ECEN 615 Methods of Electric Power Systems Analysis Lecture 16: State Estimation, EMS

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Announcements

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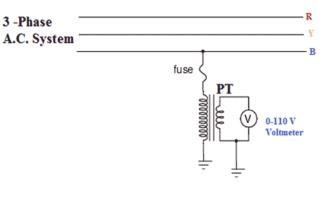
- Read Chapter 9
- Homework 4 is due today
 - In problem 5 the LODF is a vector
 - In problem 6 find the OTDF on the line between buses 1 and 2

Electric Grid Measurements



- The two major types of measurements are voltages and currents
 - The challenge for both types are doing these measurements at the high electric grid voltage levels
- Potential transformers (PTs) are used to measure voltage, using a transformer sometimes

with a set of series capacitors to drop the voltage



Potential Transformer (P.T.)



Image source: www.electrical4u.com/instrument-transformers/

Electric Grid Measurements

- Current transformers (CTs) are used to measure current, with the primary often consisting of the transmission wire itself; the secondary then has its number of turns set to give a specified current (say 5A) at a specified line current
 - Many CTs are used in the protection system so these need to be calibrated to correctly measure fault current;
 others are used to give more accurate load current values

0-5 A Ammeter

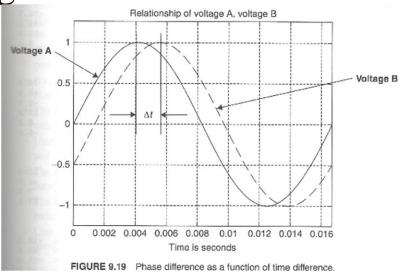
Current Transformer (C.T.)

• All meters have errors

Image source: www.electrical4u.com/instrument-transformers/

Phasor Measurement Units (PMUs)

- M.
- All AC signals have a magnitude and phase. It is very easy to measure the phase angle differences between local signals (e.g., at an electrical substation)
 - These differences are used to calculate power values
- However, it had been challenging to measure phase angle differences between signals at different locations
 - This requires access to a precise time source
 - At 60 Hz one cycle takes 16.67 ms, which means one degree takes 46 µs.



Phasor Measurement Units (PMUs)



- Widespread access to precise time became available in the 1980's when civilian use of the GPS was allowed
- PMUs use the GPS signals to determine the phase angles of voltages and currents (relative to some global reference)
 - The inputs to PMUs come from the CTs and PTs
- PMUs sample the system at rates on the order of 30 times per second
- PMU values are being used in SE algorithms

SE Example: Two Bus Case

- A M
- Assume a two bus case with a generator supplying a load through a single line with x=0.1 pu. Assume measurements of the p/q flow on both ends of the line (into line positive), and the voltage magnitude at both the generator and the load end. So $B_{12} = B_{21} = 10.0$

$$P_{ij}^{meas} - \left[V_i V_j \left(B_{ij} \sin\left(\theta_i - \theta_j\right) \right) \right]$$

$$Q_{ij}^{meas} - \left[V_i^2 B_{ij} + V_i V_j \left(-B_{ij} \cos\left(\theta_i - \theta_j\right) \right) \right]$$

 $V_i^{meas} - V_i = 0$

We need to assume a reference angle unless we're directly measuring phase angles

Example: Two Bus Case

• Let
$$\mathbf{Z}^{meas} = \begin{bmatrix} P_{12} \\ Q_{12} \\ P_{21} \\ Q_{21} \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 2.02 \\ 1.5 \\ -1.98 \\ -1 \\ 1.01 \\ 0.87 \end{bmatrix} \quad x^0 = \begin{bmatrix} V_1 \\ \theta_2 \\ V_2 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \sigma_i = 0.01 \quad \text{We assume an angle reference of } \theta_1 = 0 \end{bmatrix}$$
$$H(\mathbf{x}) = \begin{bmatrix} V_2 10\sin(-\theta_2) & -V_1V_2 10\cos(-\theta_2) & V_1 10\sin(-\theta_2) \\ 20V_1 - V_2 10\cos(-\theta_2) & -V_1V_2 10\sin(-\theta_2) & -V_1 10\cos(-\theta_2) \\ V_2 10\sin(\theta_2) & V_1V_2 10\cos(\theta_2) & V_1 10\sin(\theta_2) \\ -V_2 10\cos(\theta_2) & V_1V_2 10\sin(\theta_2) & 20V_2 - V_1 10\cos(\theta_2) \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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Example: Two Bus Case



• With a flat start guess we get

$$\mathbf{R} = \begin{bmatrix} 0 & -10 & 0 \\ 10 & 0 & -10 \\ 0 & 10 & 0 \\ -10 & 0 & 10 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \mathbf{z} - \mathbf{f}(\mathbf{x}^{0}) = \begin{bmatrix} 2.02 \\ 1.5 \\ -1.98 \\ -1 \\ 0.01 \\ -0.13 \end{bmatrix}$$
$$\mathbf{R} = \begin{bmatrix} 0.0001 & 0 & 0 & 0 & 0 \\ 0.0001 & 0 & 0 & 0 & 0 \\ 0 & 0.0001 & 0 & 0 & 0 \\ 0 & 0 & 0.0001 & 0 & 0 \\ 0 & 0 & 0 & 0.0001 & 0 \\ 0 & 0 & 0 & 0 & 0.0001 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.0001 \end{bmatrix}$$

Example: Two Bus Case

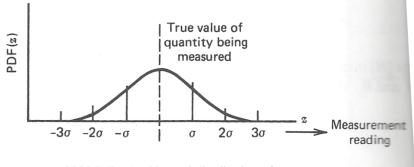
$$\mathbf{H}^{T}\mathbf{R}^{-1}\mathbf{H} = 1e^{6} \times \begin{bmatrix} 2.01 & 0 & -2 \\ 0 & 2 & 0 \\ -2 & 0 & 2.01 \end{bmatrix}$$

$$\mathbf{x}^{1} = \mathbf{x}^{0} + \begin{bmatrix} \mathbf{H}^{T} \mathbf{R}^{-1} \mathbf{H} \end{bmatrix}^{-1} \mathbf{H}^{T} \mathbf{R}^{-1} \begin{bmatrix} 2.02 \\ 1.5 \\ -1.98 \\ -1 \\ 0.01 \\ -0.13 \end{bmatrix} = \begin{bmatrix} 1.003 \\ -0.2 \\ 0.8775 \end{bmatrix}$$



Assumed SE Measurement Accuracy

- A M
- The assumed measurement standard deviations can have a significant impact on the resultant solution, or even whether the SE converges
- The assumption is a Gaussian (normal) distribution of the error with no bias





SE Observability

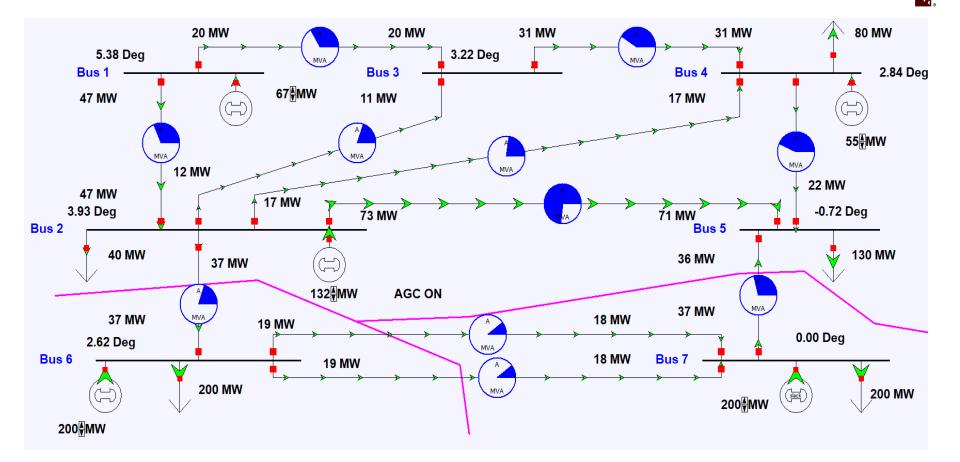


- In order to estimate all n states we need at least n measurements. However, where the measurements are located is also important, a topic known as observability
 - In order for a power system to be fully observable usually we need to have a measurement available no more than one bus away
 - At buses we need to have at least measurements on all the injections into the bus except one (including loads and gens)
 - Loads are usually flows on feeders, or the flow into a transmission to distribution transformer
 - Generators are usually just injections from the GSU

Pseudo Measurements

- Pseudo measurements are used at buses in which there is no load or generation; that is, the net injection into the bus is know with high accuracy to be zero
 - In order to enforce the net power balance at a bus we need to include an explicit net injection measurement
- To increase observability sometimes estimated values are used for loads, shunts and generator outputs
 - These "measurements" are represented as having a higher much standard deviation

SE Observability Example



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SE Bad Data Detection



- The quality of the measurements available to an SE can vary widely, and sometimes the SE model itself is wrong. Causes include
 - Modeling Errors: perhaps the assumed system topology is incorrect, or the assumed parameters for a transmission line or transformer could be wrong
 - Data Errors: measurements may be incorrect because of in correct data specifications, like the CT ratios or even flipped positive and negative directions
 - Transducer Errors: the transductors may be failing or may have bias errors
 - Sampling Errors: SCADA does not read all values simultaneously and power systems are dynamic

SE Bad Data Detection

- A M
- The challenge for SE is to determine when there is likely a bad measurement (or multiple ones), and then to determine the particular bad measurements
- J(x) is random number, with a probability density function (PDF) known as a chi-squared distribution, $\chi^2(K)$, where K is the degrees of freedom, K=m-n
- It can be shown the expected mean for $J(\mathbf{x})$ is K, with a standard deviation of $\sqrt{2K}$
 - Values of J(x) outside of several standard deviations indicate possible bad measurements, with the measurement residuals used to track down the likely bad measurements
- SE can be re-run without the bad measurements

QR Factorization



- Used in SE since it handles ill-conditioned m by n matrices (with m >= n)
- Can be used with sparse matrices
- We will first split the \mathbf{R}^{-1} matrix $\mathbf{H}^{T}\mathbf{R}^{-1}\mathbf{H} = \mathbf{H}^{T}\mathbf{R}^{-\frac{1}{2}}\mathbf{R}^{-\frac{1}{2}}\mathbf{H} = \mathbf{H}^{T}\mathbf{H}^{T}$
- QR factorization represents the m by n H' matrix as H' = QU

with \mathbf{Q} an m by m orthonormal matrix and \mathbf{U} an upper triangular matrix (most books use $\mathbf{Q} \mathbf{R}$ but we use \mathbf{U} to avoid confusion with the previous \mathbf{R}) 16

Orthonormal Matrices



- The term orthogonal is used with vectors to indicate their dot product is zero (i.e., they are perpendicular to each other)
- Orthonormal is used to indicate they are orthogonal and each has unit length (magnitude of 1)
- The definition of an orthogonal matrix is Q^TQ = I
 This implies its inverse always exists
- Its determinant is 1
- They can be used for transformations such as an angular rotation

QR Factorization

A M

- We then have $\mathbf{H'}^T \mathbf{H'} = \mathbf{U}^T \mathbf{Q}^T \mathbf{Q} \mathbf{U}$
- But since \mathbf{Q} is an orthonormal matrix, $\mathbf{Q}^T \mathbf{Q} = \mathbf{I}$
- Hence we have $\mathbf{H'}^T \mathbf{H'} = \mathbf{U}^T \mathbf{U}$ Originally $\Delta \mathbf{x} = \left[\mathbf{H}^T \mathbf{R}^{-1} \mathbf{H}\right]^{-1} \mathbf{H}^T \mathbf{R}^{-1} \left[\mathbf{z}^{meas} - \mathbf{f}(\mathbf{x})\right]$

With
$$\mathbf{H}^T \mathbf{R}^{-1} \mathbf{H} = \mathbf{H}'^T \mathbf{H}' = \mathbf{H}'^T \mathbf{H}' = \mathbf{U}^T \mathbf{U}$$
 Q is an m by m matrix

Let
$$\hat{\mathbf{z}} = \mathbf{Q}^T \mathbf{R}^{-\frac{1}{2}} \left[\mathbf{z}^{meas} - \mathbf{f}(\mathbf{x}) \right]$$

$$\Delta \mathbf{x} = \left[\mathbf{U}^T \mathbf{U} \right]^{-1} \mathbf{H}^T \mathbf{R}^{-\frac{1}{2}} \mathbf{R}^{-\frac{1}{2}} \left[\mathbf{z}^{meas} - \mathbf{f}(\mathbf{x}) \right] = \left[\mathbf{U}^T \mathbf{U} \right]^{-1} \mathbf{U}^T \hat{\mathbf{z}}$$

 $\mathbf{U}^{T}\mathbf{U}\Delta\mathbf{x} = \mathbf{U}^{T}\hat{\mathbf{z}} \rightarrow \Delta\mathbf{x} = \mathbf{U}^{-1}\hat{\mathbf{z}}$

QR Factorization



- Next we'll briefly discuss the QR factorization algorithm
- When factored the U matrix (i.e., what most call the **R** matrix) will be an m by n upper triangular matrix
- Several methods are available including the Householder method and the Givens method
- Givens is preferred when dealing with sparse matrices
- A good reference is Gene H. Golub and Charles F. Van Loan, "Matrix Computations," second edition, Johns Hopkins University Press, 1989.

Givens Algorithm for Factoring a Matrix A



• The Givens algorithm works by pre-multiplying the initial matrix, **A**, by a series of matrices and their transposes, starting with $\mathbf{G}_{1}\mathbf{G}_{1}^{\mathrm{T}}$

– If \mathbf{A} is m by n, then each \mathbf{G} is an m by m matrix

• The algorithm proceeds column by column, sequentially zeroing out elements in the lower triangle of **A**, starting at the bottom of each column

$$\mathbf{G}_{1} \dots \mathbf{G}_{p} \mathbf{G}_{p}^{T} \dots \mathbf{G}_{1}^{T} \mathbf{A} = \mathbf{Q}\mathbf{U}$$
$$\mathbf{G}_{1} \dots \mathbf{G}_{p} = \mathbf{Q}$$
$$\mathbf{G}_{p}^{T} \dots \mathbf{G}_{1}^{T} \mathbf{A} = \mathbf{U}$$

If **A** is sparse, then we can take advantage of sparsity going up the column

Givens Algorithm

- To zero out element **A**[i,j], with i > j we first solve with a=A[k,j], b= A[i,j]

$$\begin{bmatrix} c & -s \\ s & c \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} r \\ 0 \end{bmatrix}$$
$$r = \sqrt{a^2 + b^2}$$

To zero out an element we need a non-zero pivot element in column j; assume this row as k.

• A numerically safe algorithm is If b=0 then c=1, s=0 // i.e, no rotation is needed

Else If
$$|b| > |a|$$
 then $\tau = -a / b$; $s = 1 / \sqrt{1 + \tau^2}$; $c = s\tau$

Else
$$\tau = -b / a$$
; $c = 1 / \sqrt{1 + \tau^2}$; $s = c\tau$

Givens G Matrix

• The orthogonal $G(i,k,\theta)$ matrix is then

$$\mathbf{G}(i,\mathbf{k},\theta) = \begin{bmatrix} 1 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & & \vdots & & \vdots \\ 0 & \cdots & c & \cdots & s & \cdots & 0 \\ \vdots & & \vdots & \ddots & \vdots & & \vdots \\ 0 & \cdots & -s & \cdots & c & \cdots & 0 \\ \vdots & & \vdots & & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 & \cdots & 1 \end{bmatrix}$$

As noted, to zero out an element we need a non-zero pivot element in column j; assume this row as k. Row k here is the first non-zero above row i.

• Premultiplication by $G(i,k,\theta)^T$ is a rotation by θ radians in the (i,k) coordinate plane



Small Givens Example

• Let
$$\mathbf{A} = \begin{bmatrix} 4 & 2 \\ 1 & 0 \\ 0 & 5 \\ 2 & 1 \end{bmatrix}$$

First start in column j=1; we will zero out A[4,1] with i=4, k=2

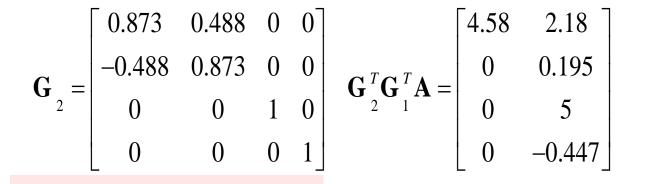
• First we zero out **A**[4,1], a=1, b=2 giving s= 0.8944, c=-0.4472

$$\mathbf{G}_{1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -0.4472 & 0 & 0.8944 \\ 0 & 0 & 1 & 0 \\ 0 & -0.8944 & 0 & -0.4472 \end{bmatrix} \quad \mathbf{G}_{1}^{T} \mathbf{A} = \begin{bmatrix} 4 & 2 \\ -2.236 & -0.8944 \\ 0 & 5 \\ 0 & -0.4472 \end{bmatrix}$$



Small Givens Example

Next zero out A[2,1] with a=4, b=-2.236, giving c= -0.8729, s=0.4880 k=1 with A[k,j]=4



j=2, k=3 with A[k,j]=5

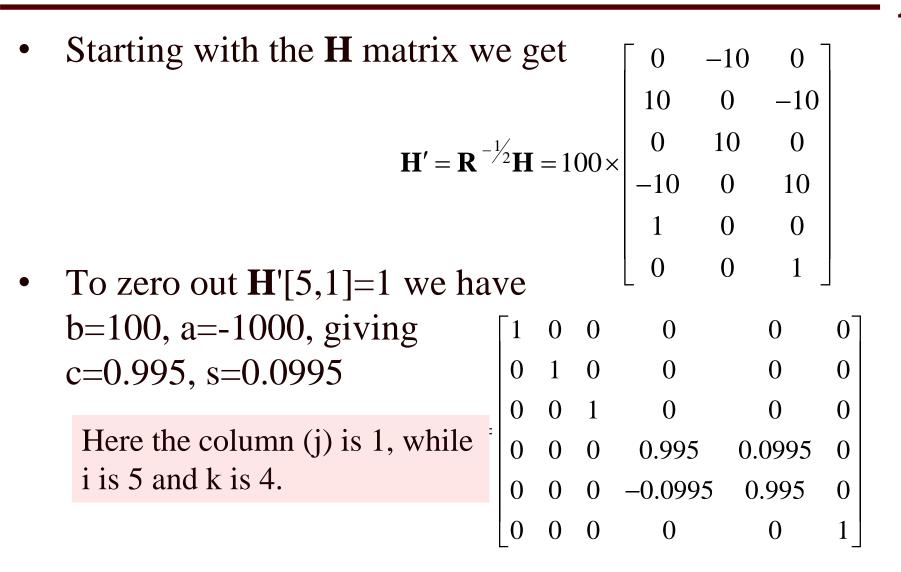
• Next zero out A[4,2] with a=5, b=-0.447, c=0.996, s=0.089 $\mathbf{G}_{3} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0.996 & 0.089 \\ 0 & 0 & -0.089 & 0.996 \end{bmatrix} \mathbf{G}_{3}^{T} \mathbf{G}_{2}^{T} \mathbf{A} = \begin{bmatrix} 4.58 & 2.18 \\ 0 & 0.195 \\ 0 & 5.020 \\ 0 & 0 \end{bmatrix}$

Small Givens Example

- Next zero out A[3,2] with a=0.195, b=5.02, c=-0.039, s=0.999 j=2, k=2 with A[k,j]=0.195 $\mathbf{G}_{4} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -0.039 & 0.999 & 0 \\ 0 & -0.999 & -0.039 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \mathbf{G}_{4}^{T} \mathbf{G}_{3}^{T} \mathbf{G}_{2}^{T} \mathbf{G}_{1}^{T} \mathbf{A} = \mathbf{U} = \begin{bmatrix} 4.58 & 2.18 \\ 0 & -5.023 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$
- Also we have

$$\mathbf{Q} = \mathbf{G}_{1}\mathbf{G}_{2}\mathbf{G}_{3}\mathbf{G}_{4} = \begin{bmatrix} 0.872 & -0.019 & 0.487 & 0\\ 0.218 & 0.094 & -0.387 & 0.891\\ 0 & -0.995 & -0.039 & 0.089\\ 0.436 & -0.009 & -0.782 & -0.445 \end{bmatrix}$$

Start of Givens for SE Example





Start of Givens for SE Example

• Which gives

$$\mathbf{G}_{1}^{T}\mathbf{H}' = 100 \times \begin{bmatrix} 0 & -10 & 0 \\ 10 & 0 & -10 \\ 0 & 10 & 0 \\ 10.049 & 0 & -9.95 \\ 0 & 0 & 0.995 \\ 0 & 0 & 1 \end{bmatrix}$$

• The next rotation would be to zero out element [4,1], continuing until all the elements in the lower triangle have been reduced

Givens Comments



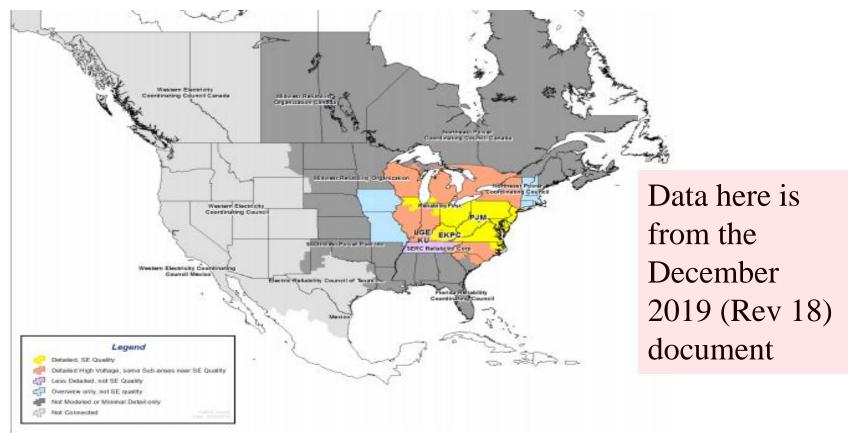
- For a full matrix, Givens is O(mn²) since each element in the lower triangle needs to be zeroed O(nm), and each operation is O(n)
- Computation can be drastically reduced for a sparse matrix since we only need to zero out the elements that are initially non-zero, and any that become non-zero (i.e., the fills)
 - Also, for each multiply we only need to deal with the nonzeros in the impacted row
- Givens rotation is commonly used to solve the SE

Example SE Application: PJM and MISO



• PJM provides information about their EMS model in

- www.pjm.com/-/media/documents/manuals/m03a.ashx



Example SE Application: PJM and MISO



- PJM measurements are required for 69 kV and up
- PJM SE is triggered to execute every minute
- PJM SE solves well over 98% of the time
- Below reference provides info on MISO SE from March 2015
 - 54,433 buses
 - 54,415 network branches
 - 6332 generating units
 - 228,673 circuit breakers
 - 289,491 mapped points

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)

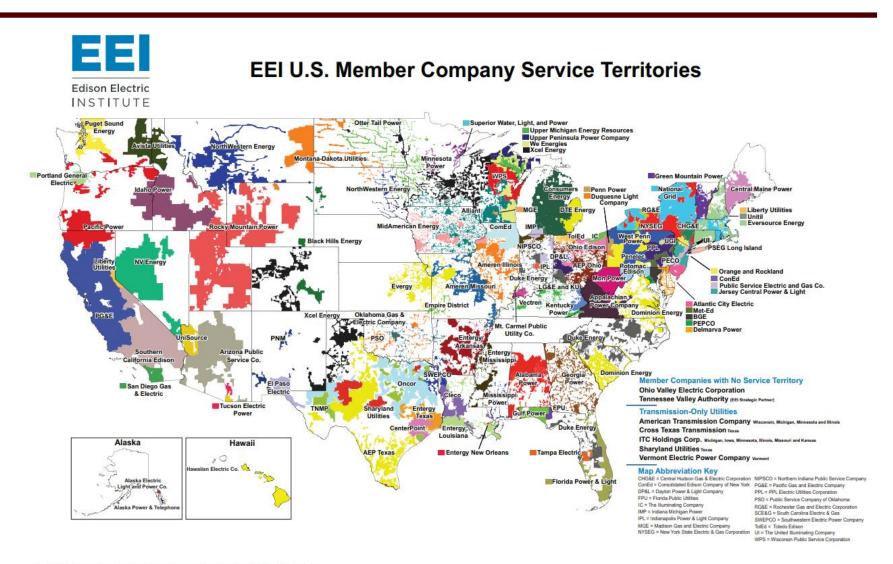
NERC Reliability Coordinators







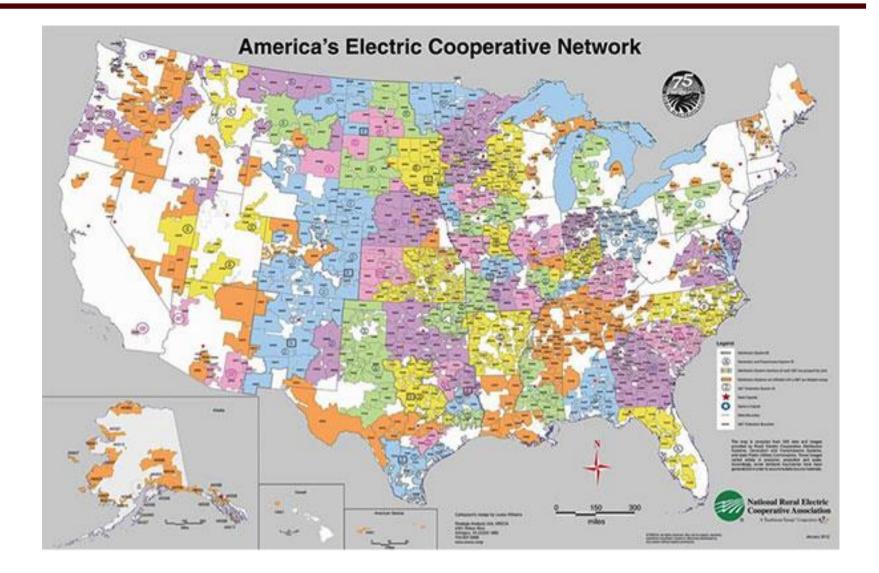
EEI Member Companies





Electric Coops





Texas Electric Coops

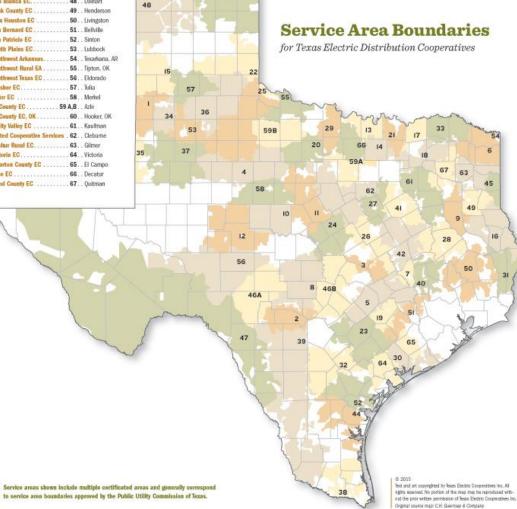
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Swisher EC		
Taylor EC		
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