ECEN 460
Power System Operation and Control
Spring 2025

Lecture 18: Design Project, Power System Stability

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Design Project Overview

- The goal of the project is to give experience in planning new transmission for a relatively large-scale electric grid while working as part of a four person engineering design team
- Project is motivated by the July 2024 ERCOT report to plan for new transmission in the Permian Basin to accommodate large amounts of new load

Summer Net Coincident Peak Demand Forecast 2024-2033

	COAST	EAST	FWEST	NCENT	NORTH	SCENT	SOUTH	WEST	ERCOT
2024	21,093	2,836	8,348	26,653	2,653	15,223	7,161	2,051	86,017
2025	21,257	2,858	8,760	26,715	4,677	15,707	7,551	2,946	90,472
2026	21,902	2,924	12,784	30,470	5,901	18,851	7,763	5,810	106,405
2027	24,670	2,959	13,915	34,012	6,246	20,411	10,638	8,290	121,140
2028	25,460	2,894	16,142	38,692	8,484	22,372	14,674	8,601	137,319
2029	25,663	2,917	17,264	38,950	8,587	23,092	15,481	8,917	140,872
2030	26,063	2,960	19,083	41,833	8,698	23,637	16,766	8,938	147,977
2031	26,348	2,986	19,588	42,226	8,797	24,023	16,835	8,956	149,758
2032	26,626	3,012	20,085	42,614	8,895	24,404	16,902	8,973	151,510
2033	26,901	3,040	20,567	42,996	8,992	24,776	16,968	8,990	153,230

This includes an assumption of LFL reduction to 15% of normal consumption and includes contracts and officer

ERCOT Permian Basin Reliability Plan Study

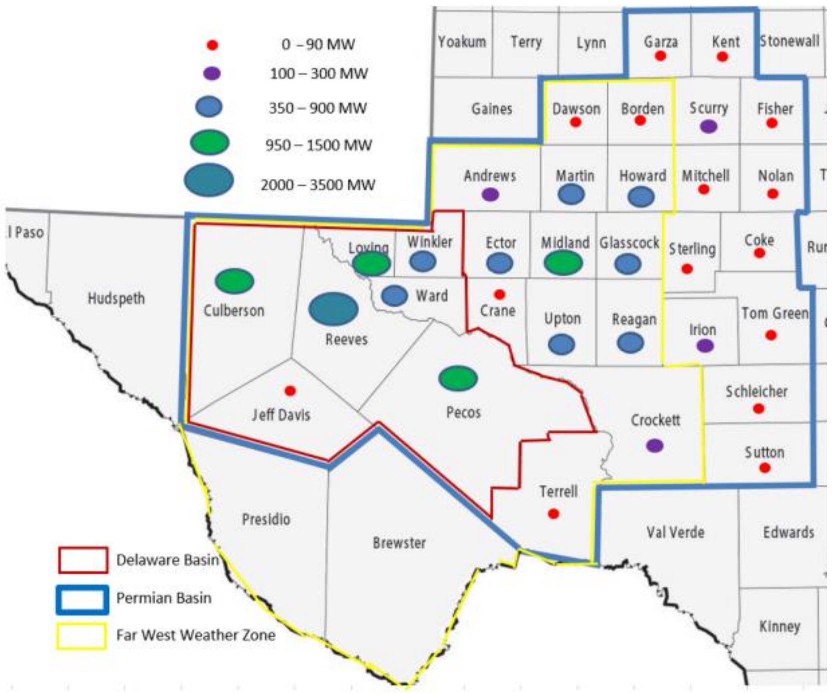
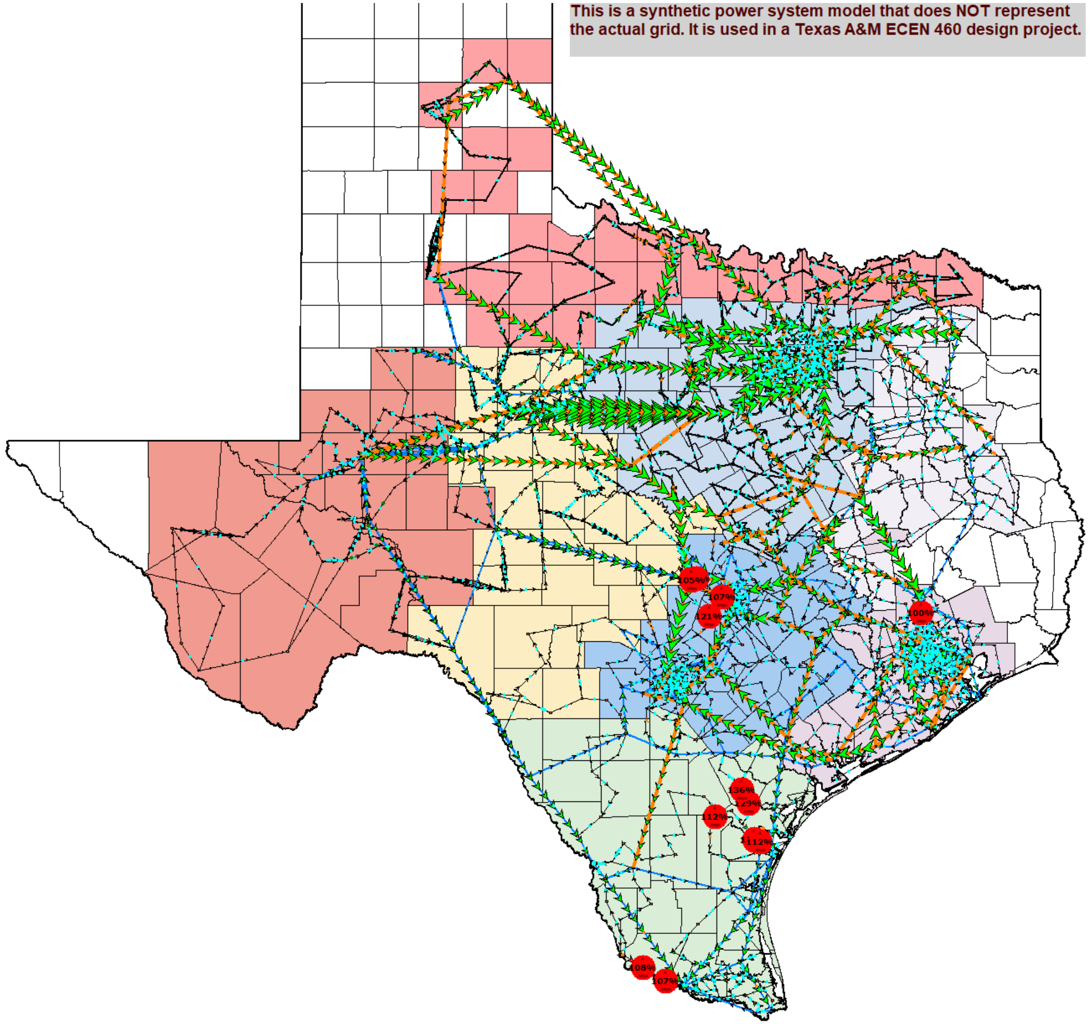


Figure 2.3: County-Level S&P Global Permian Basin Load Forecast in 2039

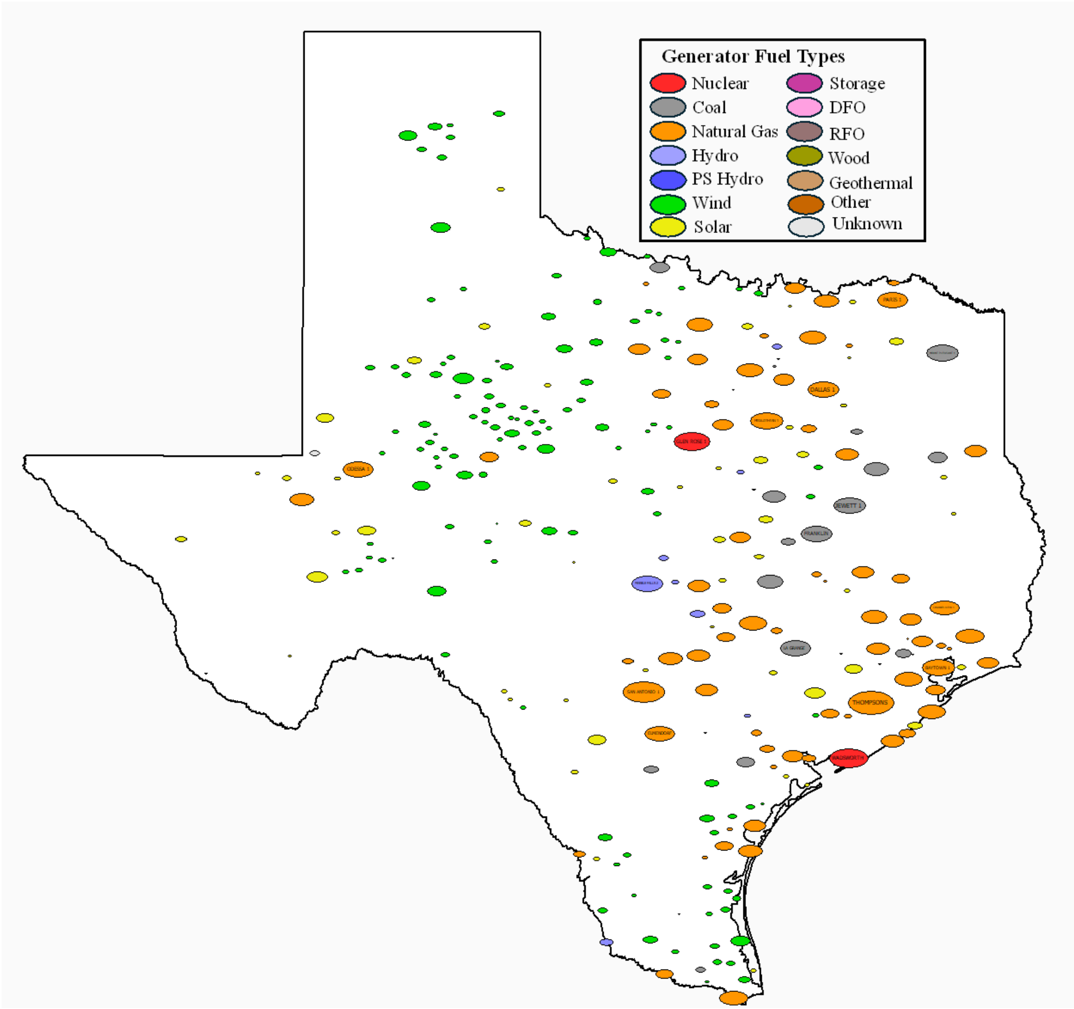
Design Project Overview, cont.

- Since the actual grid models are not publicly available due to them being CEII, you’ll be working with an enhanced version of the 2000 bus grid we’ve been using in 460
  - This enhanced grid has much more wind and solar and a higher load; this grid uses at 500/230/161/115 kV transmission grid
- Your design goal is to optimally provide reliable electricity to 5 new loads in (or close to) the Permian Basin, with each load requiring 1000 MW at 230 kV
- There will be a number of assumptions to simplify the project, including using a DC OPF, only considering four distinct operating points, and ignoring all contingencies except those associated with your new transmission lines and transformers

Design Project Overview: Starting Grid Flows and Generation by Fuel Type



Available generation by fuel type



Design Project Overview: Generation by Fuel Type and Total Generation Supply Curve

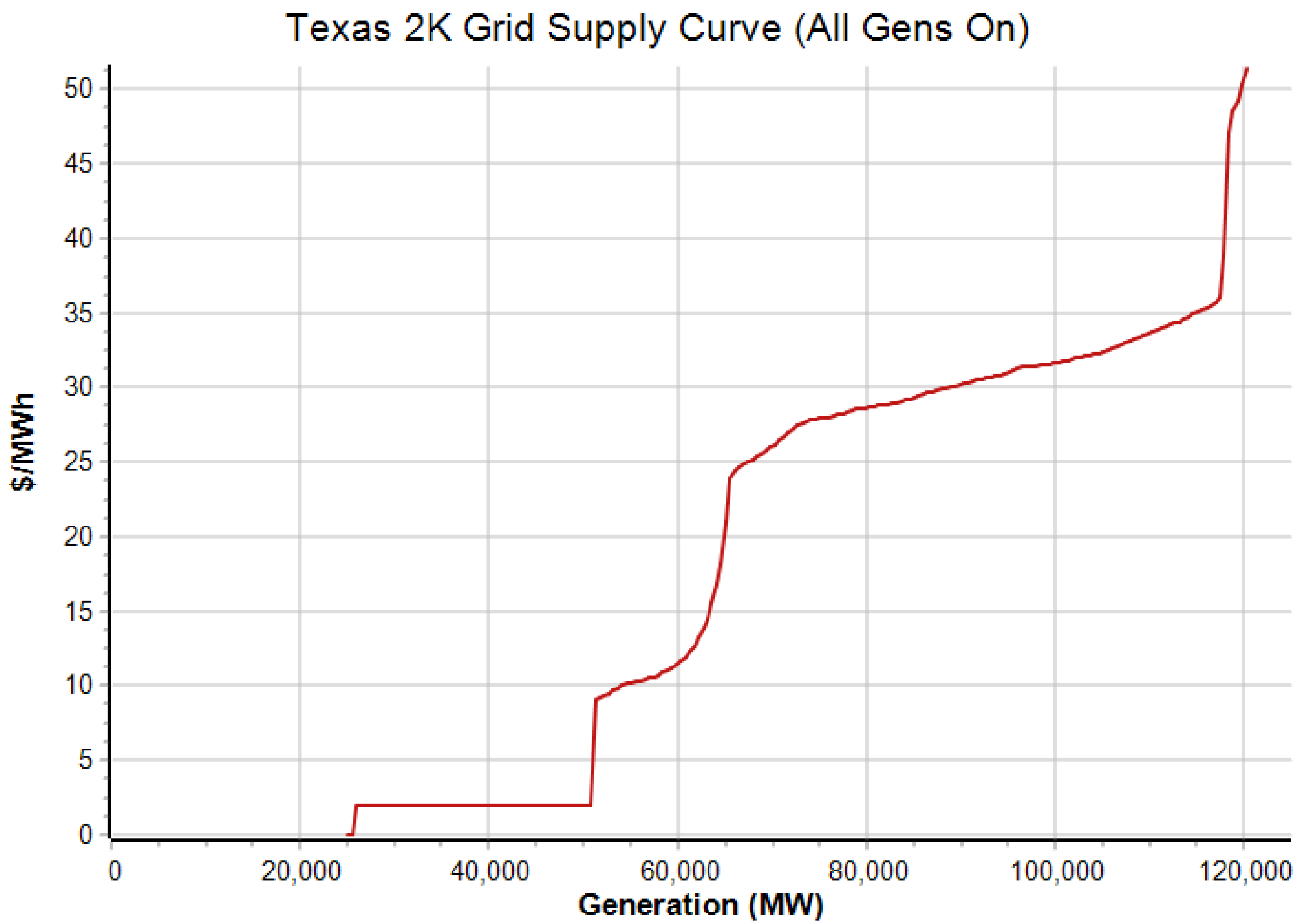
Generation by Generic Fuel Type

Availability by Insevice Date Status

(•) All ( ) Available ( ) Retired ( ) Future

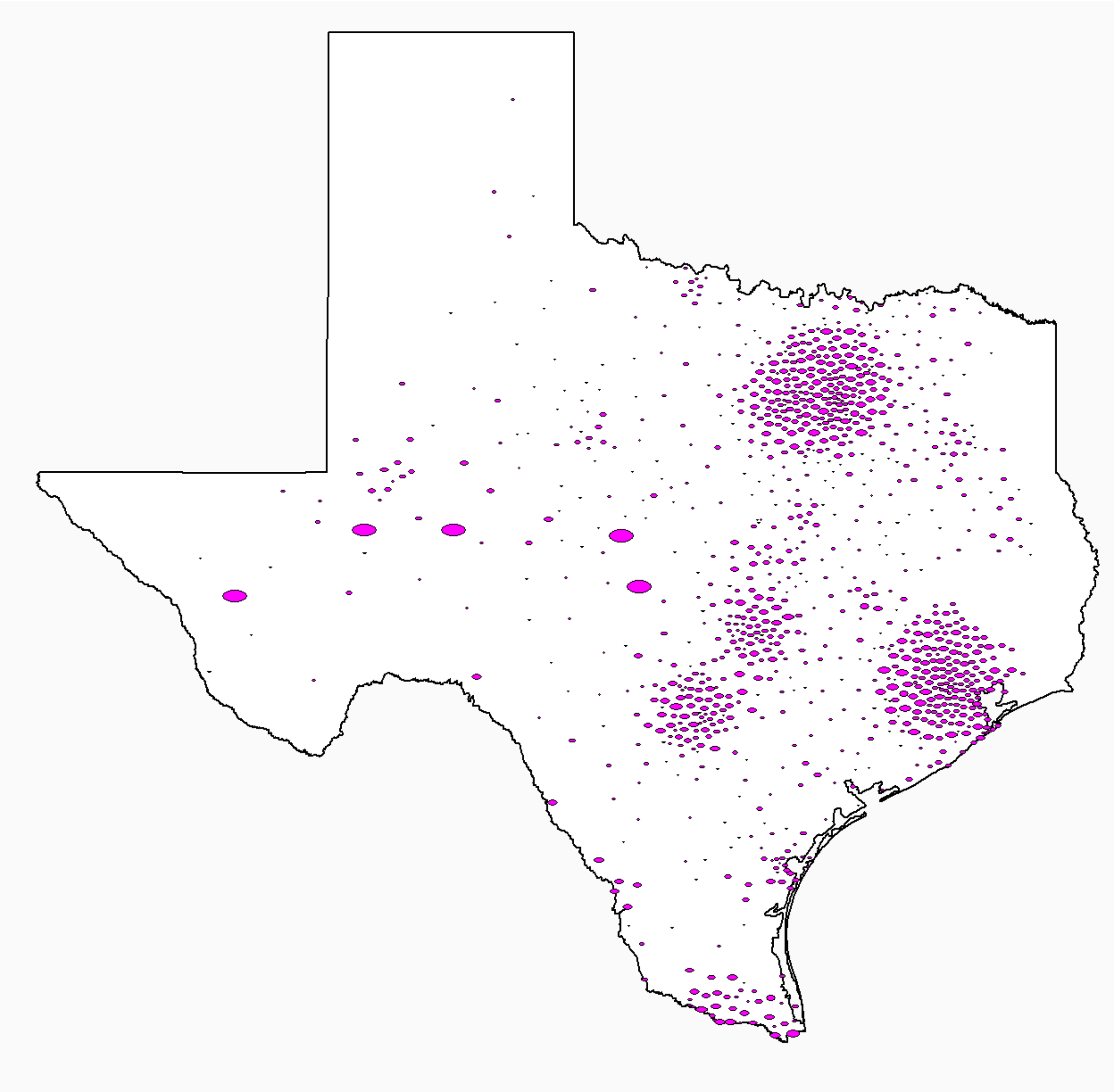
	Actual MW	Max MW (On)	Max MW (All)
Total All	87627.5	120303.9	120303.9
Natural Gas	32744.6	63810.2	63810.2
Coal	13875.2	14501.6	14501.6
Wind	21073.9	22058.4	22058.4
Nuclear	5138.6	5138.6	5138.6
Solar	11327.7	11327.7	11327.7
Hydro	3278.9	3278.9	3278.9
DFO	0.0	0.0	0.0
Storage	0.0	0.0	0.0
Wood/Bio	0.0	0.0	0.0
Jef Fuel	0.0	0.0	0.0
Geothermal	0.0	0.0	0.0
HydroPS	0.0	0.0	0.0
Waste Heat	0.0	0.0	0.0
RFO	0.0	0.0	0.0
Other	0.0	0.0	0.0
Unknown	188.5	188.5	188.5

Supply Curve



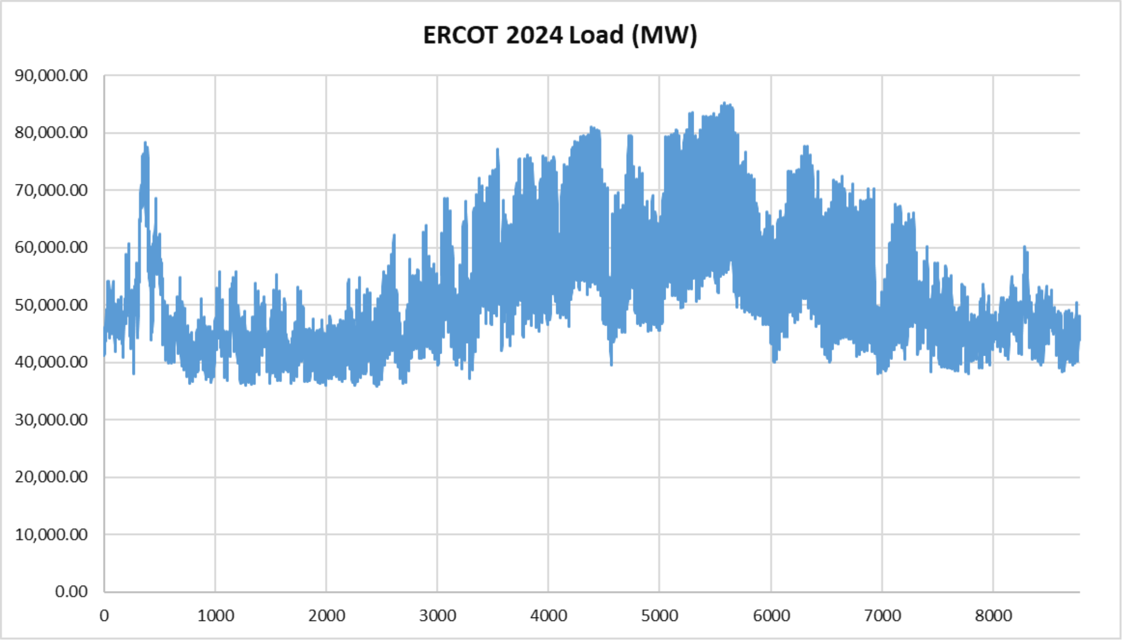
Existing and New Load

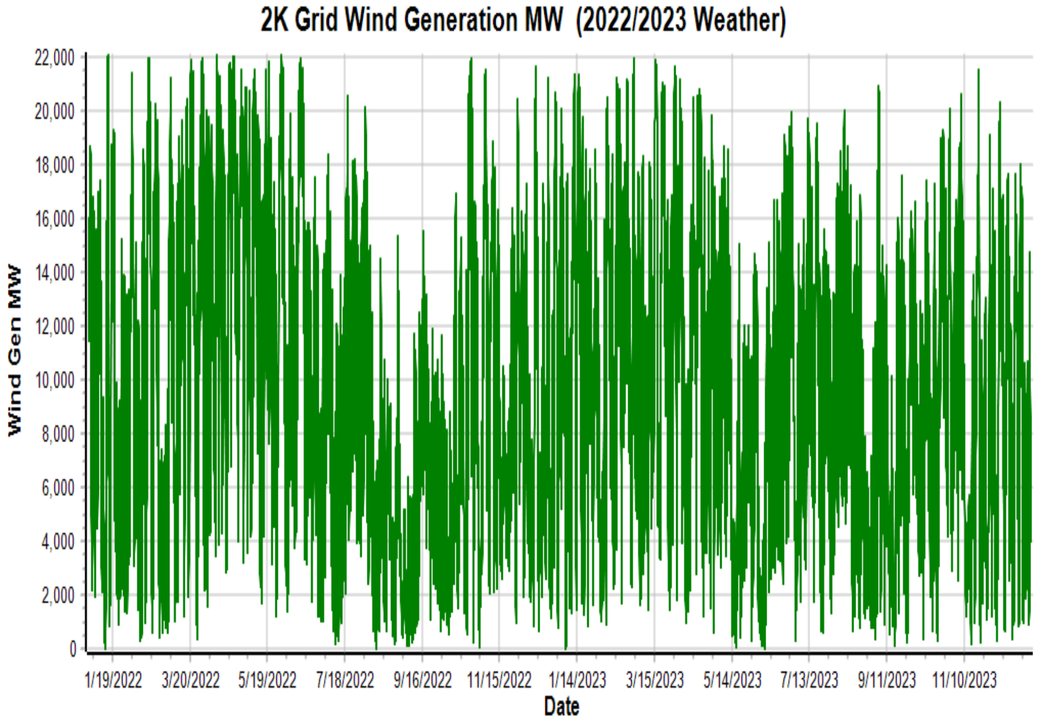
- This image shows the existing loads, with the ovals proportional to the load
  - A layout algorithm has been used to remove overlap, somewhat expanding the large metro areas
- The five large ovals towards the left represent the new, currently not connected, load



Design Project Scenarios

- A transmission system design needs to work well under varying system conditions. In ERCOT key system variations are due to 1) the changing load, and 2) varying amounts of wind and solar generation





Design Project Scenarios, Cont.

- To simplify the design project, we'll just be considering four scenarios, with the assumption that the system operates in each scenario for 25% of the time
  - Maximum load, with maximum wind and solar available (**Texas2K_ScenarioA**)
  - 80% load with high solar, low wind (August 15, 2023 at 4 pm) (**Texas2K_ScenarioB)**
  - 70% load with low solar, low wind (August 25, 2022 at 9 am) (**Texas2K_ScenarioC)**
  - 60% load with medium wind, no solar (May 2, 2023 at 2 am) (**Texas2K_ScenarioD)**
  - In all scenarios the five new loads stay fixed at 1000 MW each
- Assume transmission right-of-way (ROW) lengths are 120% of the geographic distance between the substations;
  - there are many online tools to allow you to calculate geographic distance (e.g., www.nhc.noaa.gov/gccalc.shtml)

Design Project Lines and Transformers

- To serve the new loads you'll need to modify the grids by adding some combination of
  - 500 kV lines with a fixed cost of $15 million and variable costs of $3 million per mile; X=0.0002 pu per mile, rating of 1600 MVA, max ROW length of 200 miles
  - 230 kV lines with a fixed cost of $8 million and variable costs of $1.3 million per mile, X=0.0012 pu per mile, rating of 400 MVA, max ROW length of 115 miles
  - 500 kV/230 kV transformers with a total cost of $12 million, X=0.015, MVA of 1100
  - 230/115 kV transformers with a total cost of $1.8 million, X=0.05, MVA of 200
  - Upgrading a 230 kV substation to 500KV is $8 million; a new 500 kV substations costs $11 million plus an extra $2.5 million to also include 230 kV. A new 230 kV substation costs $ 6 million.
  - Existing lines cannot be modified except you can open them if desired. Do not make any new connections with the existing 161 kV lines

Adding New Simulator Objects via Spreadsheet

- Simulator has a number of ways to automate the addition of new objects (e.g., lines, transformers, buses and substations) or modifying existing objects
- One approach is in the **Edit Mode** to paste new objects into a **Case Information Display** from a spreadsheet
- Pasting requires 1) the spreadsheet has a description of the data in the first row and column (e.g., **Substation**, **Bus**, **Branch**), 2) Key and Required field headers in the second row, and then 3) data in subsequent rows
  - Examples are included in the **Example_Design_Changes .xls** file

Example_Design_Changes File

- This file is used to create a new 500/230 kV substation, adding two new buses, a transformer between the buses, and two transmission lines connecting it to other buses; first paste in the substation data, then the buses, then the lines

	A	B	C	D	E
1	Substation				
2	Sub Num	Sub Name	Sub ID	Latitude	Longitude
3	2005	Sub2005	2005	30.3	-99.5

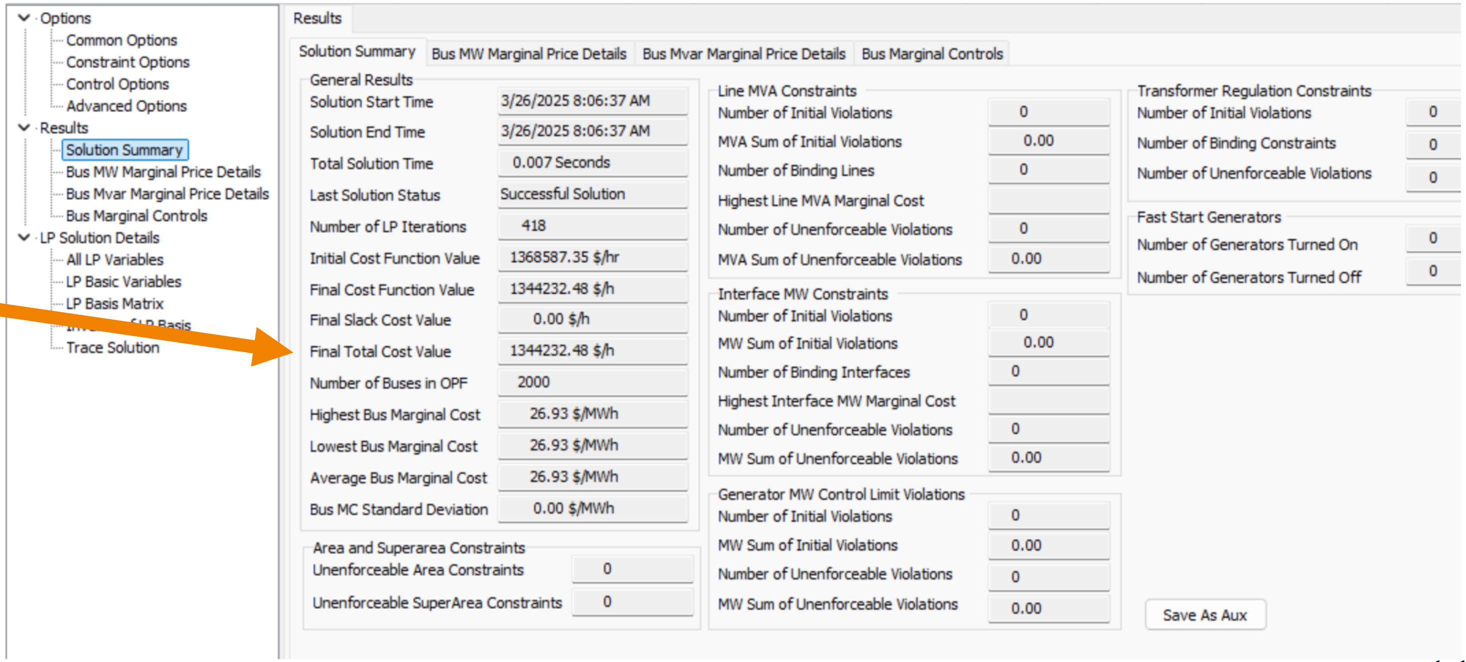
	A	B	C	D	E	F	G	H
1	Bus							
2	Number	Sub Num	Name	Nom kV	PU Volt	Angle (Deg	Area Num	Zone Num
3	1103	2005	Example500	500	1	0	1	9
4	1104	2005	Example230	230	1	0	1	9

	A	B	C	D	E	F	G	H	I	J	K
1	Branch										
2	From Num	To Numbe	Circuit	Status	Branch De	Xfrmr	R	X	Lim MVA A	Lim MVA B	Lim MVA C
3	1103	1104	NE	Closed	Transform	Yes	0	0.015	1100	1100	1100
4	1103	6045	NE	Closed	Line	No	0	0.0173	1600	1600	1600
5	1104	3201	NE	Closed	Line	No	0	0.1	400	400	400

DC OPF Solutions

- With the new transmission grid additions, for each scenario you'll ultimately be solving a DC OPF solution
- A key value from the solution is the Final Total Cost Value in $/hr
  - This is shown on the **Add Ons, OPF Case Info, OPF Options and Results** dialog, **Solution Summary Page**

It is OK to have some congestions, but there should be no unenforceable constraints



Your Goal

- The overall goal is to minimize the sum of the **total yearly production cost** plus 0.129 times the new transmission costs
  - The **total yearly production cost** is calculated assuming the grid operates in each of the four scenarios for 25% of the time over a year (i.e., 2190 hours each). So, to get the **total yearly production cost** sum the **Total Final Cost Values** for each of the four scenarios and multiply by 2190.
  - The 0.129 (12.9%) is based on the value ERCOT uses in their production cost savings test associated with the first-year annual revenue requirement
- Example: if the hoursly costs for the scenarios are 1.6, 1.4, 1.2 and 1.0 million dollars per hour, and your total transmission costs are two billion dollars, then the total value in million dollars is 2190*(1.6 + 1.4 + 1.2 + 1.0) + 0.129*2000 = $11.646 billion

You are Encouraged to Read the ERCOT Report

- It will be included with the design project. This image is a solution presented in the report. However, they are designing for the existing 345/138 kV grid, not your 500/161 kV grid
- The ERCOT report is estimating costs on the order of $ 13 billion

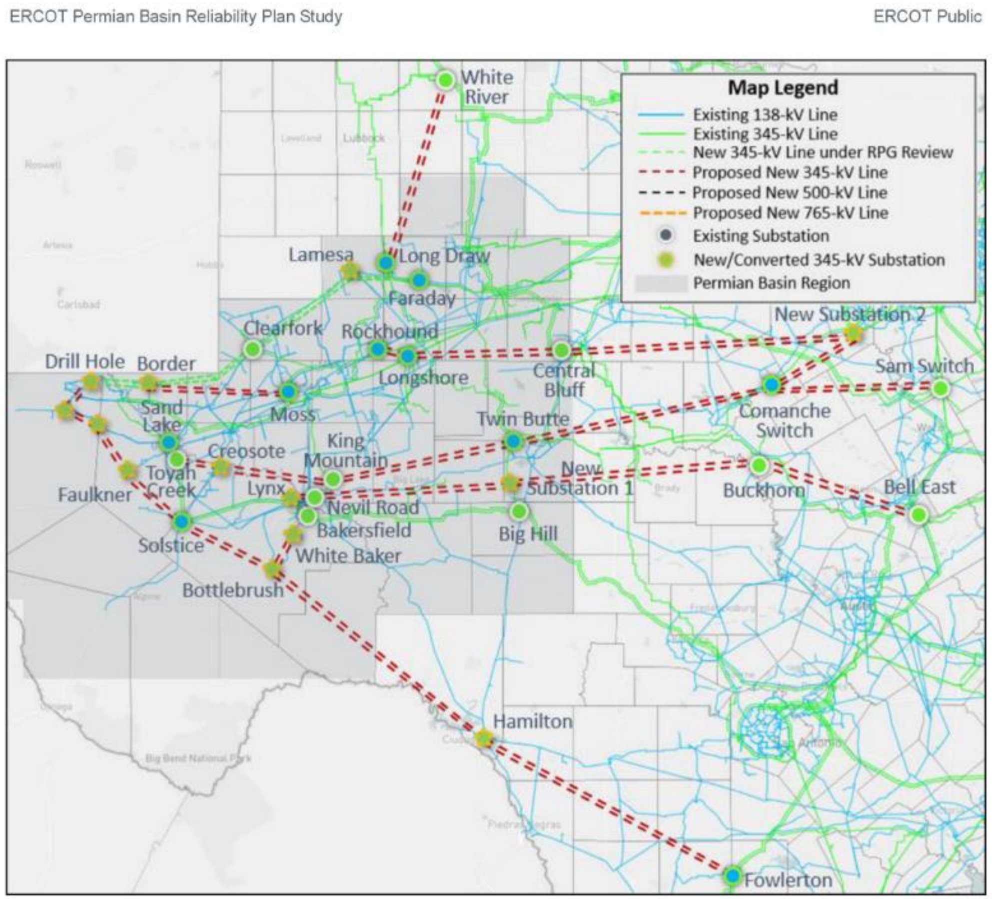
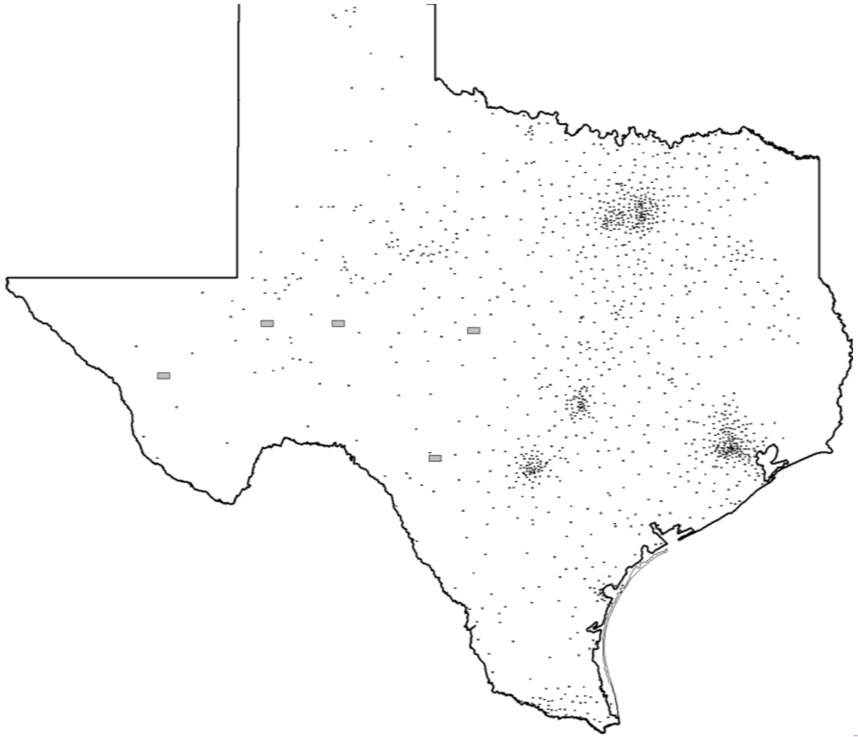
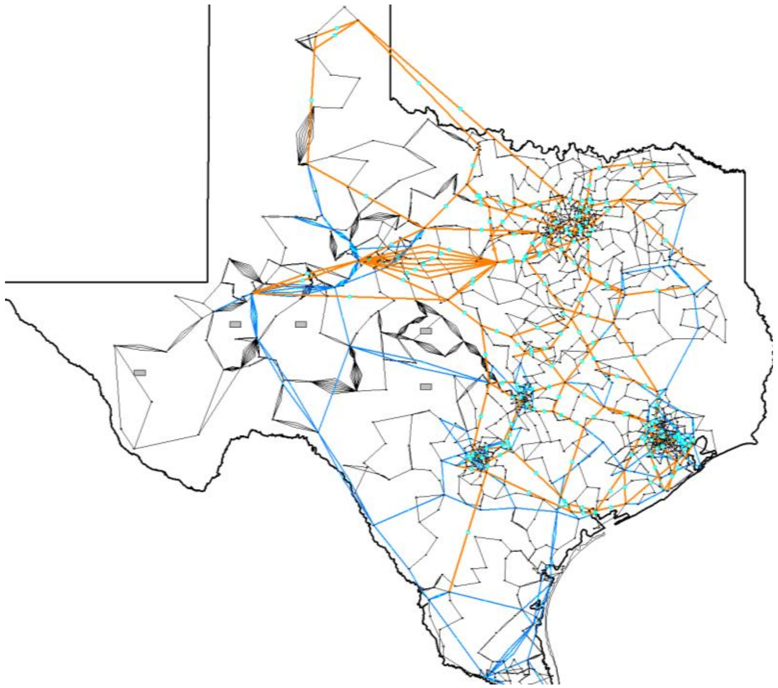


Figure 5.8: 345-kV Import Paths in 2038 (Includes Import Paths Needed in 2030)

Quickly Auto-Drawing a Transmission Grid

- Simulator does make it extremely easy to auto-draw a transmission grid. To do this with one of the design project cases open, open the oneline **Texas_2K_SubGDVDesign**; then in the **Edit Mode** select **Draw, Auto Insert, Lines** (click **Default Drawing Values** to Customize), click **OK**





Switching Back to Dynamics: Differential Algebraic Equations

- Because of the complexity of modern electric grid, stability is determined using numerical techniques. Many problems, including many in the power area, can be formulated as a set of differential, algebraic equations (DAE) of the form

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

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

- A power example is transient stability, in which **f** represents (primarily) the generator dynamics, and **g** (primarily) the bus power balance equations
- We'll initially consider the simpler problem of just

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x})$$

Ordinary Differential Equations (ODEs)

- Assume we have a problem of the form

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) \quad \text{with } \mathbf{x}(t_0) = \mathbf{x}_0$$

- This is known as an initial value problem, since the initial value of $\mathbf{x}$ is given at some time t_0
  - We need to determine $\mathbf{x}(t)$ for future time
  - Initial value, $\mathbf{x}_0$, must be either be given or determined by solving for an equilibrium point, $\mathbf{f}(\mathbf{x}) = \mathbf{0}$
  - Higher-order systems can be put into this first order form
- Except for special cases, such as linear systems, an analytic solution is usually not possible – numerical methods must be used

Initial value Problem Examples

Example 1: Exponential Decay

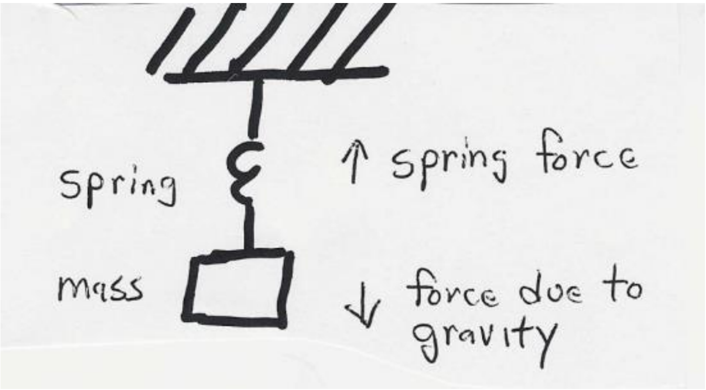
A simple example with an analytic solution is

$$\dot{x} = -x \quad \text{with } x(0) = x_0$$

This has a solution $x(t) = x_0 e^{-t}$

Example 2: Mass-Spring System

Example 2 is similar to the SMIB swing equation



$$kx - gM = M\ddot{x} + D\dot{x}$$

or

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = \frac{1}{M}\left(k x_1 - g M - D x_2\right)$$

Numerical Solution Methods

- Numerical solution methods do not generate exact solutions; they practically always introduce some error
  - Methods assume time advances in discrete increments, called a stepsize (or time step), Δt
  - Speed accuracy tradeoff: a smaller Δt usually gives a better solution, but it takes longer to compute
  - Numeric round-off error due to finite computer word size
- Key issue is the derivative of **x, f(x)** depends on **x**, the value we are trying to determine
- A solution exists as long as **f**(**x**) is continuously differentiable

Numerical Solution Methods

- There are a wide variety of different solution approaches, we will only touch on two
- One-step methods: require information about solution just at one point, $\mathbf{x}(t)$
  - Forward Euler
  - Runge-Kutta
- Multi-step methods: make use of information at more than one point, $\mathbf{x}(t)$, $\mathbf{x}(t-\Delta t)$, $\mathbf{x}(t-\Delta 2t)$…
  - Adams-Bashforth
- Predictor-Corrector Methods: implicit
  - Backward Euler

Error Propagation

- At each time step the total round-off error is the sum of the local round-off at time and the propagated error from steps $1, 2, \ldots, k-1$
- An algorithm with the desirable property that local round-off error decays with increasing number of steps is said to be numerically stable
- Otherwise, the algorithm is numerically unstable
- Numerically unstable algorithms can nevertheless give quite good performance if appropriate time steps are used
  - This is particularly true when coupled with algebraic equations

Euler's Method

- The simplest technique for numerically integrating these equations is known as Euler's method, which dates to about 1768
- The key idea is to approximate

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}(t)) = \frac{\mathrm{d}\mathbf{x}}{\mathrm{dt}} \text{ as } \frac{\Delta\mathbf{x}}{\Delta \mathrm{t}}$$

- Then

$$\mathbf{x}(t+\Delta t) \approx \mathbf{x}(t) + \Delta t\, \mathbf{f}(\mathbf{x}(t))$$

- In general, the smaller the time step, Δt, the better the approximation

Euler's Method Algorithm

Set t = t_0 (usually 0)

$$\mathbf{x}(t_0) = \mathbf{x}_0$$

Pick the time step Δt, which is problem specific

While $t \leq t^{end}$ Do

$$\mathbf{x}(t+\Delta t) = \mathbf{x}(t) + \Delta t\,\mathbf{f}(\mathbf{x}(t))$$

$$t = t + \Delta t$$

End While

Euler's Method Example 1, cont'd

- Consider the exponential decay example with

$$\dot{x} = -x \qquad \text{with } x(0) = x_0$$

This has a solution $x(t) = x_0 e^{-t}$

- Since we know the solution, we can compare the accuracy of Euler's method for different time steps

t	$x^{actual}(t)$	x(t) Δt=0.1	x(t) Δt=0.05
0	10	10	10
0.1	9.048	9	9.02
0.2	8.187	8.10	8.15
0.3	7.408	7.29	7.35
…	…	…	…
1.0	3.678	3.49	3.58
…	…	…	…
2.0	1.353	1.22	1.29

Euler's Method Example 2

Consider the equations describing the horizontal position of a cart attached to a lossless spring:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = -x_1$$

Assuming initial conditions of $x_1(0) = 1$ and $x_2(0) = 0$, the analytic solution is $x_1(t) = \cos t$.

We can again compare the results of the analytic and numerical solutions

Euler's Method Example 2, cont'd

Starting from the initial conditions at t =0 we next calculate the value of x(t) at time t = 0.25.

$$\begin{aligned} x_1(0.25) &= x_1(0) + 0.25\,x_2(0) &&= 1.0 \\ x_2(0.25) &= x_2(0) - 0.25\,x_1(0) &&= -0.25 \end{aligned}$$

Then we continue on to the next time step, t = 0.50

$$\begin{aligned} x_1(0.50) &= x_1(0.25) + 0.25\,x_2(0.25) &&= \\ &= 1.0 + 0.25 \times (-0.25) &&= 0.9375 \\ x_2(0.50) &= x_2(0.25) - 0.25\,x_1(0.25) &&= \\ &= -0.25 - 0.25 \times (1.0) &&= -0.50 \end{aligned}$$

Euler's Method Example 2, cont'd

t	$x_1^{actual}(t)$	$x_1(t)$ Δt=0.25
0	1	1
0.25	0.9689	1
0.50	0.8776	0.9375
0.75	0.7317	0.8125
1.00	0.5403	0.6289
…	…	…
10.0	-0.8391	-3.129
100.0	0.8623	-151,983

Since we know from the exact solution that x_1 is bounded between -1 and 1, clearly the method is not working well, and is actually numerically unstable. Below is a comparison of the solution values for $x_1(t)$ at time t = 10 seconds

Δt	$x_1(10)$
actual	-0.8391
0.25	-3.129
0.10	-1.4088
0.01	-0.8823
0.001	-0.8423

Second Order Runge-Kutta Method

- Runge-Kutta methods improve on Euler's method by evaluating **f**(**x**) at selected points over the time step
- Simplest method is the second order method in which

$$\mathbf{x}(t+\Delta t) = \mathbf{x}(t) + \frac{1}{2}(\mathbf{k}_1 + \mathbf{k}_2)$$

where

$$\mathbf{k}_1 = \Delta t\ \mathbf{f}\left(\mathbf{x}(t)\right)$$

$$\mathbf{k}_2 = \Delta t\ \mathbf{f}\left(\mathbf{x}(t) + \mathbf{k}_1\right)$$

- That is, $\mathbf{k}_1$ is what we get from Euler's; $\mathbf{k}_2$ improves on this by reevaluating at the estimated end of the time step

RK2 Oscillating Cart

- Consider the same example from before the position of a cart attached to a lossless spring. Again, with initial conditions of $x_1(0) = 1$ and $x_2(0) = 0$, the analytic solution is $x_1(t) = \cos(t)$

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -x_1$$

- With $\Delta t = 0.25$ at $t = 0$

$$\mathbf{k}_1 = (0.25) \times \begin{bmatrix} 0 \\ -1 \end{bmatrix} = \begin{bmatrix} 0 \\ -0.25 \end{bmatrix}, \quad \mathbf{x}(0) + \mathbf{k}1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ -0.25 \end{bmatrix} = \begin{bmatrix} 1 \\ -0.25 \end{bmatrix}$$

$$\mathbf{k}_2 = (0.25) \times \mathbf{f}\left(\mathbf{x}(0) + \mathbf{k}_1\right) = \begin{bmatrix} -0.0625 \\ -0.25 \end{bmatrix}, \quad \mathbf{x}(0.25) = \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \frac{1}{2}\left(\mathbf{k}_1 + \mathbf{k}_2\right) = \begin{bmatrix} 0.96875 \\ -0.25 \end{bmatrix}$$

Comparison

- The below table compares the numeric and exact solutions for $x_1(t)$ using the RK2 algorithm

time	actual $x_1(t)$	$x_1(t)$ with RK2 $\Delta t=0.25$
0	1	1
0.25	0.9689	0.969
0.50	0.8776	0.876
0.75	0.7317	0.728
1.00	0.5403	0.533
10.0	-0.8391	-0.795
100.0	0.8623	1.072

The below table compares the $x_1(10)$ values for different values of Δt; recall with Euler's with $\Delta t=0.1$ was -1.41 and with 0.01 was -0.8823

Δt	$x_1(10)$
actual	-0.8391
0.25	-0.7946
0.10	-0.8310
0.01	-0.8390
0.001	-0.8391

RK2 Versus Euler's

- RK2 requires twice the function evaluations per iteration, but gives much better results
- With RK2 the error tends to vary with the cube of the step size, compared with the square of the step size for Euler's
- The smaller error allows for larger step sizes compared to the Euler Method

Multistep Methods

- Euler's and Runge-Kutta methods are single step approaches, in that they only use information at **x**(t) to determine its value at the next time step
- Multistep methods take advantage of the fact that using we have information about previous time steps **x**(t-Δt), **x**(t-2Δt), etc
- These methods can be explicit or implicit (dependent on **x**(t+Δt) values; we'll just consider the explicit Adams-Bashforth approach

Second Order

$$\mathbf{x}(t+\Delta t) = \mathbf{x}(t) + \frac{\Delta t}{2}\big(3\mathbf{f}(\mathrm{x}(t)) - \mathbf{f}(x(t-\Delta t))\big) + O(\Delta t^3)$$

Third Order

$$\mathbf{x}(t+\Delta t) = \mathbf{x}(t) + \frac{\Delta t}{12}\big(23\mathbf{f}(\mathrm{x}(t)) - 16\mathbf{f}(x(t-\Delta t)) + 5\mathbf{f}(x(t-2\Delta t))\big) + O(\Delta t^4)$$

Numerical Instability

- All explicit methods can suffer from numerical instability if the time step is not correctly chosen for the problem eigenvalues

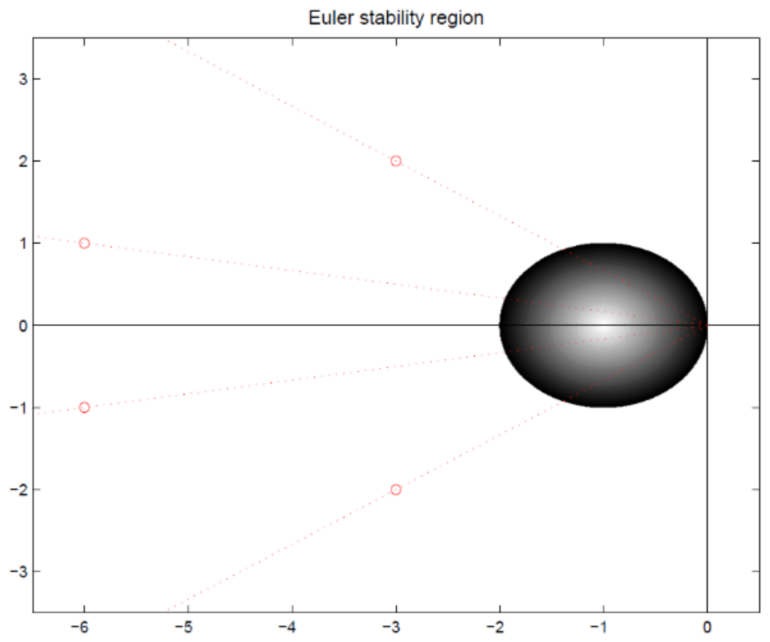


Figure 10.2: The spectrum of A is scaled by h. Stability of the origin is recovered if $h\lambda$ is in tl
region of absolute stability $|1+z|<1$ in the complex plane.

Values are scaled by the time step; the shape for RK2 has similar dimensions but is closer to a square. Key point is to make sure the time step is small enough relative to the eigenvalues.

Image source: http://www.staff.science.uu.nl/~frank011/Classes/numwisk/ch10.pdf

Implicit

- Implicit solution methods have the advantage of being numerically stable over the entire left half plane
- Only method considered here is the Backward Euler

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}(t)) = \mathbf{A}\mathbf{x}(t))$$

Then using backward Euler

$$\mathbf{x}(t+\Delta t) = \mathbf{x}(t) + \Delta t\, \mathbf{A}(\mathbf{x}(t+\Delta t))$$

$$\left[I - \Delta t\, \mathbf{A}\right]\mathbf{x}(t+\Delta t) = \mathbf{x}(t)$$

$$\mathbf{x}(t+\Delta t) = \left[I - \Delta t\, \mathbf{A}\right]^{-1}\mathbf{x}(t)$$

We'll only consider linear equations

Backward Euler Cart Example

- Returning to the cart example

$$\dot{\mathbf{x}} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \mathbf{x}(t))$$

Then using backward Euler with $\Delta t = 0.25$

$$\mathbf{x}(t+\Delta t) = [I - \Delta t\,\mathbf{A}]^{-1}\mathbf{x}(t) = \begin{bmatrix} 1 & -0.25 \\ 0.25 & 1 \end{bmatrix}^{-1} \mathbf{x}(t)$$

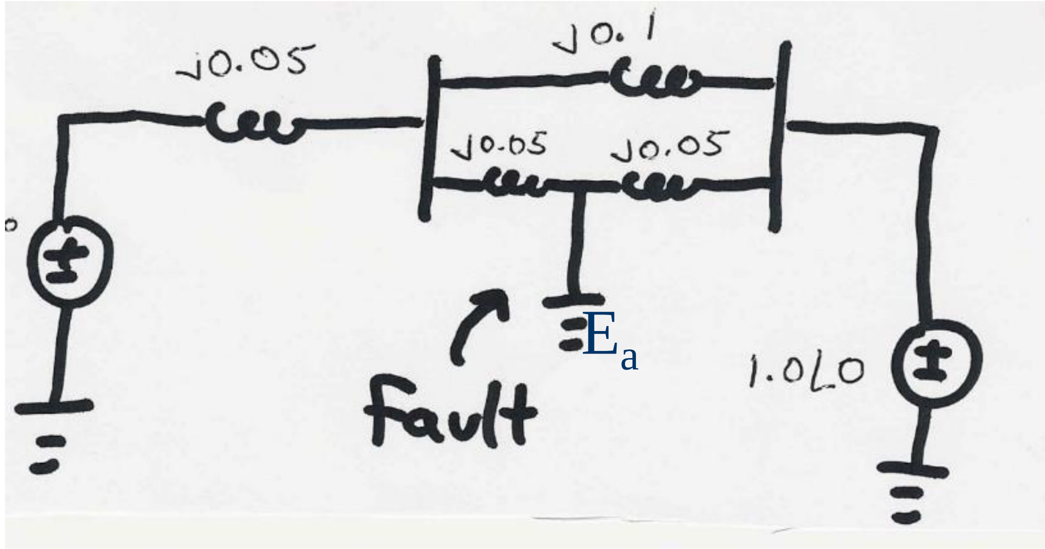
Note: Just because the method is numerically stable doesn't mean it is error free! RK2 is more accurate than backward Euler with a small enough timestep.

Results with Δt = 0.25 and 0.05

time	actual $x_1(t)$	$x_1(t)$ with Δt=0.25	$x_1(t)$ with Δt=0.05
0	1	1	1
0.25	0.9689	0.9411	0.9629
0.50	0.8776	0.8304	0.8700
0.75	0.7317	0.6774	0.7185
1.00	0.5403	0.4935	0.5277
2.00	-0.416	-0.298	-0.3944

Transient Stability Example

- A 60 Hz generator is supplying 550 MW to an infinite bus (with 1.0 per unit voltage) through two parallel transmission lines. Determine initial angle change for a fault midway down one of the lines.
  H = 20 seconds, D = 0.1. Use Δt = 0.01 second.



Transient Stability Example, cont'd

We first need to determine the pre-fault values.

Since P = 550 MW (5.5 pu) $\rightarrow$ I = 5.5 $\rightarrow$

$$\mathrm{E_a} = 1.0 + j0.1 \times 5.5 = 1.141\angle 28.8°$$

Next to get $\mathrm{P_e}(\delta)$ we need to determine the thevenin equivalent during the fault looking into the network from the generator

$$Z_{th} \quad = \quad j0.05 + j0.05 \parallel j0.1 = j0.08333$$

$$V_{th} \quad = \quad 0.3333\angle 0°$$

Transient Stability Example, cont'd

Therefore prefault we have $P_e^{prefault}(\delta) = \dfrac{1.141 \times 1.0}{0.1} \sin\delta$

and $P_m = 5.5 \rightarrow \ \delta(0) = 28.8° \rightarrow \delta(0) = 0.50265$ radians

and during the fault $P_e^{faulted}(\delta) = \dfrac{1.141 \times 0.3333}{0.08333} \sin\delta$

Let $x_1 = \delta$ and $x_2 = \dot{\delta}$. The equations to integrate are

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = \frac{1}{20/60\pi}\left(5.5 - \frac{1.141 \times 0.3333}{0.08333} \sin x_1 - 0.1 x_2\right)$$

$$x_1(0) = 0.50265 \qquad x_2(0) = 0.0$$

Transient Stability Example, cont'd

$$\begin{aligned}\dot{x}_1 &= x_2\\ \dot{x}_2 &= 9.425\left(5.5-4.564\sin x_1-0.1x_2\right)\\ \mathbf{x}(0) &= \begin{bmatrix}0.50265\\ 0\end{bmatrix}\end{aligned}$$

With Euler's Method we get

$$\mathbf{x}(0.01) = \begin{bmatrix}0.50265\\ 0\end{bmatrix}+0.01\times\begin{bmatrix}0\\ 31.11\end{bmatrix}=\begin{bmatrix}0.50265\\ 0.3111\end{bmatrix}$$

$$\mathbf{x}(0.02) = \begin{bmatrix}0.50265\\ 0.3111\end{bmatrix}+0.01\times\begin{bmatrix}0.3111\\ 30.82\end{bmatrix}=\begin{bmatrix}0.50576\\ 0.6193\end{bmatrix}$$

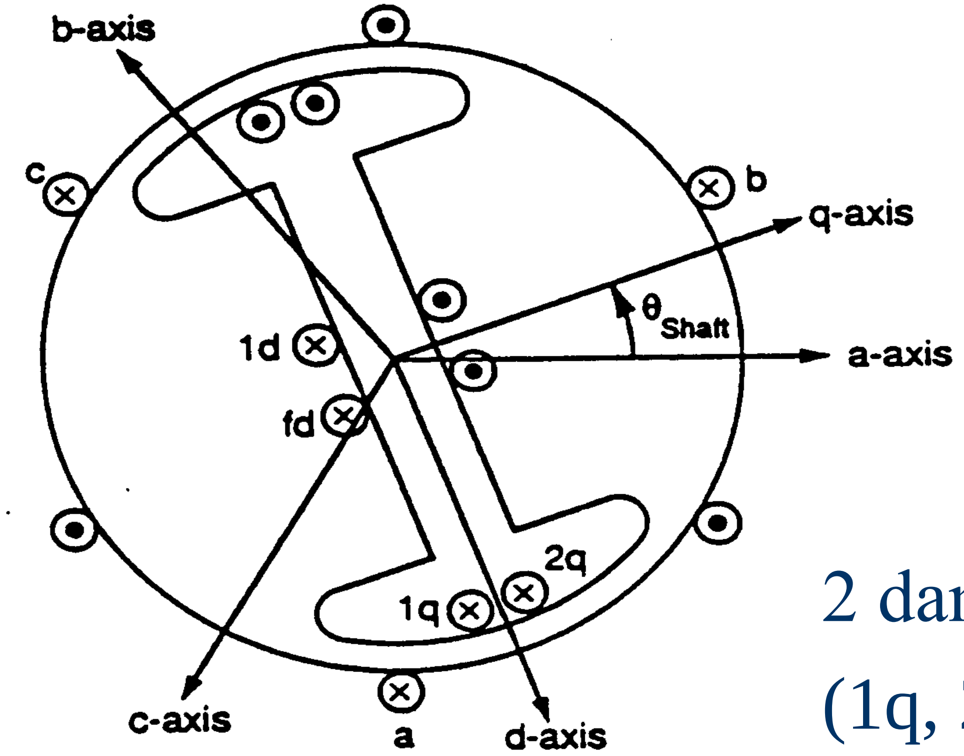
Two-Axis Synchronous Machine Model

- Classical model is appropriate only for the most basic studies; no longer widely used in practice
- More realistic models are required to couple in other devices such as exciters and governors
- A more realistic synchronous machine model requires that the machine be expressed in a reference frame that rotates at rotor speed
- Standard approach is d-q reference frame, in which the major (direct or d-axis) is aligned with the rotor poles and the quadrature (q-axis) leads the direct axis by 90°

Synchronous Machine Modeling

3ϕ bal. windings (a,b,c) – stator

Damper windings are added to help damp out oscillations



Field winding (fd) on rotor

Damper in "d" axis (1d) on rotor

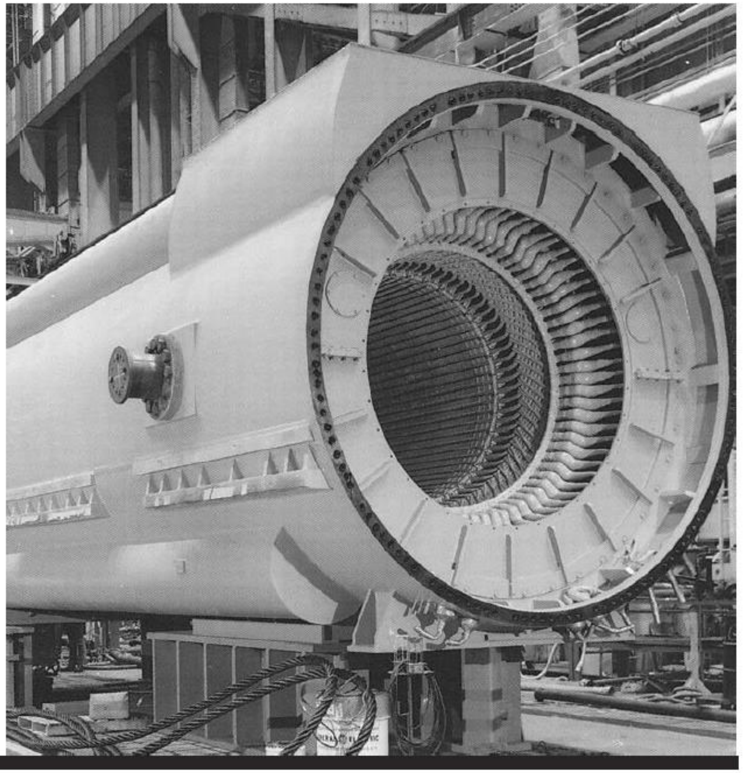
2 dampers in "q" axis (1q, 2q) on rotor

Two Main Types of Synchronous Machines

- Round Rotor
  - Air-gap is constant, used with higher speed machines
- Salient Rotor (often called Salient Pole)
  - Air-gap varies circumferentially
  - Used with many pole, slower machines such as hydro
  - Narrowest part of gap in the d-axis and the widest along the q-axis

Book Chapter 9 Photo

Generator stator showing completed windings for a 757-MVA, 3600-RPM, 60-Hz synchronous generator (Courtesy of General Electric)



8

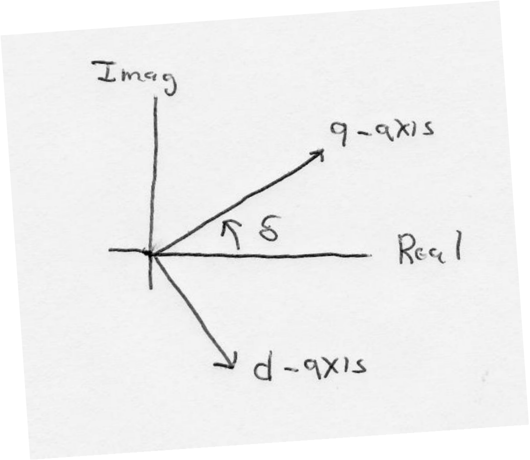
SYMMETRICAL COMPONENTS

D-q Reference Frame

- Analyzing synchronous machines is done using Park's transformation (from 1929) to change the machine differential equations with time-varying components into a set of equations with time invariant components
- That is, the machine voltages and currents are "transformed" into what is known as the d-q reference frame using the rotor angle, δ
  - Terminal voltage in network (power flow) reference frame are $V_T = V_r - V_i$

$$\begin{bmatrix} V_r \\ V_i \end{bmatrix} = \begin{bmatrix} \sin\delta & \cos\delta \\ -\cos\delta & \sin\delta \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix}$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \sin\delta & -\cos\delta \\ \cos\delta & \sin\delta \end{bmatrix} \begin{bmatrix} V_{real} \\ V_{imag} \end{bmatrix}$$



Top Electric Power Papers of the 20th Century

- In 2000 Park’s paper was voted the second most important power paper of the 20th Century

NAPS, University of Waterloo, Canada, October 23–24, 2000

High Impact Papers in Power Engineering, 1900 – 1999

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Celebration 2000

The passing of the year 1999 into history, and the recognition of the roll-over of the calendar to 2000 has not occurred without reminiscence of the past and wonderment for the future. The use of digital controls, accounting, and computer operations in many elements of modern life has produced the scare popularly known as ‘the Y2K bug’. In power engineering, some citizens worried about the power system and its component power generating stations to withstand the rollover. But we have come though the calendar change totally unscathed, and it is time to celebrate the past as well as work for the future. Part of the celebration is, it seems, to take the time to recognize the accomplishments of the past century. Power engineering has a considerable number of accomplishments that should be acknowledged at this time.

In 2000, that National Academy of Engineering of the United States invited participating professional engineering societies (ASME, IEEE, AICHE, ANS, ASCE, AIAA) to submit a list of nominations for the engineering feats of the past century that have had the greatest impact on society. Among approximately 100 nominations, including the formation of the Internet, the invention of the airplane, and the development of the transistor, one nomination was selected as *the* most important feat of the century: this was the mass electrification of the world and the utilization of electric power to relieve man of his burden.

As part of the year 2000 celebration, the organizers of the North American Power Symposium 2000, held in Waterloo, Ontario, chose to recognize accomplishments of the past by assessing the written contributions to electric power engineering. A list of 39 technical papers was collected by the authors of this paper. These nominations were collected by an announcement in the power engineering listserver known as the Power Globe, by an announcement at the 1999 Summer Power meeting in Edmonton, Alberta, and by an announcement at the 2000 Winter Power Meeting in Singapore. Additionally, the organizers informally polled their colleagues and students. Over 50 nominations were received as high impact papers of the years 1900 - 1999. Approximately 11 of the informal nominations were unable to be identified in the literature, and thus the list was reduced to 39 nominations.

The high impact paper list

The 39 high impact papers are deemed to be an unscientific and possibly faulty list of papers. This is concluded from email interchanges from researchers around the world who lamented that some papers had been omitted (especially papers by A. Blondel -- but the main papers of Blondel were published in 1895-99, outside the time windów of interest). In some cases, papers written in languages other than English were not nominated – not because they were not of high impact, but because our colleagues were not conversant with the work. A further confusion occurred when some nominations were entire books. With all these difficulties, the high impact paper list was nonetheless compiled.

The 39 nominated high impact papers appear in Table (1).

The final four

The indicated 39 papers and books were circulated to colleagues, members of the Power Globe, and some students. These persons were asked to indicate the three papers that seemed to be the highest impact papers. The results of the vote are:

- Over 231 ‘votes’ were cast
- About 73 persons responded to the call for votes
- Respondents came mostly from the United States (approximately 50.6 %), but many other countries and regions were well represented as shown in Figure (1). Of the seven continents of the world, five continents were represented in the vote.
- About 20% of the respondents seemed to be from industry. The remainder seemed to be university professors but some students also voted.

Table (1) Nominated high impact papers of 1900 – 1999

Year	*Authors*	*Title*	*Citation*
1908	W. Lyon	*Problems in Electrical Engineering Alternating Currents*	McGraw Hill, NY
1918	C. Fortescue	Method of Symmetrical Coordinates Applied to the Solution of Polyphase Networks	Trans. AIEE, v. 37, p. 1027-1140
1925	C. Fortescue	Transmission Stability, Analytical Discussion of Some Factors Entering Into The Problem	Trans. AIEE, September, p. 984 - 994
1926	J. Carson	Wave Propagation in Overhead Wires with Ground Return	Bell System Technical Journal, October, v. 5, p. 539-554
1929	R. Park	Two Reaction Theory of Synchronous Machines	Trans. AIEE, v. 48, p. 716-730
1929	C. Fortescue, A. Atherton, J. Cox	Theoretical and Field Investigations of Lightning	Trans. AIEE, v. 48, April, p. 449-468
1931	E. Clarke	Simultaneous Faults on Three Phase Systems	Trans. AIEE, v. 50, March, p. 919-941
1933	C. Wagner, R. D. Evans	*Symmetrical Components*	McGraw-Hill, NY
1933	L. Bewley	*Traveling Waves on Transmission Systems*	John Wiley, NY
1937	C. Concordia	Two Reaction Theory of Synchronous Machines with Any Balanced Terminal Impedance	Trans. AIEE, v. 56, p. 1124-1127
1937	C. Concordia, J. Butler	Analysis of Series Capacitor Applications Problems	Trans. AIEE, v. 56, p. 975-988
1938	E. Clarke	Problems Solved by Modified Symmetrical Components	General Electric Review, v. 41, p. 488-494, 545-549
1942	Westinghouse Electric	*Electrical Transmission and Distribution Reference Book*	Westinghouse, E. Pittsburgh, PA
1943	E. Clarke	*Circuit Analysis of AC Power Systems, Symmetrical and Related Components*	John Wiley, NY
1944	C. Concordia	Steady State Stability of Synchronous Machines as Affected by Voltage Regulator Characteristics	Trans. AIEE, v. 63, p. 215-220
1951	C. Condordia	*Synchronous Machines*	Chapman and Hall, London
1952	A. Fitzgerald, C. Kingsley	*Electric Machinery*	McGraw Hill, NY
1956	C. Mason	*The Art and Science of Protective Relaying*	John Wiley, NY
1956	J. Ward, H. Hale	Digital Computer Solution of Power Flow Problems	Trans. AIEE, v. 75, Pt. III, p. 398-404
1959	J. Van Ness	Iteration Methods for Digital Load Flow Studies	Trans. AIEE, v. 78, August, p. 583-588
1959	L. Kirchmayer	*Economic Control of Interconnected Systems*	John Wiley, NY
1960	W. Tinney, C. McIntyre	A Digital Method for Obtaining a Loop Connection Matrix	Trans. AIEE, v. 79, October, p. 740-745
1961	N. Cohn	*Control of Generation and Power Flow on Interconnected Power Systems*	John Wiley, NY
1962	J. Carpentier	Contribution a' L'Etude du Dispatching Economique	Bulletin Societe Française des Electriciens, Ser. 8, v. 3, August, p. 431-447
1963	J. Carpentier, J. Siroux	L'optimisation de la Production a' l'Electricite de France	Bulletin de la Societe Française des Electriciens, March
1963	H. Brown, G. Carter, H. Happ, C. Person	Power Flow Solution by the Impedance Matrix Method	Trans. AIEE, v. 82, pt. III, p. 1-8
1963	G. Kron	*Diakoptics*	Macdonald, London
1966	A. El-Abiad, K. Nagappan	Transient Stability Regions of Multimachine Power Systems	IEEE Trans. Power Apparatus and Systems, PAS-85, No. 2, p. 169-179
1968	G. Stagg, A. El-Abiad	*Computer Methods in Power Systems Analysis*	McGraw Hill, NY
1968	H. Dommel, W. Tinney	Optimal Power-Flow Solutions	IEEE Trans. Power Apparatus and Systems, PAS-87, p. 1866-1876
1970	R. Billinton	*Power System Reliability Evaluation*	Gordon Breach Science Publishers
1972	N. Hingorani	Report on DC Transmission	IEEE Trans. Power Apparatus and Systems, PAS-91, No 6, p. 2313-2318
1973	P. Anderson	*Analysis of Faulted Power Systems,*	Iowa State University Press
1974	B. Stott, O. Alsac	Fast Decoupled Load Flow	IEEE Trans. Power Apparatus and Systems, PAS-91, No. 3, p. 859-869
1977	P. Anderson, A. Fouad	*Power System Control and Stability*	Iowa State University Press
1978	F. Alvarado	Penalty factors from Newton's method	IEEE Trans. Power Apparatus and Systems, PAS-97, No 6, p. 2031-2040
1978	G. Rockefeller	Fault Protection with a Digital Computer	IEEE Trans. Power Apparatus and Systems, PAS-88, No. 2, p. 438-464
1981	E. Abed, P. Varaiya	Oscillations in Power Systems via Hopf Bifurcations	Proceedings 20th Conference on Decision and Control, San Diego, IEEE Press
1995	C. Concordia, J. Paserba	Opportunities for Damping Oscillations by Applying Power Electronics in Electric Power Systems	CIGRE Symposium, Tokyo, report No. 38.01.07

- The ‘vote’ taken should not be viewed too scientifically: that is, the vote was contaminated by the fact that books were mixed into the list, many excellent papers were missing (especially papers written in German, French, Russian, and other languages). Also, a few voters voted for four papers, and a few voted for only one. The deadline for the receipt of votes was not given and votes may still be trailing in at this time! However, it seems to be a consensus that Charles Fortescue’s paper on symmetrical components is highly regarded in the power engineering community.

The ‘top eight’ papers are shown in Table (2).

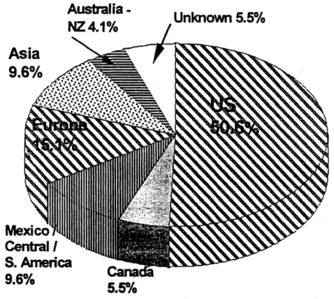

Figure (1) Respondent origins

Table (2) Eight high impact papers of the past century

Votes received from 73 respondents	*Author*	*Year of publication*
47	Fortescue	1918
36	Park	1929
19	Ward, Hale	1956
19	Carson	1926
17	Dommel, Tinney	1968
11	Stott, Alsac	1974
9	Bewley	1933
7	Concordia	1944