matrix, then $\mathbf{A}^{+} = \mathbf{A}^{-1}$
- Quite useful for solving the least squares problem since the least squares solution of $\mathbf{A}\mathbf{x} = \mathbf{b}$ is $\mathbf{x} = \mathbf{A}^{+}\mathbf{b}$
- Can be calculated using an SVD

$$\mathbf{A} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^{T}$$

$$\mathbf{A}^{+} = \mathbf{V}\boldsymbol{\Sigma}^{+}\mathbf{U}^{T}$$

Aside: Pseudoinverse Least Squares Matrix Example

- Assume we wish to fit a line ($mx + b = y$) to three data points: (1,1), (2,4), (6,4)
- Two unknowns, m and b; hence $\mathbf{x} = [m \;\; b]^T$
- Setup in form of $\mathbf{Ax} = \mathbf{b}$

$$\begin{bmatrix} 1 & 1 \\ 2 & 1 \\ 6 & 1 \end{bmatrix} \begin{bmatrix} m \\ b \end{bmatrix} = \begin{bmatrix} 1 \\ 4 \\ 4 \end{bmatrix} \quad \text{so} \quad \mathbf{A} = \begin{bmatrix} 1 & 1 \\ 2 & 1 \\ 6 & 1 \end{bmatrix}$$

Aside: Pseudoinverse Least Squares Matrix Example

- Doing an economy SVD

$$\mathbf{A} = \mathbf{U\Sigma V}^T = \begin{bmatrix} -0.182 & -0.765 \\ -0.331 & -0.543 \\ -0.926 & 0.345 \end{bmatrix} \begin{bmatrix} 6.559 & 0 \\ 0 & 0.988 \end{bmatrix} \begin{bmatrix} -0.976 & -0.219 \\ 0.219 & -0.976 \end{bmatrix}$$

- Computing the pseudoinverse

$$\mathbf{A}^+ = \mathbf{V}\,\mathbf{\Sigma}^+\mathbf{U}^T = \begin{bmatrix} -0.976 & 0.219 \\ -0.219 & -0.976 \end{bmatrix} \begin{bmatrix} 0.152 & 0 \\ 0 & 1.012 \end{bmatrix} \begin{bmatrix} -0.182 & -0.331 & -0.926 \\ -0.765 & -0.543 & 0.345 \end{bmatrix}$$

$$\mathbf{A}^+ = \mathbf{V}\,\mathbf{\Sigma}^+\mathbf{U}^T = \begin{bmatrix} -0.143 & -0.071 & 0.214 \\ 0.762 & 0.548 & -0.310 \end{bmatrix}$$

In an economy SVD the Σ matrix has dimensions of m by m if m < n or n by n if n < m

Least Squares Matrix Pseudoinverse Example, cont.

- Computing $\mathbf{x} = [\mathrm{m\ b}]^T$ gives

$$\mathbf{A}^{+}\mathbf{b} = \begin{bmatrix} -0.143 & -0.071 & 0.214 \\ 0.762 & 0.548 & -0.310 \end{bmatrix} \begin{bmatrix} 1 \\ 4 \\ 4 \end{bmatrix} = \begin{bmatrix} 0.429 \\ 1.71 \end{bmatrix}$$

- With the pseudoinverse approach we immediately see the sensitivity of the elements of **x** to the elements of **b**
  - New values of m and b can be readily calculated if **y** changes
- Computationally the SVD is order mn^2+n^3 (with $n < m$)

Power System Equivalents

- No electric grid model is ever going to completely represent a real electric grid
  - "All models are wrong but some models are useful"
- A key modeling consideration is how much of the electric grid to represent
  - For large-scale systems the distribution system is usually equivalenced at some point; this has few system level ramifications if it is radial; if it is networked then there are potential issues
  - At the transmission level either the full interconnect is represented or it is equivalenced
  - In an SE model in large grids (like the Eastern Interconnect) it is always an electrical equivalent

Kron Reduction, Ward Equivalents

- For decades power system network models have been equivalenced using the approach originally presented by J.B. Ward in 1949 AIEE paper "Equivalent Circuits for Power-Flow Studies"
  - Paper's single reference is to 1939 book by Gabriel Kron, so this is also known as Kron's reduction or a Ward equivalent
- System buses are partitioned into a study system (s) to be retained and an external system (e) to be eliminated; buses in study system that connect to the external are known as boundary buses

Ward Equivalents

- The Ward approach is based on the below relationship

$$\begin{bmatrix} I_s \\ I_e \end{bmatrix} = \begin{bmatrix} Y_{ss} & Y_{se} \\ Y_{es} & Y_{ee} \end{bmatrix} \begin{bmatrix} V_s \\ V_e \end{bmatrix}$$

$$\left(I_s - Y_{se} Y_{ee}^{-1} I_e \right) = \left(Y_{ss} - Y_{se} Y_{ee}^{-1} Y_{es} \right) V_s$$

- No impact on study, non-boundary buses
- Equivalent is created by doing a partial factorization of the $\mathbf{Y}_{\text{bus}}$
  - Computationally efficient

Other Types of Equivalents

- There are many different methods available for creating power system equivalents
  - A classic paper is by S. Deckmann, et. al., "Studies on Power System Load Flow Equivalencing," *IEEE Transactions Power App. And Syst.*, Nov/Dec 1980
  - Companion paper covers numerical testing of equivalents
- The major equivalencing types are
  - Ward-Type Equivalence: this is what we'll be covering, with the major differences associated with how the generator buses and equivalent loads are represented
  - REI Equivalents: All boundary buses connect to one "REI" bus
  - Linearized Methods: Linearize about an operating point
  - Others: PTDF-based, backbone type

Equivalent System Properties

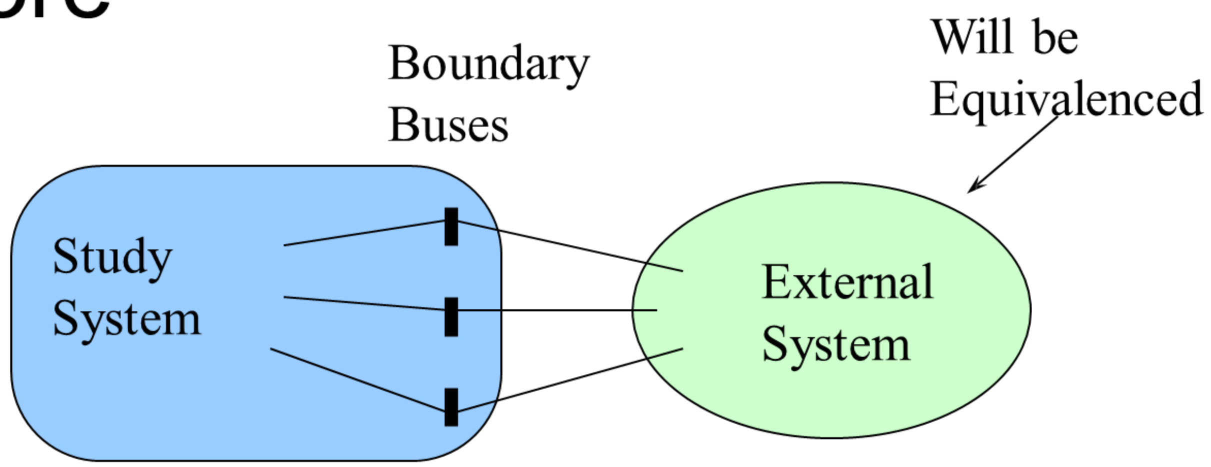
- An equivalent is usually created from a larger model
  - In the Eastern Interconnect there are full grid models that are used for wide-area planning, these are equivalenced for real-time usage or more specialized studies
- The equivalent is usually smaller and less detailed
  - Solves quicker
  - Requires less storage
  - Requires less up-to-date data
- Equivalences contain fictitious elements
  - This can make modeling/updating more difficult
- The equivalent only approximates the behavior of the original

Study vs External System

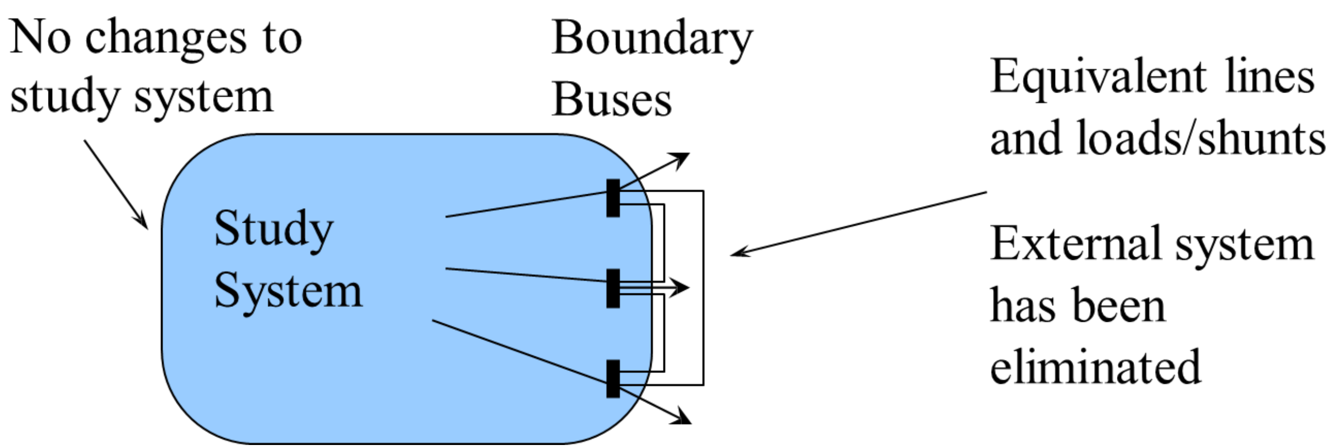
- The key decision in creating an equivalent is to divide the system into a study portion that is represented in detail, and an external portion that is represented by the equivalent
- The two systems are joined at boundary buses, which are part of the study subsystem
- How this is done is application specific; for example:
  - for real-time use it does not make sense to retain significant portions of the grid for which there is no real-time information
  - for contingency analysis the impact of the contingency is localized
  - for planning the new system additions have localized impacts

Ward Type Equivalencing

Before



After



Ward Type Equivalencing Considerations

- The Ward equivalent is calculated by doing a partial factorization of the $\mathbf{Y}_{\text{bus}}$
  - The equivalent buses are numbered before the study buses
  - As the equivalent buses are eliminated their first neighbors are joined together
  - At the end, many of the boundary buses are connected
  - This can GREATLY decrease the sparsity of the system
  - Buses with different voltages can be directly connected

$$\begin{bmatrix} I_s \\ I_e \end{bmatrix} = \begin{bmatrix} Y_{ss} & Y_{se} \\ Y_{es} & Y_{ee} \end{bmatrix} \begin{bmatrix} V_s \\ V_e \end{bmatrix}$$

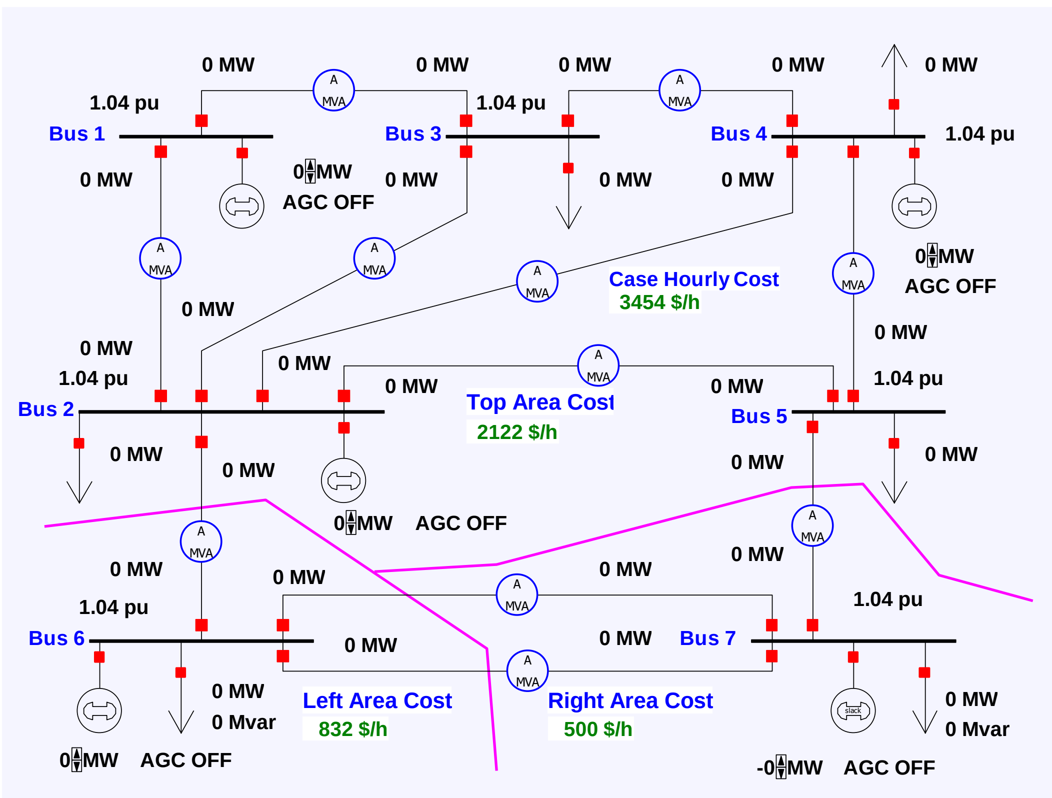
$$\left(I_s - Y_{se} Y_{ee}^{-1} I_e \right) = \left(Y_{ss} - Y_{se} Y_{ee}^{-1} Y_{es} \right) V_s$$

Ward Type Equivalencing Considerations

- At the end of the Ward process often many of the new equivalent lines have high impedances
  - Often there is an impedance threshold, and lines with impedances above this value are eliminated
- The equivalent lines may have unusual values, including negative resistances
- Load and generation is represented as equivalent current injections or shunts; sometimes these values are converted back to constant power
- Consideration needs to be given to loss of reactive support; the equivalent embeds the present load and generation values

B7Flat_Eqv Example

- In this example the B7Flat_Eqv case is reduced, eliminating buses 1, 3 and 4. The study system is then 2, 5, 6, 7, with buses 2 and 5 the boundary buses



For ease of comparison system is modeled unloaded

B7Flat_Eqv Example

- Original $\mathbf{Y}_{\text{bus}}$

$$\mathbf{Y}_{bus} = j\begin{bmatrix} -20.83 & 16.67 & 4.17 & 0 & 0 & 0 & 0 \\ 16.67 & -52.78 & 5.56 & 5.56 & 8.33 & 16.67 & 0 \\ 4.17 & 5.56 & -43.1 & 33.3 & 0 & 0 & 0 \\ 0 & 5.56 & 33.3 & -43.1 & 4.17 & 0 & 0 \\ 0 & 8.33 & 0 & 4.17 & -29.17 & 0 & 16.67 \\ 0 & 16.67 & 0 & 0 & 0 & -25 & 8.33 \\ 0 & 0 & 0 & 0 & 16.67 & 8.33 & -25 \end{bmatrix}$$

$$\mathbf{Y}_{ee} = j\begin{bmatrix} -20.833 & 4.167 & 0 \\ 4.167 & -43.056 & 33.333 \\ 0 & 33.333 & -43.056 \end{bmatrix}$$

B7Flat_Eqv Example

$$\mathbf{Y}_{es} = j\begin{bmatrix} 16.667 & 0 & 0 & 0 \\ 5.556 & 0 & 0 & 0 \\ 5.556 & 4.167 & 0 & 0 \end{bmatrix} \qquad \mathbf{Y}_{se} = j\begin{bmatrix} 16.667 & 5.556 & 5.556 \\ 0 & 0 & 4.167 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

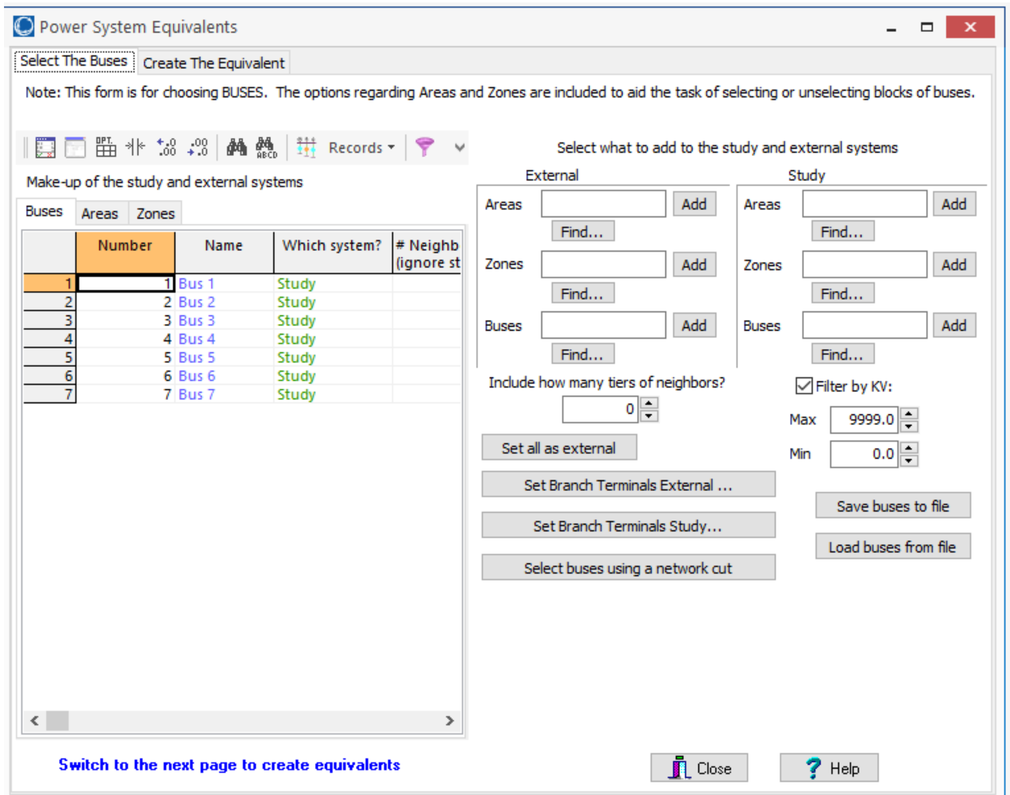
$$\mathbf{Y}_{ss} = j\begin{bmatrix} -52.778 & 8.333 & 16.667 & 0 \\ 8.333 & -29.167 & 0 & 16.667 \\ 16.667 & 0 & -25.0 & 8.333 \\ 0 & 16.667 & 8.333 & -25.0 \end{bmatrix}$$

Note $\mathbf{Y}_{es}=\mathbf{Y}_{se}'$ if no phase shifters

$$\left(\mathbf{Y}_{ss} - \mathbf{Y}_{se}\mathbf{Y}_{ee}^{-1}\mathbf{Y}_{es}\right) = j\begin{bmatrix} -28.128 & 11.463 & 16.667 & 0 \\ 11.463 & -28.130 & 0 & 16.667 \\ 16.667 & 0 & -25.0 & 8.333 \\ 0 & 16.667 & 8.333 & -25.0 \end{bmatrix}$$

Equivalencing in PowerWorld

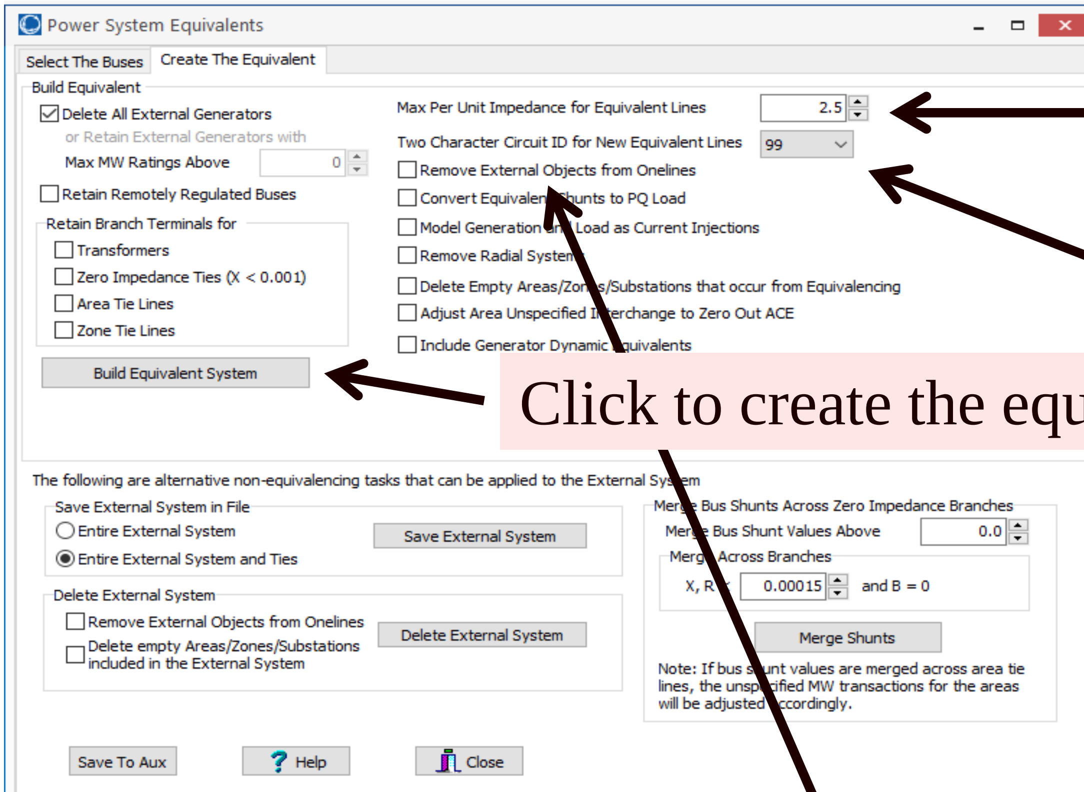
- Open a case and solve it; then select **Edit Mode**, **Tools**, **Equivalencing;** this displays the Power System Equivalents Form



Next step is then to divide the buses into the study system and the external system; buses can be loaded from a text file as well

Equivalencing in PowerWorld

- Then go to the **Create The Equivalent** page, select the desired options and select **Build Equivalent System**



Maximum impedance lines to retain

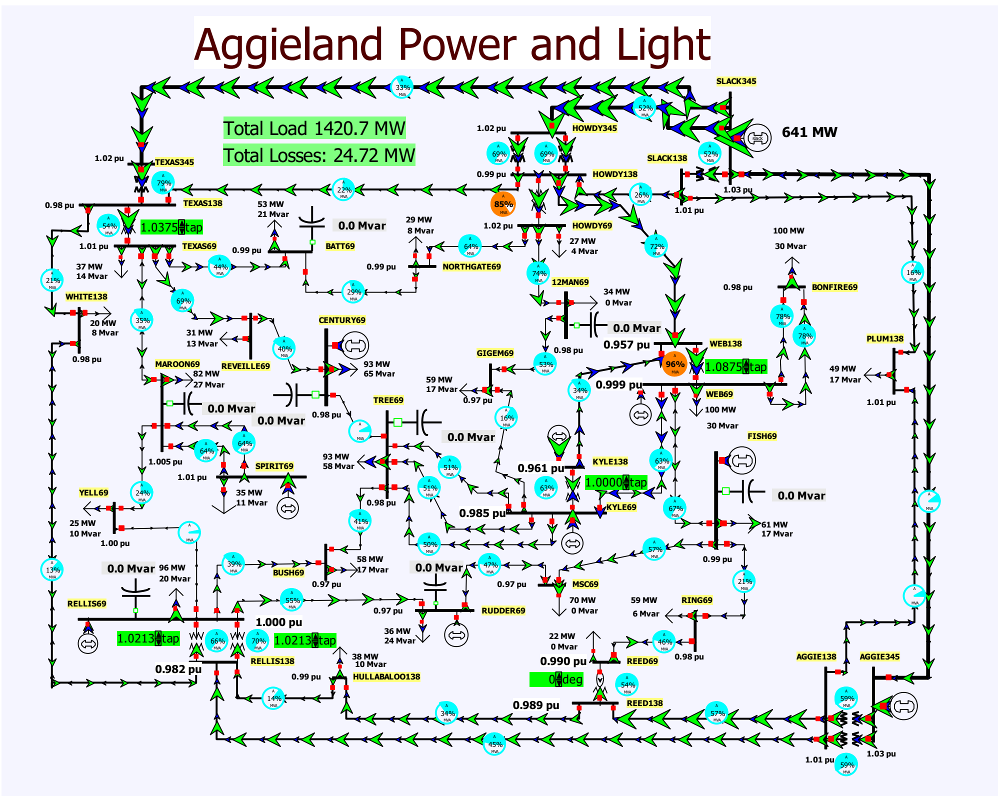
Click to create the equivalent

'99' or 'EQ' are common circuit values for equivalent lines

Removes equivalenced objects from the oneline

Small System Equivalent Example

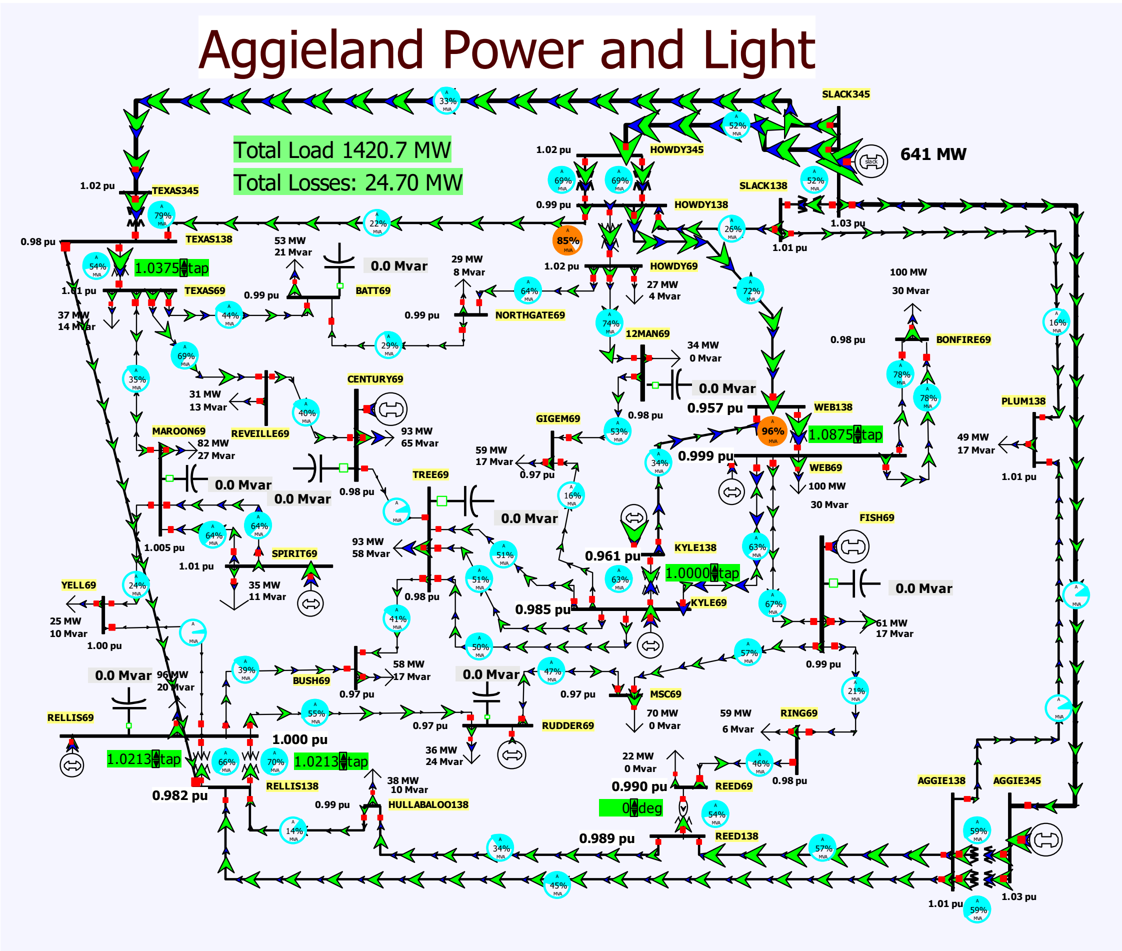
- Example shows the creation of an equivalent for Aggieland37 example



First example is simple, just removing WHITE138 (bus 3); note TEXAS138 is now directly joined to RELLIS138..

Case is Aggieland37_HW5

Small System Equivalent Example

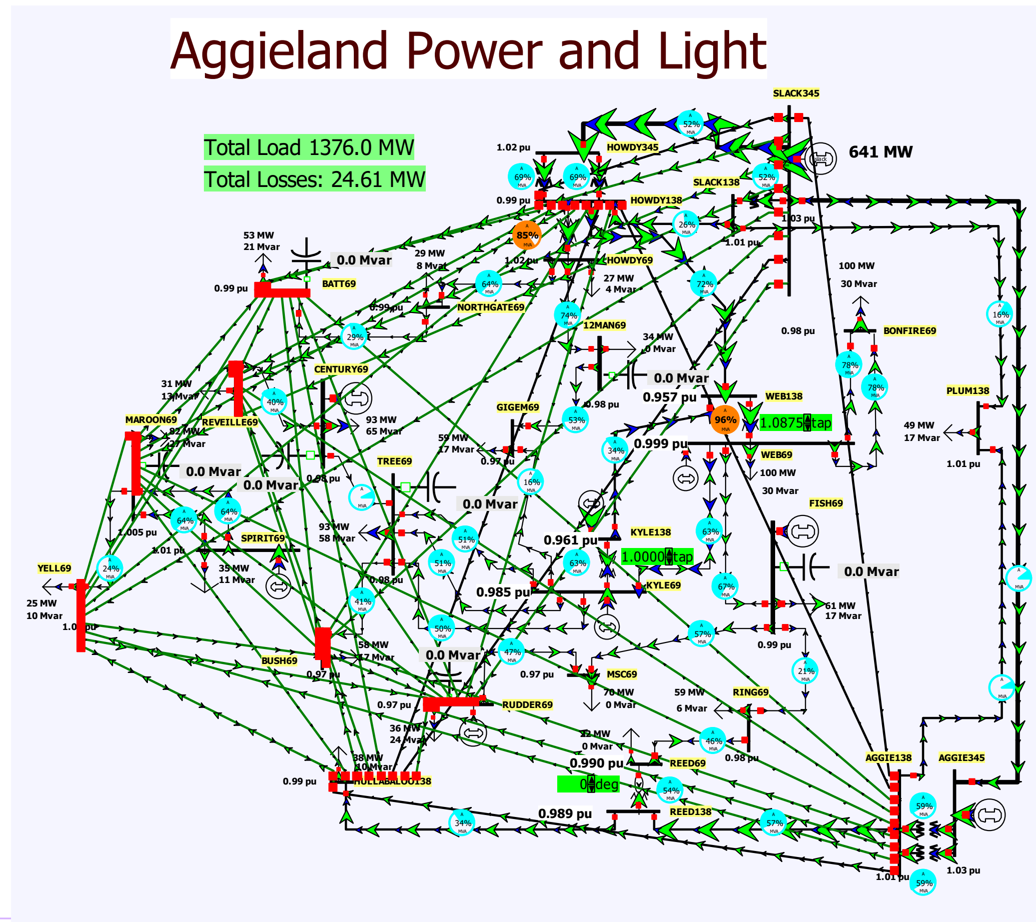


Only bus 3 was removed; the new equivalent line was auto-inserted.

Don’t save the equivalent with the same name as the original, unless you want to lose the original

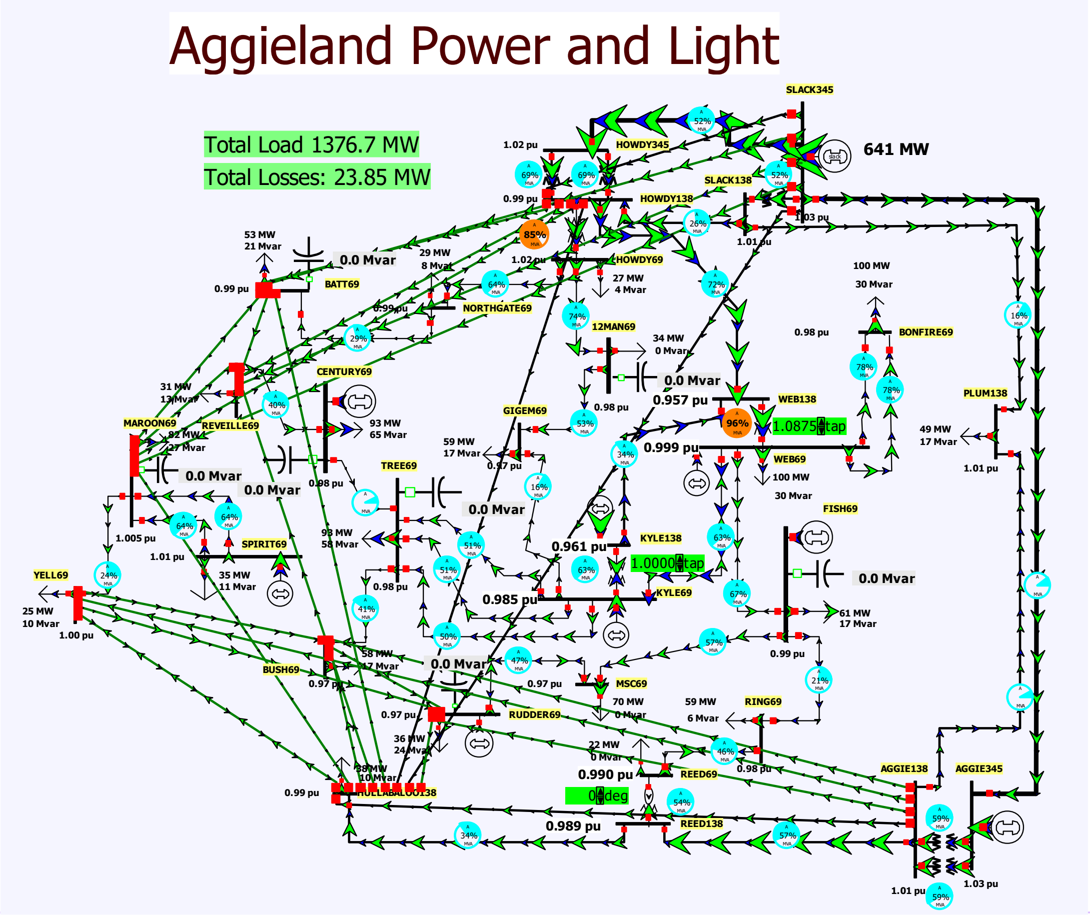
Small System Equivalent Example

- Now remove buses at WHITE138 and TEXAS and RELLIS (1, 3, 12, 40, 41, 44); set **Max Per Unit Impedance for Equivalent Lines** to 99 (per unit) to retain all lines. Again to an auto-insert to show the equivalent lines.



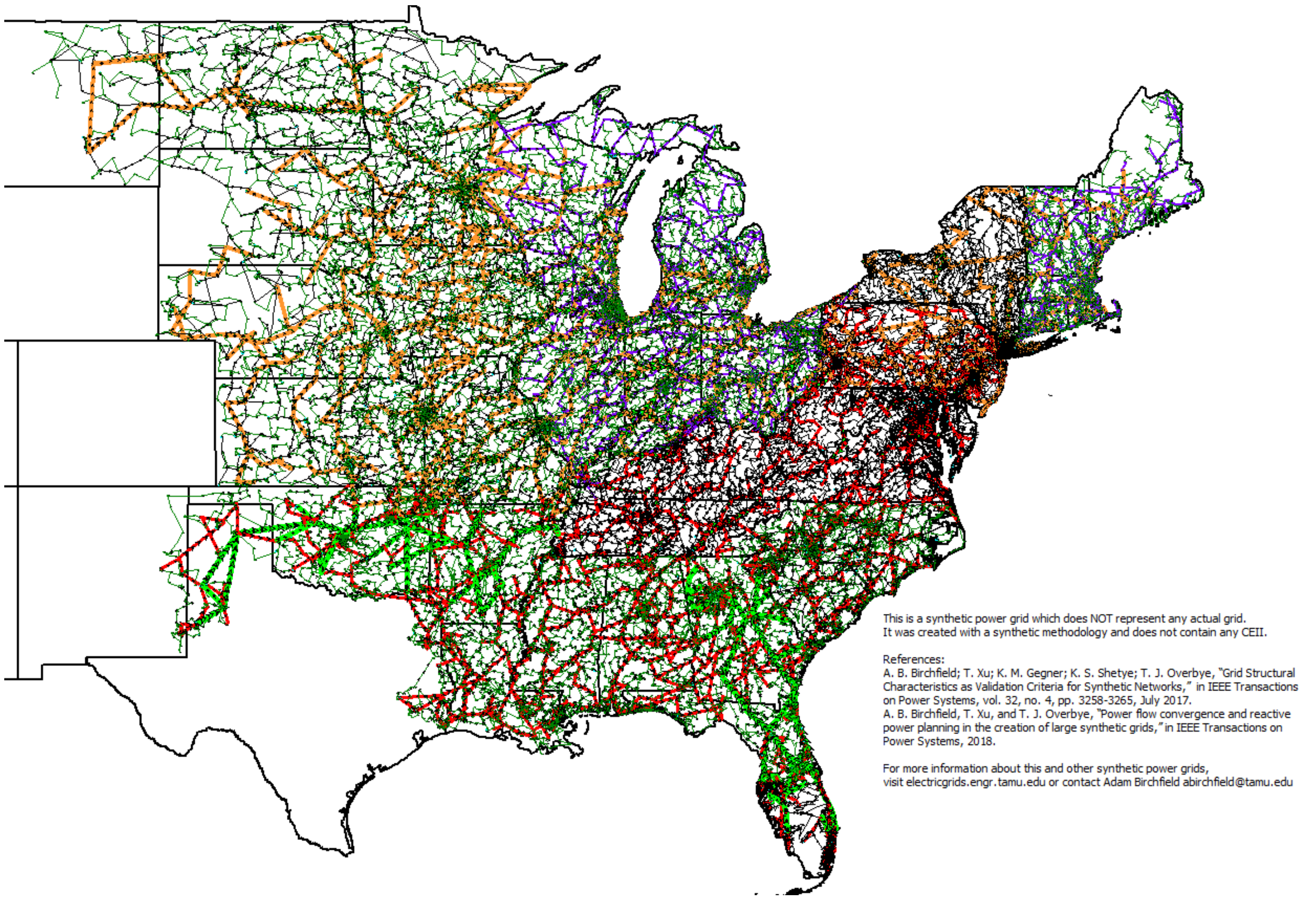
Small System Equivalent Example

- Now set the **Max Per Unit Impedance for Equivalent Lines to 2.5.**



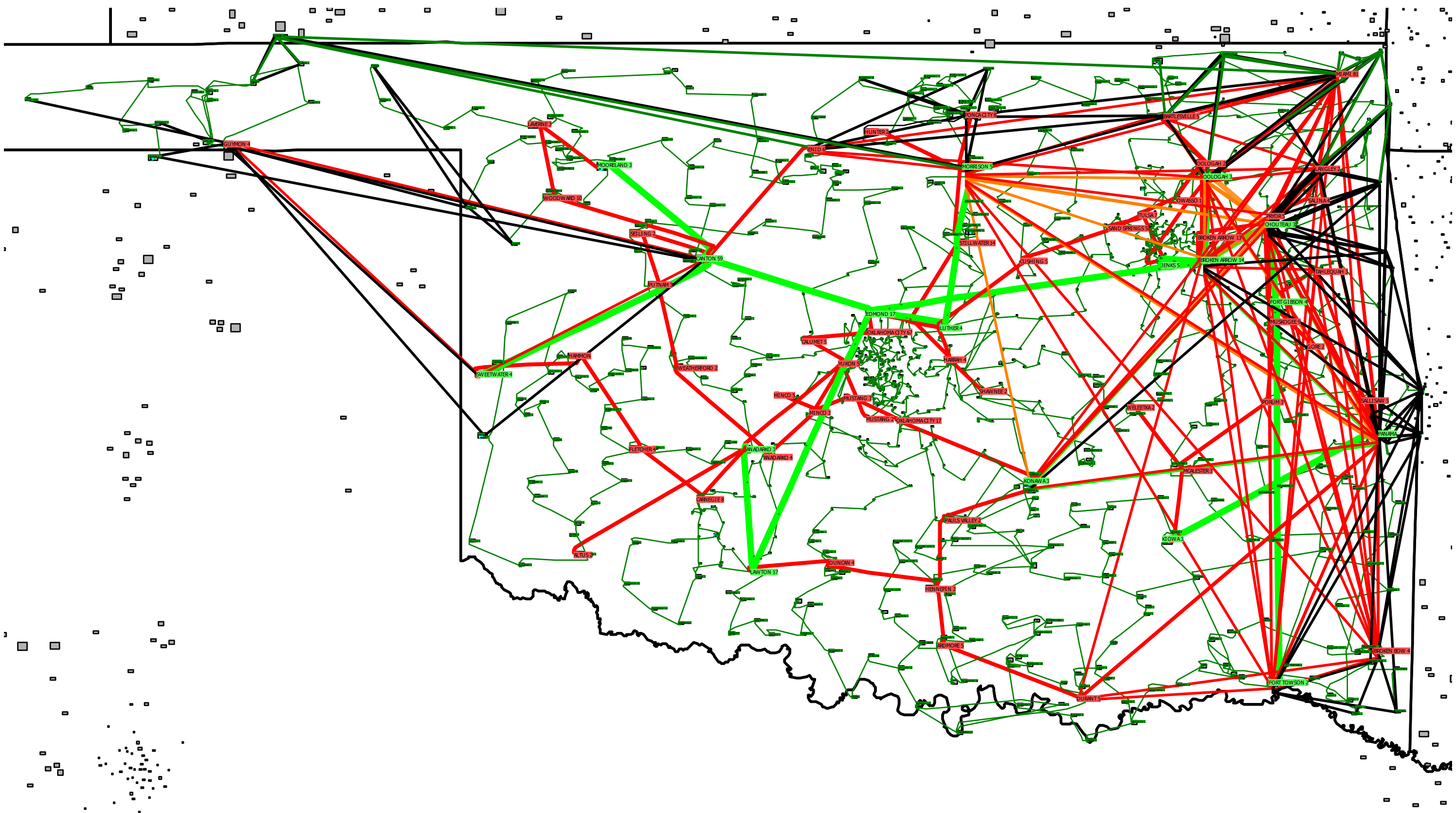
Large System Example: 70K Case

- Original System has 70,000 buses and 71,343 lines



Large System Example: 70K Case

- Just retain the Oklahoma Area; now 1591 buses and 1745 lines (deleting ones above 2.5 pu impedance)



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 ten 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 ten year old case with about 5000 buses and 5000 lines had 600 equivalent lines

Example: PJM EMS Equivalent

- PJM provides information about their EMS model in
  - www.pjm.com/-/media/documents/manuals/m03a.ashx

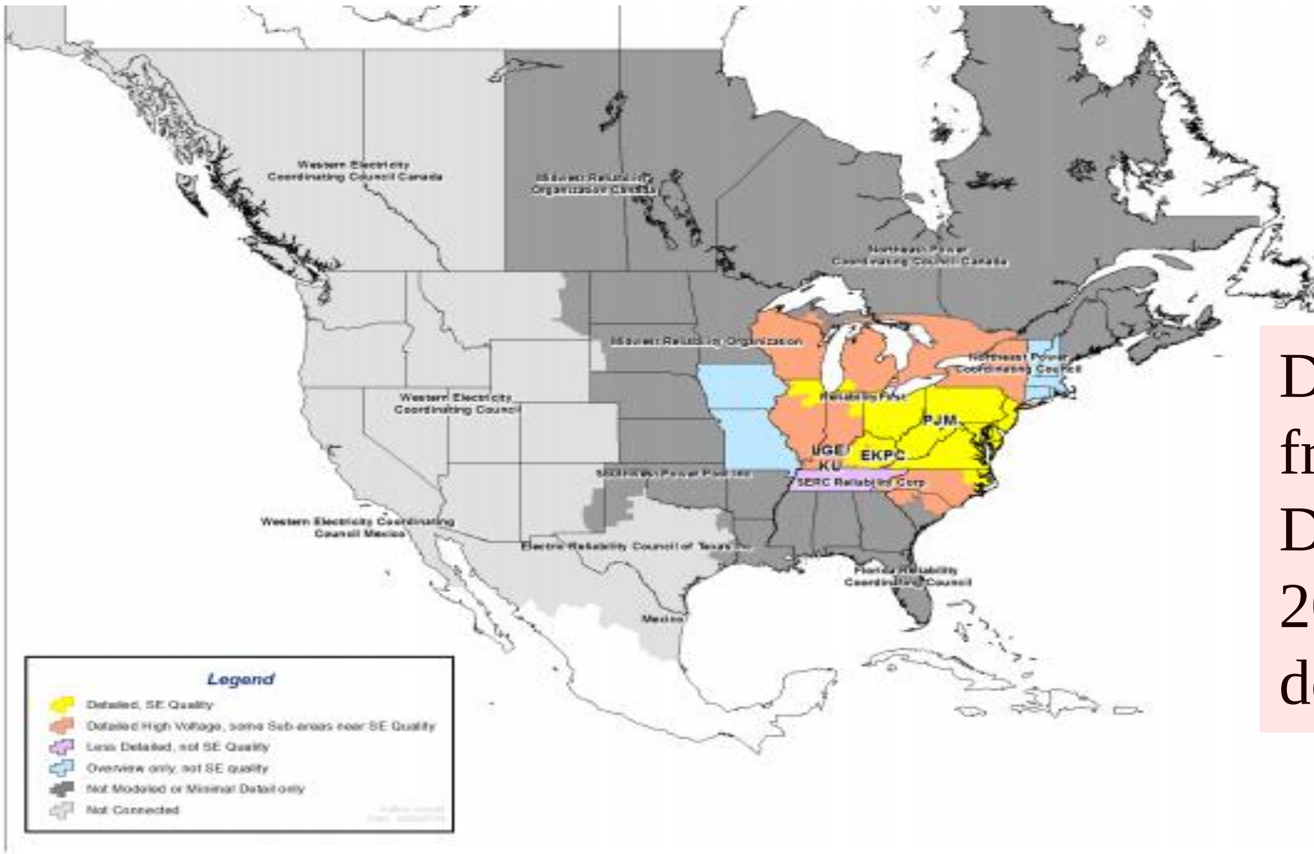


Exhibit 4: PJM EMS Model Details

Data here is from the December 2019 (Rev 18) document