ECEN 615
Methods of Electric Power Systems Analysis

Lecture 18: State Estimation

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Announcements

- Read Chapter 9 from the book
- Homework 4 is due on Thursday October 31.

Nonlinear Formulation

- A regular ac power system is nonlinear, so we need to use an iterative solution approach. This is similar to the Newton power flow. Here assume m measurements and n state variables (usually bus voltage magnitudes and angles) Then the Jacobian is the **H** matrix

$$\mathbf{H}(\mathbf{x}) = \frac{\partial \mathbf{f}(\mathbf{x})}{\partial \mathbf{x}} = \begin{bmatrix} \frac{\partial f_1}{x_1} & \cdots & \frac{\partial f_1}{x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_m}{x_1} & \cdots & \frac{\partial f_m}{x_n} \end{bmatrix}$$

Measurement Example

- Assume we measure the real and reactive power flowing into one end of a transmission line; then the z_i-$f_i(\mathbf{x})$ functions for these two are

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

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

  - Two measurements for four unknowns
- Other measurements, such as the flow at the other end, and voltage magnitudes, add redundancy

SE Iterative Solution Algorithm

- We then make an initial guess of **x**, $\mathbf{x}^{(0)}$ and iterate, calculating $\Delta\mathbf{x}$ each iteration

$$\Delta\mathbf{x} = \left[\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H}\right]^{-1}\mathbf{H}^T\mathbf{R}^{-1}\begin{bmatrix} z_1 - f_1(\mathbf{x}) \\ \vdots \\ z_m - f_m(\mathbf{x}) \end{bmatrix}$$

$$\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} + \Delta\mathbf{x}$$

Keep in mind that H is no longer constant, but varies as x changes. often ill-conditioned

This is exactly the least squares form developed earlier with $\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H}$ an n by n matrix. This could be solved with Gaussian elimination, but this isn't preferred because the problem is often ill-conditioned

Nonlinear SE Solution Algorithm, Book Figure 9.11

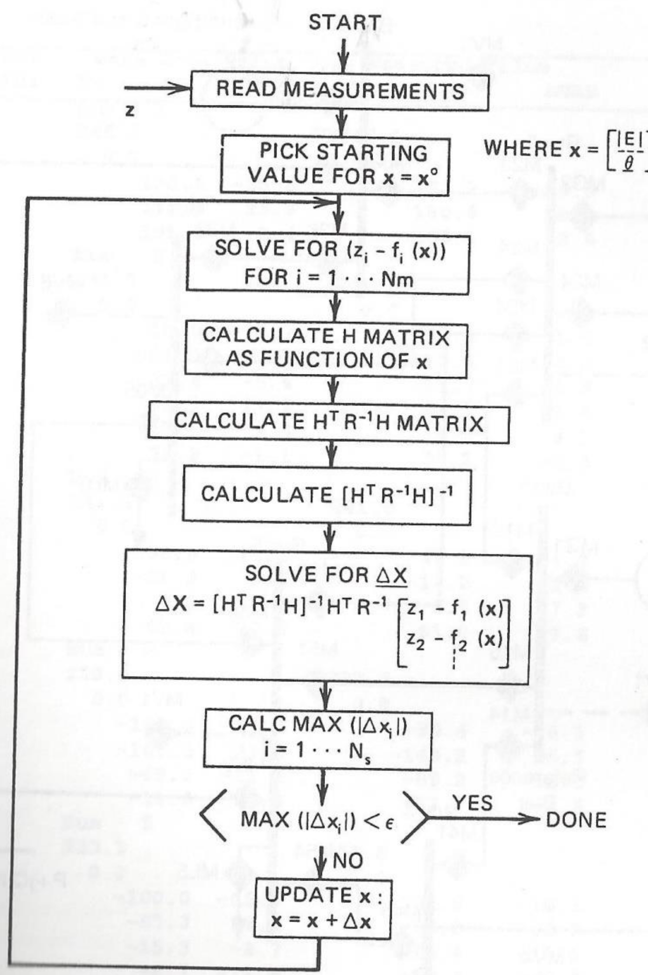


FIGURE 9.11 State estimation solution algorithm.

Example: Two Bus Case

- 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 directly measuring phase

Example: Two Bus Case

- Let $\mathbf{z}^{meas} = \begin{bmatrix} P_{12} \\ Q_{12} \\ P_{21} \\ Q_{21} \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 2.02 \\ 1.5 \\ -1.98 \\ -1 \\ 1.01 \\ 0.87 \end{bmatrix}$ $\quad x^0 = \begin{bmatrix} V_1 \\ \theta_2 \\ V_2 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \sigma_i = 0.01$

We assume an angle reference of $\theta_1=0$

$$H(\mathbf{x}) = \begin{bmatrix} V_2 10\sin(-\theta_2) & -V_1V_2 10\cos(-\theta_2) & V_1 10\sin(-\theta_2) \\ 20V_1 - V_2 10\cos(-\theta_2) & -V_1V_2 10\sin(-\theta_2) & -V_1 10\cos(-\theta_2) \\ V_2 10\sin(\theta_2) & V_1V_2 10\cos(\theta_2) & V_1 10\sin(\theta_2) \\ -V_2 10\cos(\theta_2) & V_1V_2 10\sin(\theta_2) & 20V_2 - V_1 10\cos(\theta_2) \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Example: Two Bus Case

- With a flat start guess we get

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

$$\mathbf{R} = \begin{bmatrix} 0.0001 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.0001 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.0001 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0001 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.0001 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.0001 \end{bmatrix}$$

Example: Two Bus Case

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

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

Assumed SE Measurement Accuracy

- 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

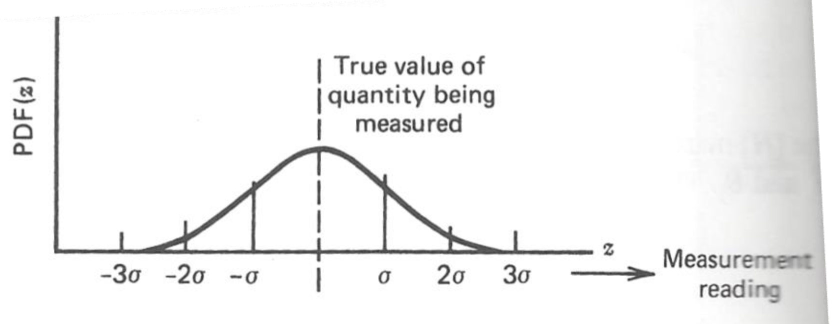


FIGURE 9.8 Normal distribution of meter errors.

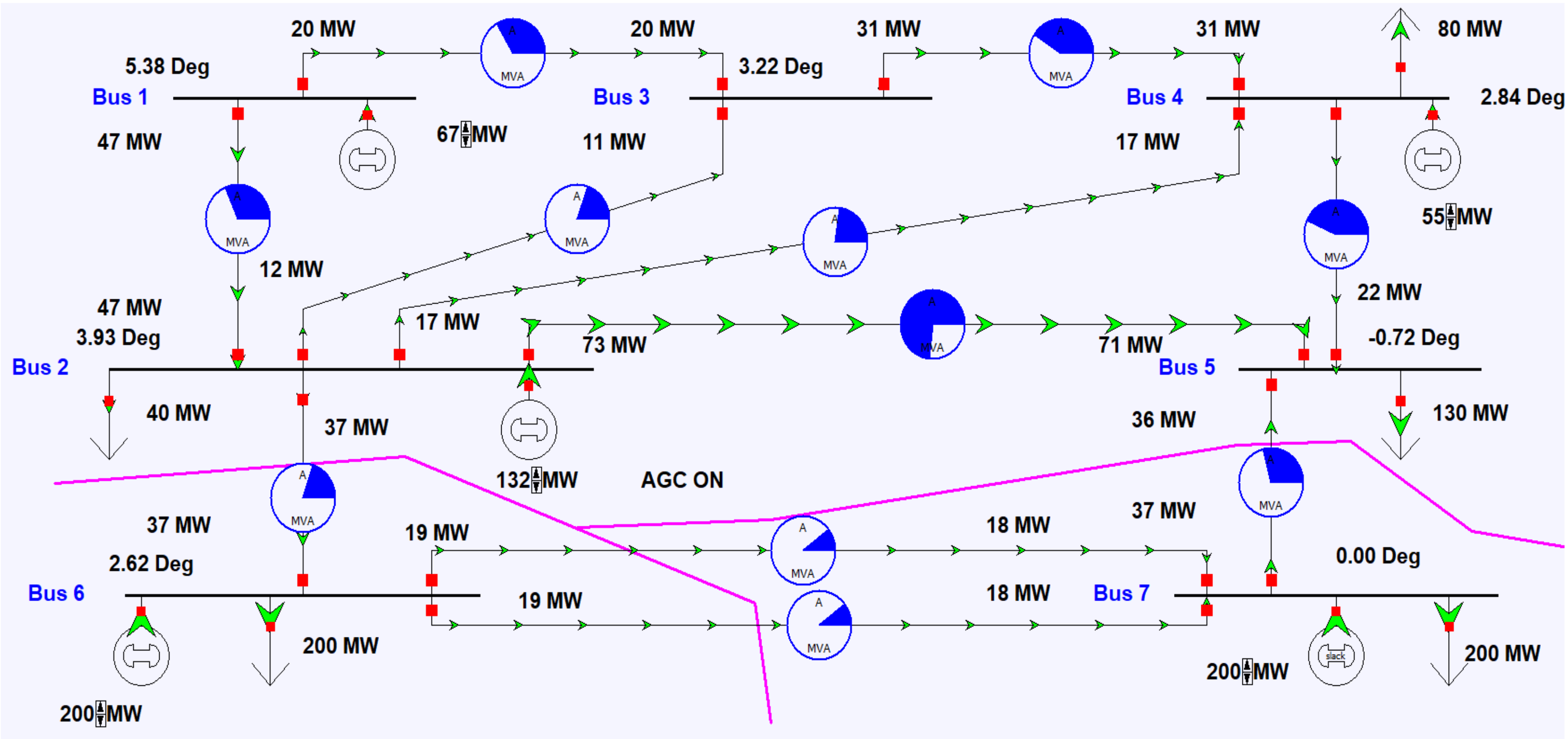
SE Observability

- 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



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

- 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, χ^2(K), where K is the degrees of freedom, K=m-n
- It can be shown the expected mean for J(**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

Example SE Application: PJM and MISO

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

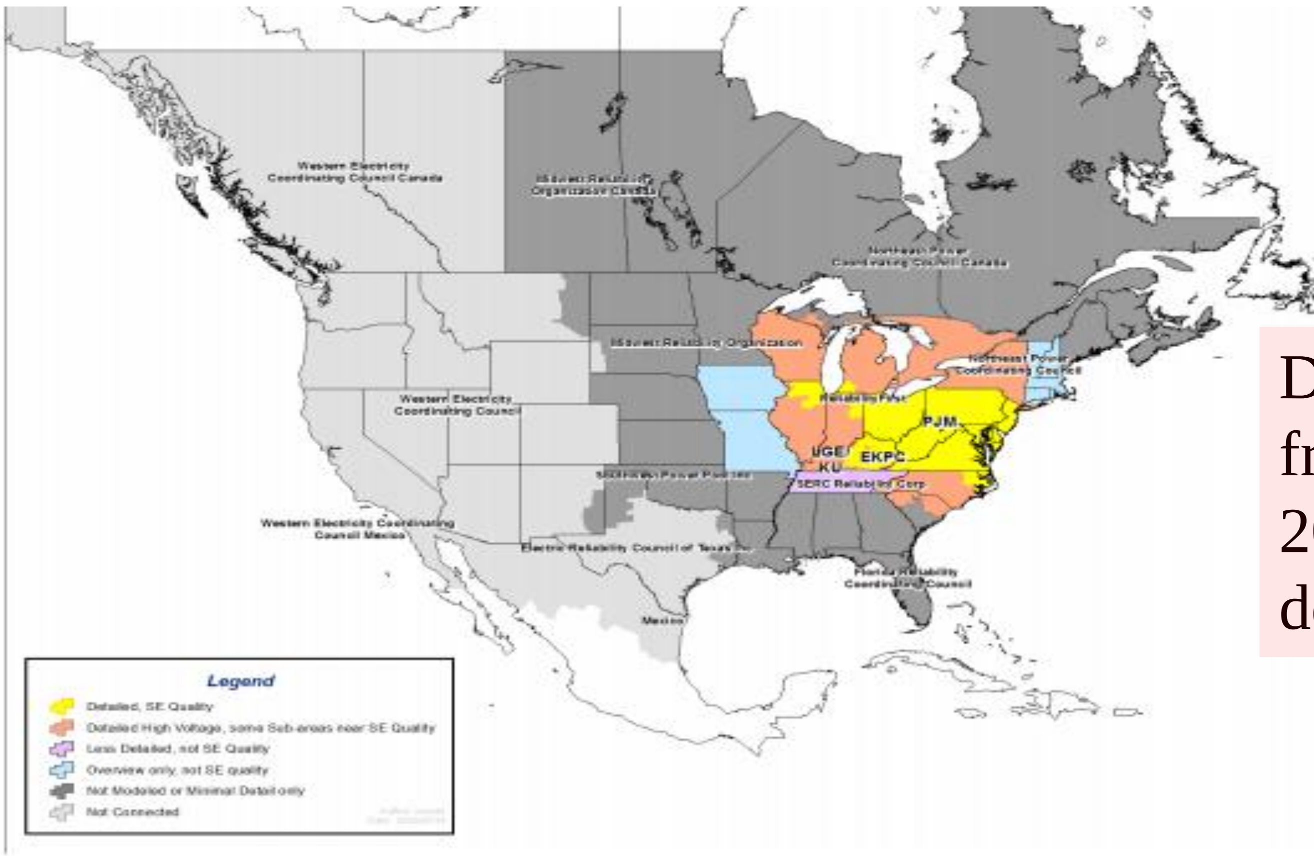


Exhibit 4: PJM EMS Model Details

Data here is from the Sept 2018 (Rev 16) document

Example SE Application: PJM and MISO

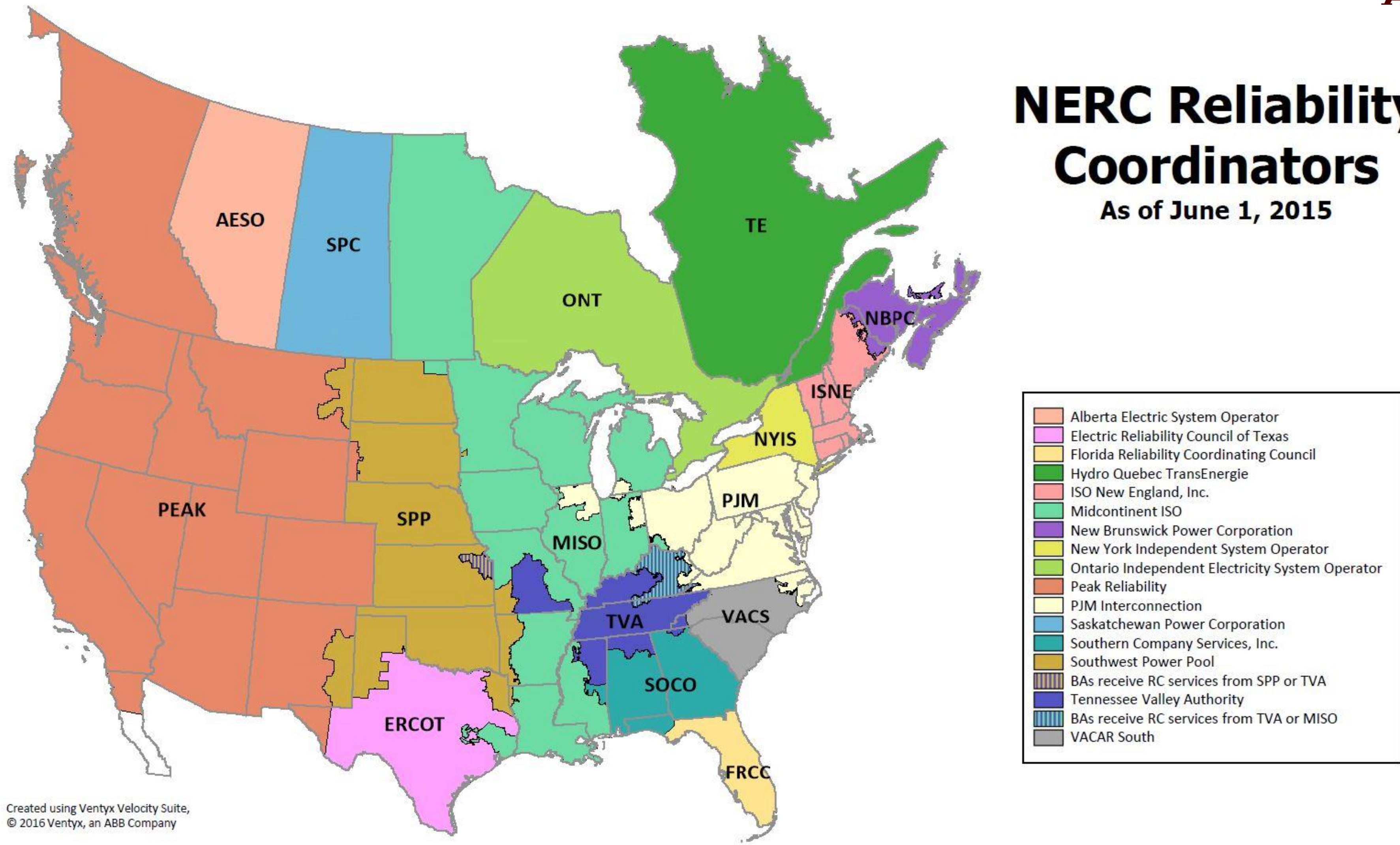
- PJM measurements are required for 69 kV and up
- PJM SE is triggered to execute every minute
- PJM SE solves well over 98% of the time
- Below reference provides info on MISO SE from March 2015
  - 54,433 buses
  - 54,415 network branches
  - 6332 generating units
  - 228,673 circuit breakers
  - 289,491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

https://www.naspi.org/sites/default/files/2017-05/3a%20MISO-NASPIWokshop-Synchrophasor%20Data%20and%20State%20Estimation.pdf

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

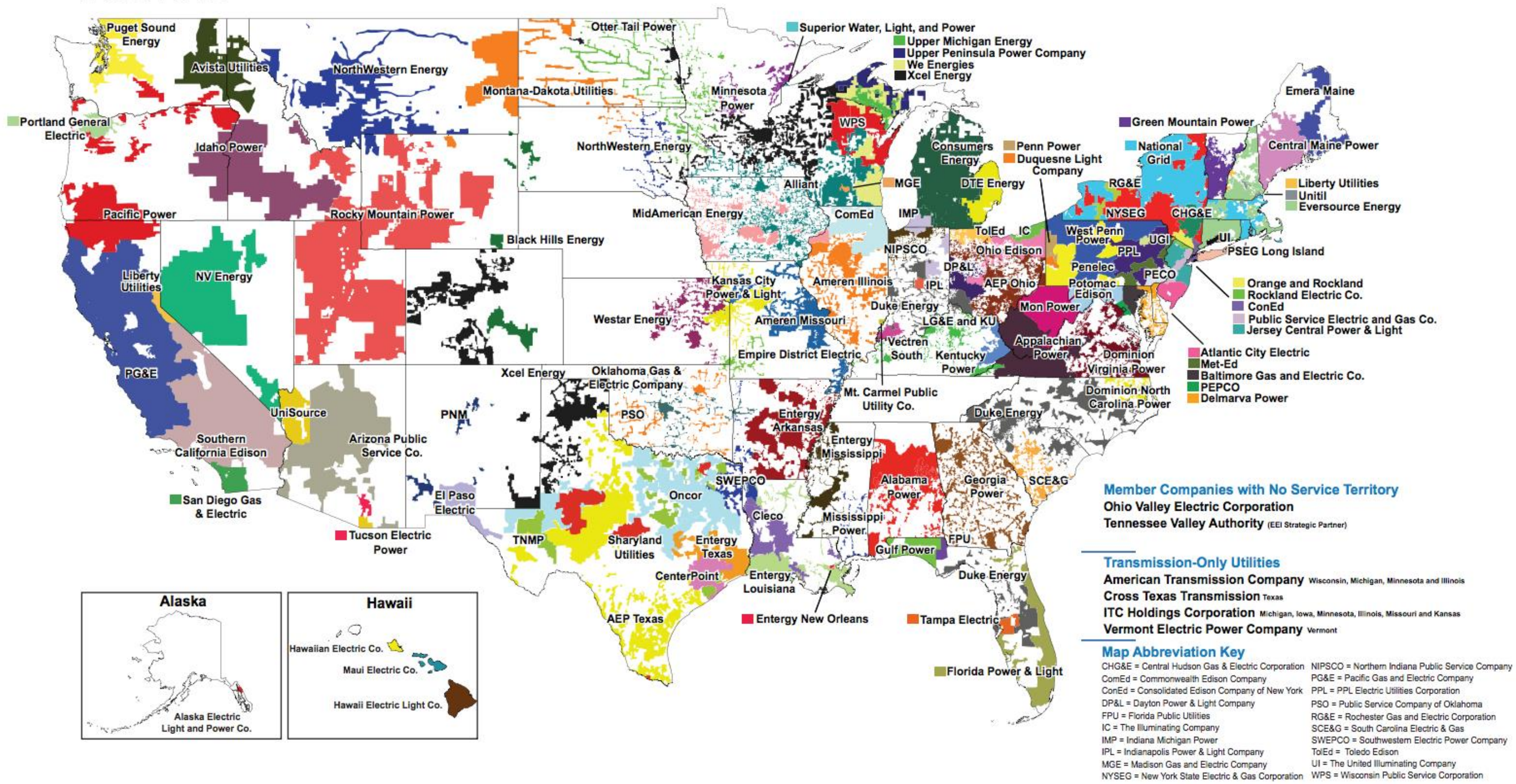


Source: www.nerc.com/pa/rrm/TLR/Pages/Reliability-Coordinators.aspx

EEI Member Companies

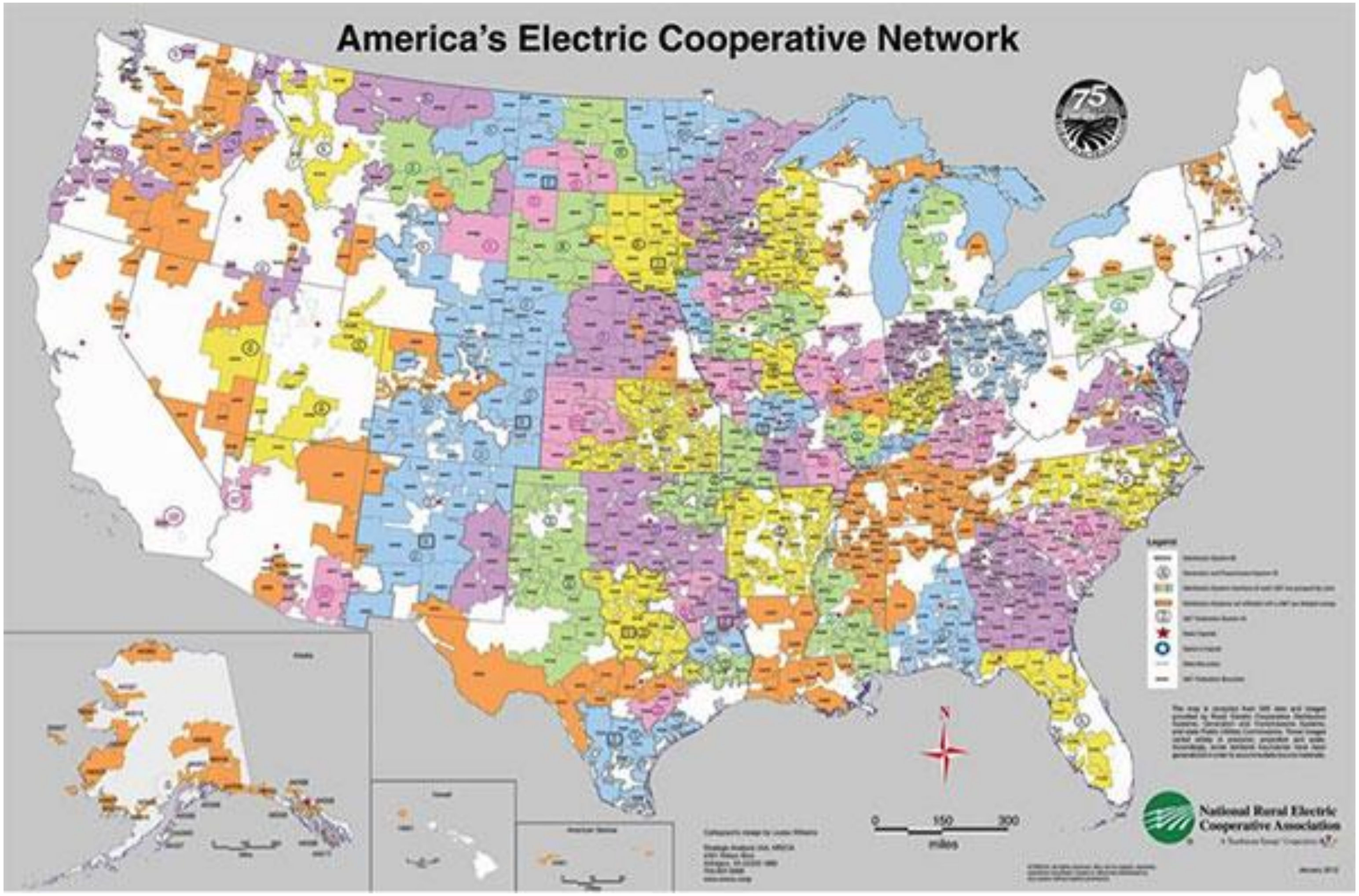
EEI
Edison Electric INSTITUTE

EEI U.S. Member Company Service Territories



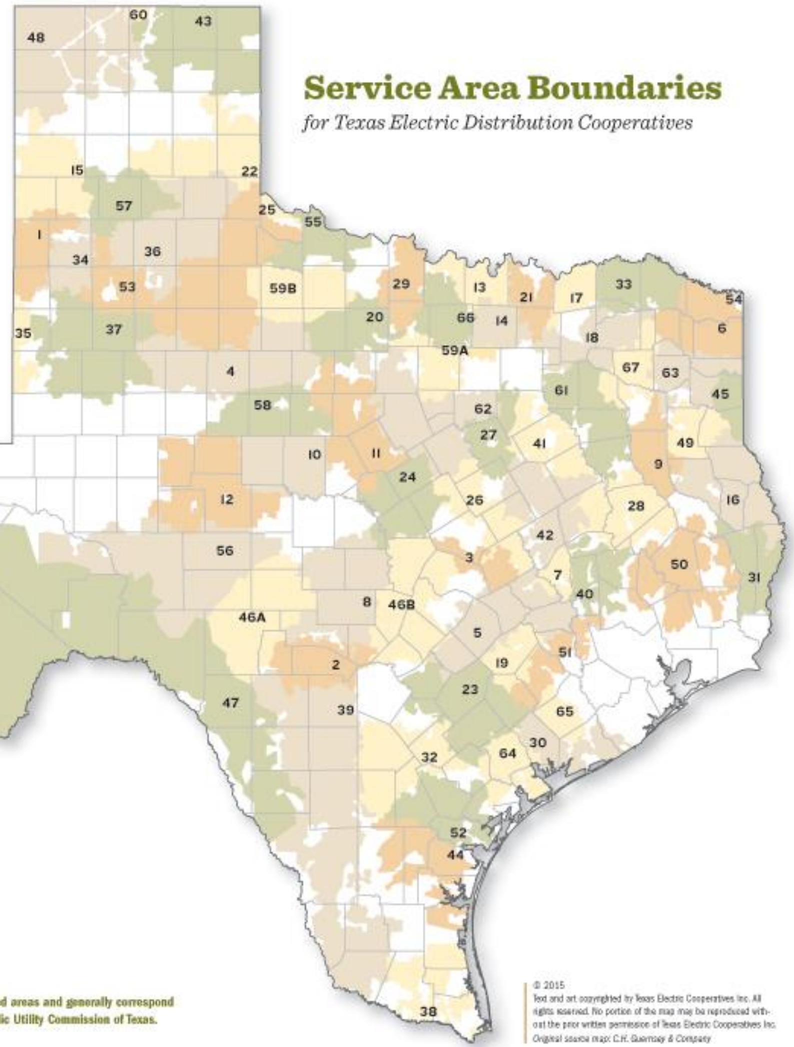
Produced by Edison Electric Institute. Data Source: ABB, Velocity Suite. July 2017

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
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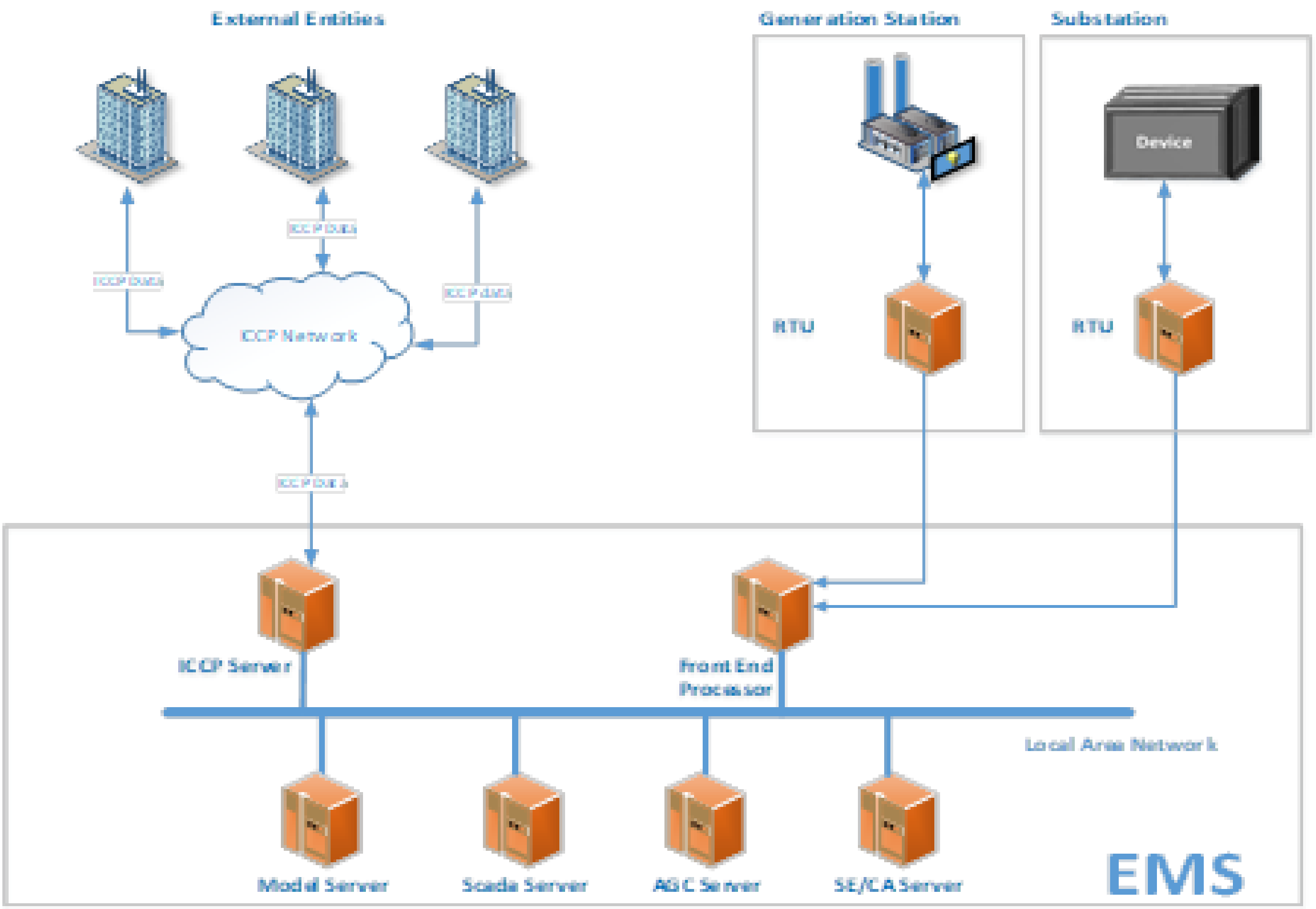
(512) 454-0311 · www.texas-ec.org

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

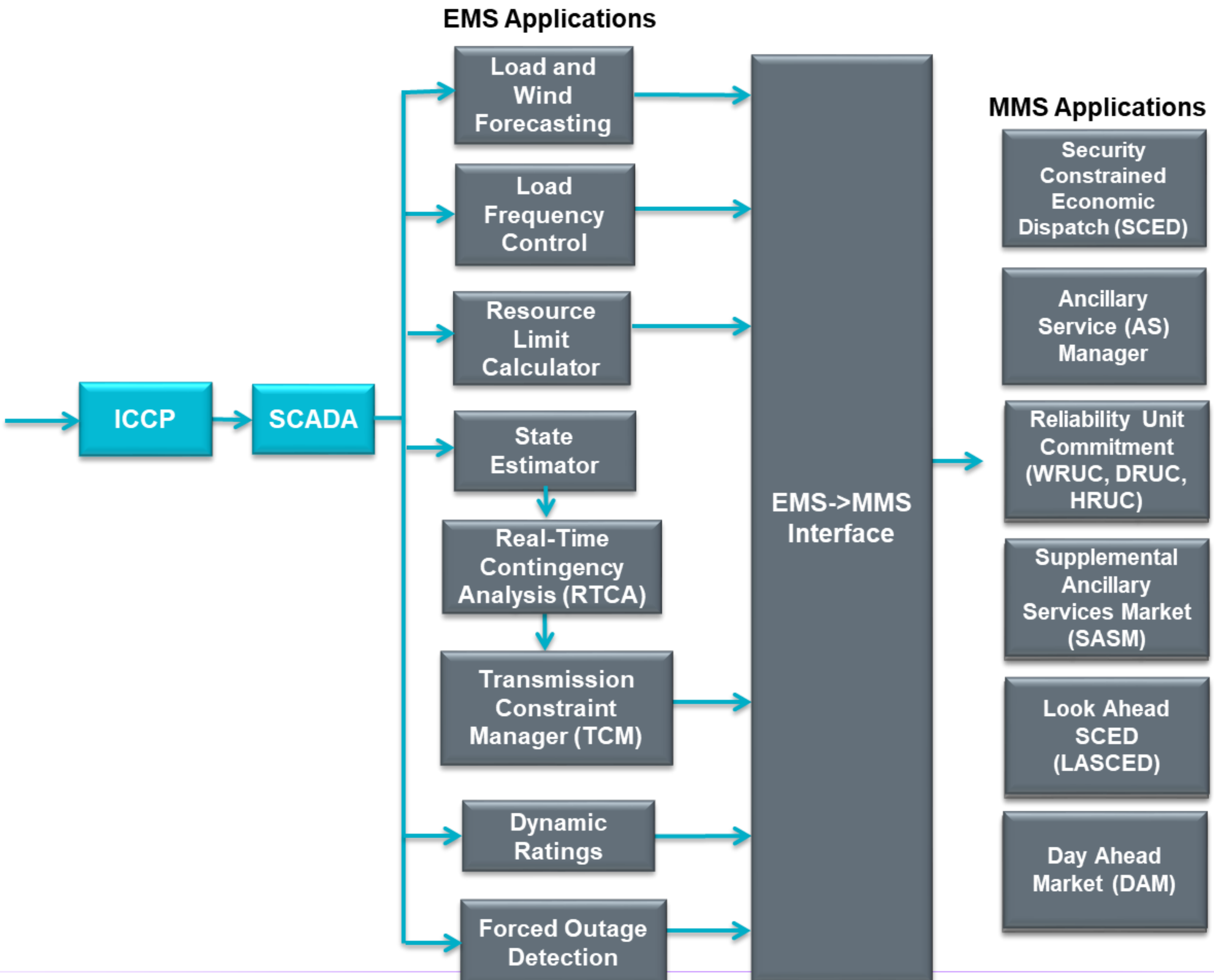
Source: www.texastribune.org/2016/05/17/texas-market-forces-driving-shift-coal-study-says/

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)