ECEN 615 Methods of Electric Power Systems Analysis Lecture 17:EMSs, SVD, Pseudo Inverse,

Equivalents

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Announcements

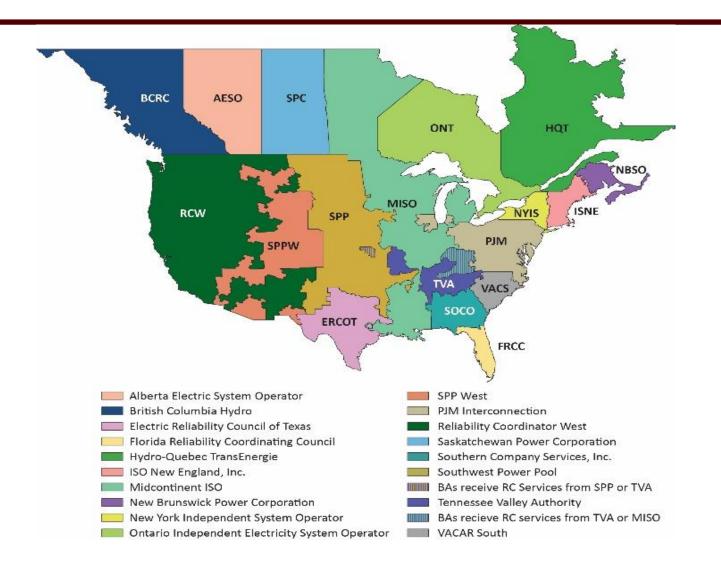
- Skim Chapters 3, 4 and 5
- Starting reading Chapter 8
- Homework 5 is due on Thursday Oct 29



Energy Management Systems (EMSs)

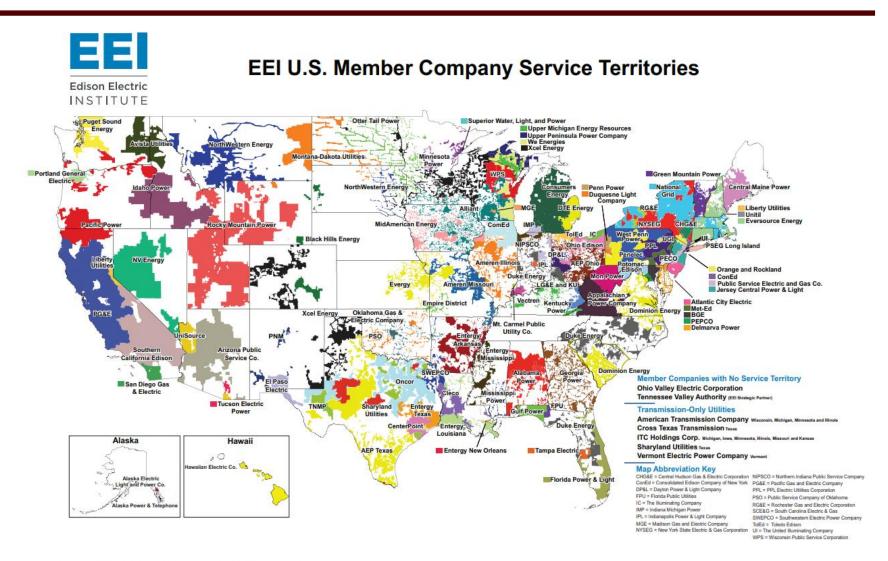
- EMSs are now used to control most large scale electric grids
- EMSs developed in the 1970's and 1980's out of SCADA systems
 - An EMS usually includes a SCADA system; sometimes called a SCADA/EMS
- Having a SE is almost the definition of an EMS. The SE then feeds data to the more advanced functions
- 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

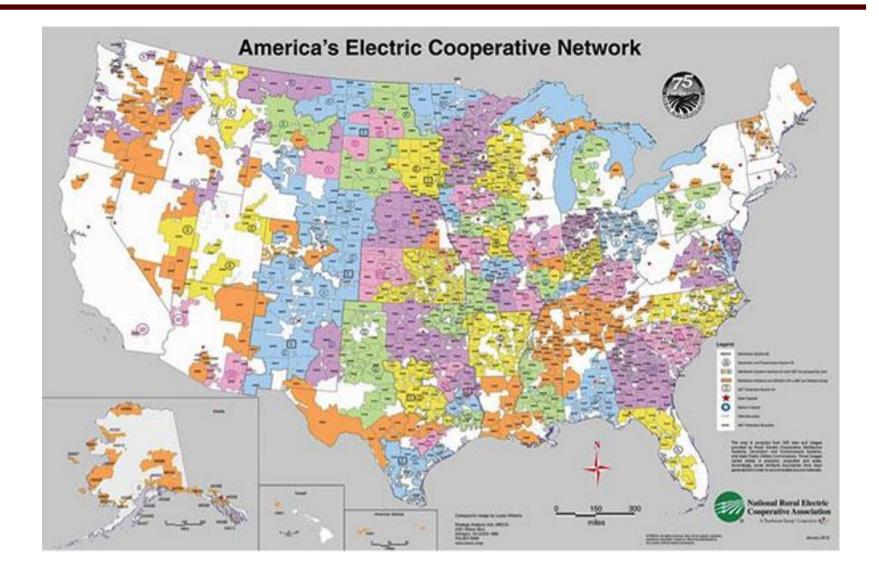
EEI Member Companies



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

Electric Coops

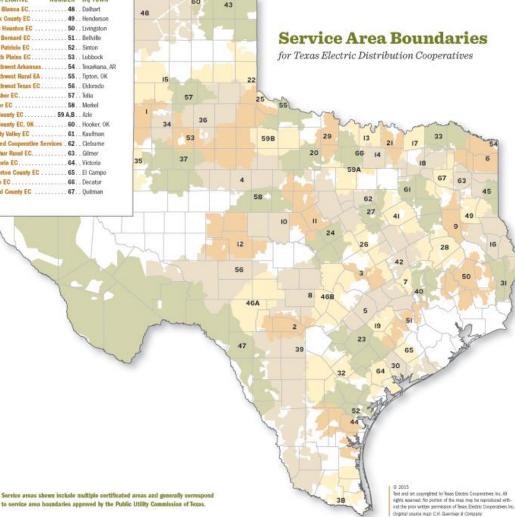




Texas Electric Coops

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Sam Houston EC		. Livingston
San Bernard EC		_ Belhille
San Patricio EC		
South Plains EC		. Lubbock
Southwest Arkansas.		. Texarkana, A
Southwest Rural EA		. Tipton, OK
Southwest Texas EC .		- Eldorado
Swisher EC		
Taylor EC		. Merkel
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Trinity Valley EC		
United Cooperative S	ervices . 62.	. Cleburne
Upshur Rural EC		. Gilmer
Victoria EC.		. Victoria
Wharton County EC .		. El Campo
Wise EC		
Wood County EC		. Ouitman



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to service area boundaries approved by the Public Utility Commission of Texas.

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ERCOT Control Center with EMS

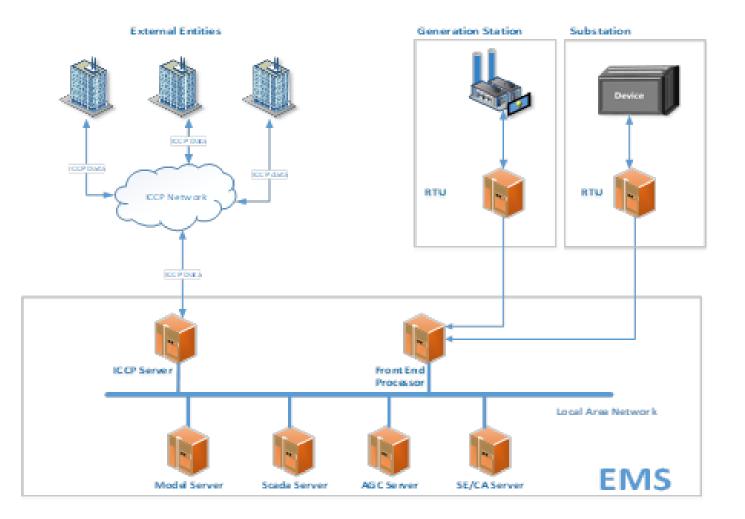


Source: www.texastribune.org/2016/05/17/texas-market-forces-driving-shift-coal-study-says/



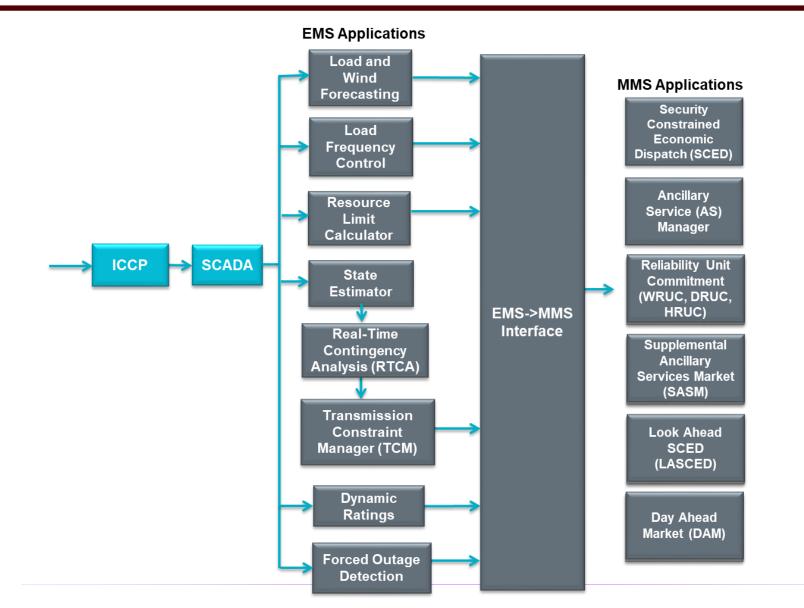
ERCOT EMS





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

ERCOT EMS





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 The original concept is more than produce

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

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



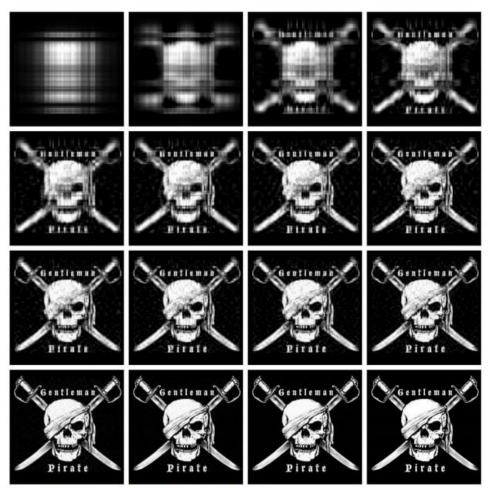


Figure 3.1: Image size 250x236 – modes used {{1,2,4,6},{8,10,12,14},{16,18,20,25},{50,75,100,original image}}

Image Source: www.math.utah.edu/~goller/F15_M22/0/BradyMathews_SVDImage.pdf

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

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 A^+
- Satisfies $AA^+A = A$
- 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 Ax = b is $x = A^+ b$ $A = U\Sigma V^T$
- Can be calculated using an SVD $\mathbf{A}^+ = \mathbf{V} \mathbf{\Sigma}^+ \mathbf{U}^T$

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 Ax = b

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

Aside: Pseudoinverse Least Squares Matrix Example

Doing an economy SVD

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

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 $\mathbf{x} = [\mathbf{m} \mathbf{b}]^T$ 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}_{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

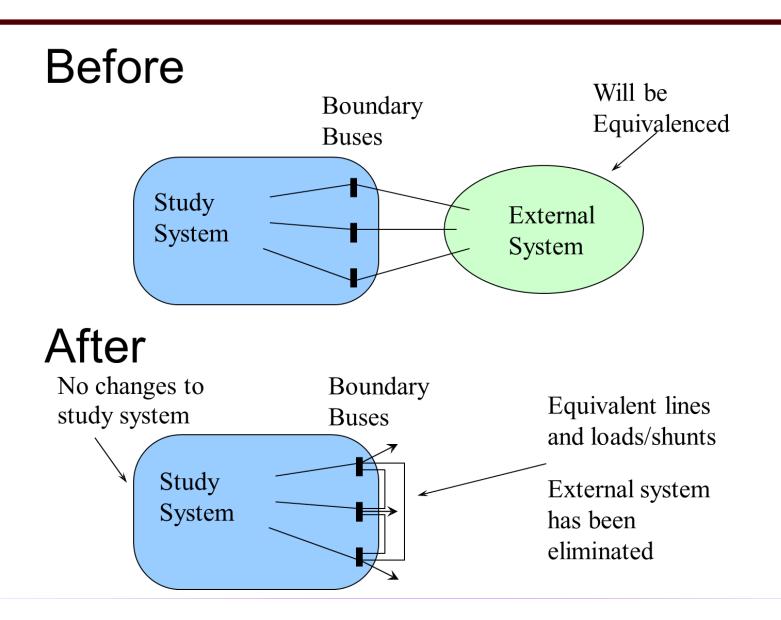


- An equivalent is usually created from a larger model
 - In the Eastern Interconnect there are full grid models that are used for wide-area planning, these are equivalenced for realtime usage or more specialized studies
- The equivalent is usually smaller and less detailed
 - Solves quicker
 - Requires 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

- A M
- 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





Ward Type Equivalencing Considerations



- The Ward equivalent is calculated by doing a partial factorization of the \mathbf{Y}_{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

$$\begin{bmatrix} I_{s} \\ I_{e} \end{bmatrix} = \begin{bmatrix} Y_{ss} & Y_{se} \\ Y_{es} & Y_{ee} \end{bmatrix} \begin{bmatrix} V_{s} \\ V_{e} \end{bmatrix}$$
$$\left(I_{s} - Y_{se} Y_{ee}^{-1} I_{e} \right) = \left(Y_{ss} - Y_{se} Y_{ee}^{-1} Y_{es} \right) V_{s}$$

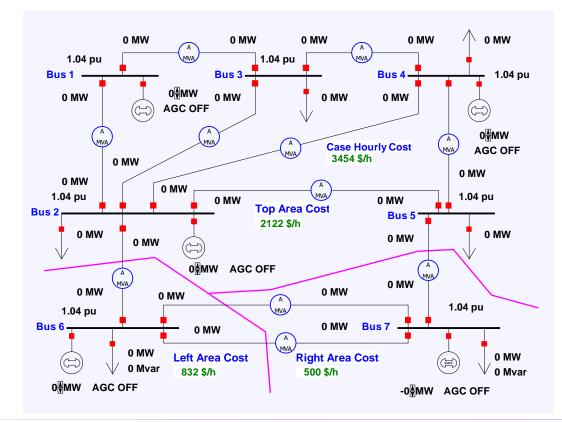
Ward Type Equivalencing Considerations



- 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 **Y**_{bus}

	-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
$\mathbf{Y}_{bus} = j$	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
	-20.833	8 4.167	7	0]			
$\mathbf{Y}_{ee} = j$	4.167	-43.05	56 33	8.333			
	0	33.33	3 -4.	3.056			

B7Flat_Eqv Example

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Equivalencing in PowerWorld

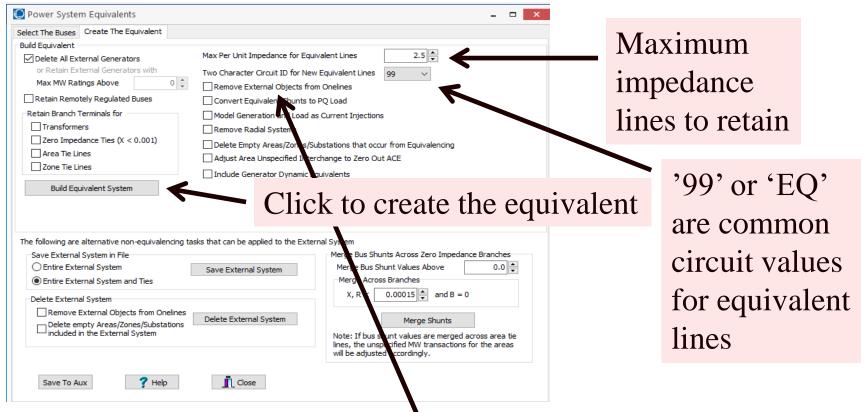
 Open a case and solve it; then select Edit Mode, Tools, Equivalencing; this displays the Power System Equivalents Form

O Power System	m Equivalents							- 🗆 🗙
Select The Buses	Create The Equiva	lent						
🗮 📄 🏪 🕯	-	Records	-	Đ	select what to ad	d to the stu	udy and	Study
Buses Areas		Which system? Study Study Study Study Study Study	# Neighb (ignore st	Set al Se	Find Find Find Find Find Find as external t Branch Terminals E set Branch Terminals	xternal Study		Add Find Add Find Add Find Filter by KV: Max 9999.0 • Min 0.0 • Save buses to file Load buses from file
< Switch to	the next page to	create equivalen	> ts			L Close		? Help

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

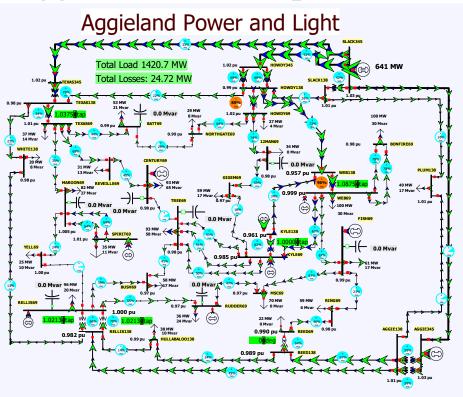
• Then go to the **Create The Equivalent** page, select the desired options and select **Build Equivalent System**



Removes equivalenced objects from the oneline

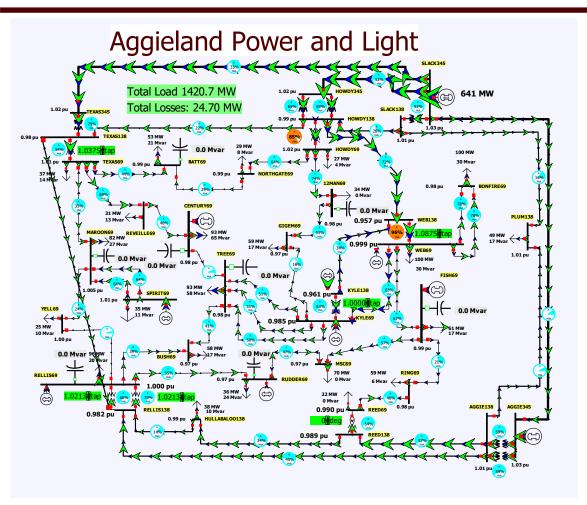


• Example shows the creation of an equivalent for Aggieland37 example



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

Case is Aggieland37_HW5



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

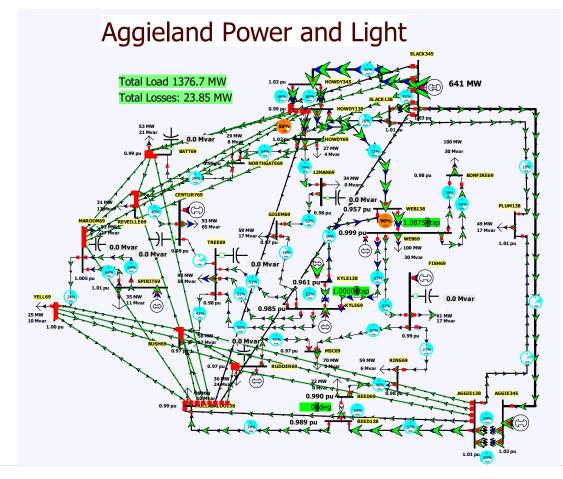
Don't save the equivalent with the same name as the original, unless you want to lose the original

Now remove buses at WHITE138 and TEXAS and RELLIS (1, 3, 12, 40, 41, 44); set Max Per Unit **Impedance** for Aggieland Power and Light Equivalent tal Load 1376.0 641 MW otal Losses: 24.61 MV **Lines** to 99 (per unit) to retain all lines. Again to an autoinsert to show the equivalent lines.





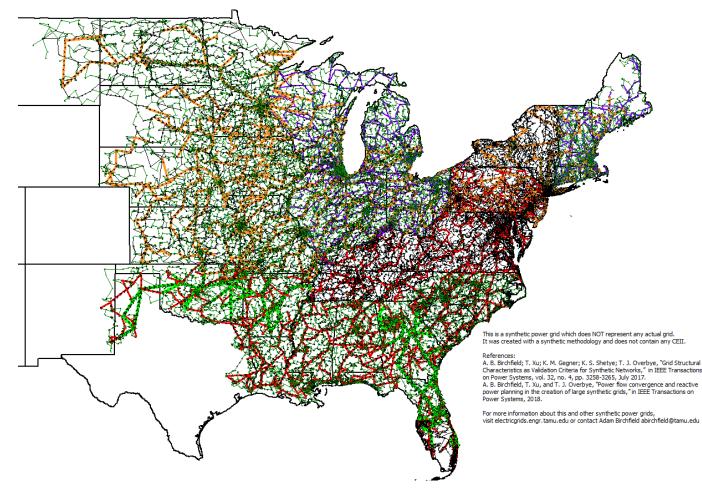
• Now set the Max Per Unit Impedance for Equivalent Lines to 2.5.



Large System Example: 70K Case



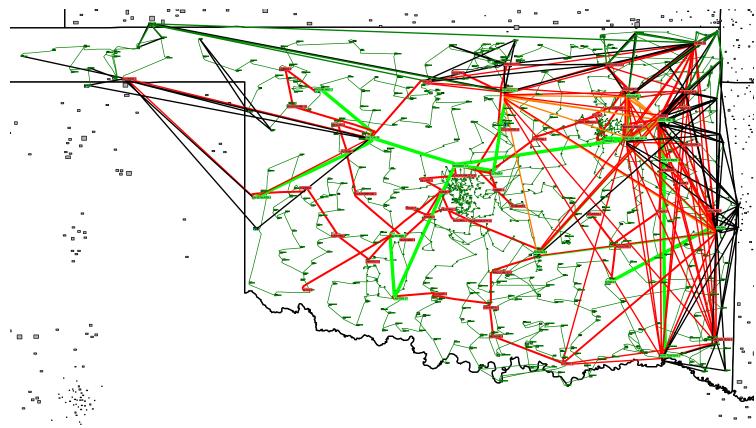
• Original System has 70,000 buses and 71,343 lines



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Large System Example: 70K Case

- Ă,M
- 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

