ECEN 667
Power System Stability

Lecture 23: Mode Visualization, Stabilizers

Prof. Tom Overbye
Dept. of Electrical and Computer Engineering
Texas A&M University
overbye@tamu.edu

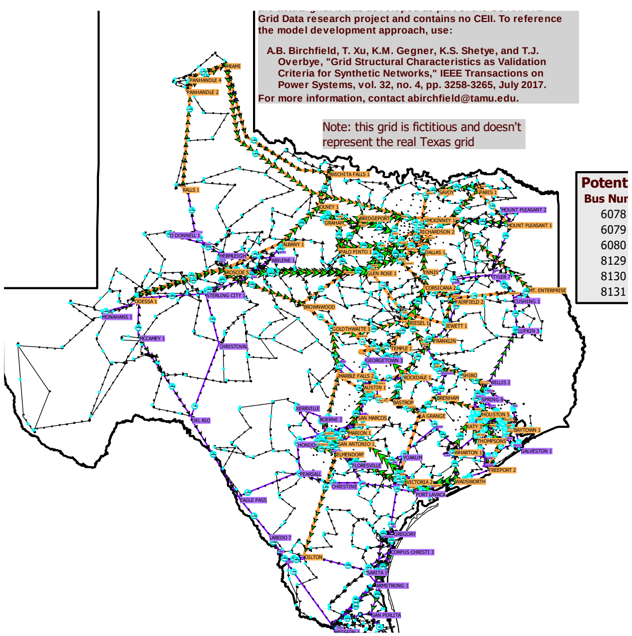
TEXAS A&M UNIVERSITY

Announcements

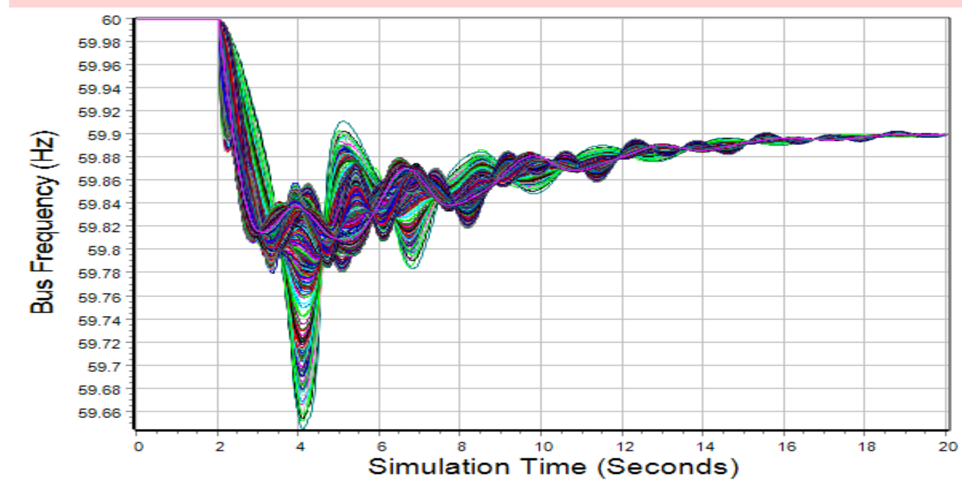
- Read Chapter 9
- Homework 7 should be done before the second exam but need not be turned in

Texas 2000 Bus Synthetic Grid Example

- For this example we'll again use the Texas 2000 bus grid, saved as **TSGC_2000_GenDrop**
- We'll use the Iterative Matrix Pencil Method to examine its modes
  - The contingency is the loss of two large generators (at bus 7098 and 7099)



The measurements will be the frequencies at all 2000 buses



2000 Bus System Example, Iterative Matrix Pencil

- The Iterative Matrix Pencil intelligently adds signals until a specified number is met
  - Doing ten iterations takes about four seconds

Number of Complex and Real Modes: 11

Lowest Percent Damping: 6.082

☑ Include Detrend in Reproduced Signals

☐ Subtract Reproduced from Actual

Update Reproduced Signals

Real and Complex Modes - Editable to Change Initial Guesses

	Frequency (Hz)	Damping (%	Largest Component in Mode, Unscaled	Name of Signal with Largest Component in Mode, Unscaled	Largest Component in Mode, Scaled	Name of Signal with Largest Component in Mode, Scaled	Lambda	Include in Reproduced Signal
1	0.631	6.082	0.10313	Bus BROWNSVI	3.292	Bus BROWNSVI	-0.2415	YES
2	0.959	7.068	0.04897	Bus SAN ANTOI	1.890	Bus SAN ANTOI	-0.4269	YES
3	1.364	7.246	0.03780	Bus ODESSA 1 :	1.420	Bus CHRISTINE	-0.6228	YES
4	0.593	7.897	0.07205	Bus BROWNSVI	2.300	Bus BROWNSVI	-0.2949	YES
5	1.602	8.562	0.04887	Bus FANNIN 2 F	2.032	Bus FANNIN 2 F	-0.8650	YES
6	0.732	11.936	0.21348	Bus MONAHAN	4.054	Bus MONAHAN	-0.5529	YES
7	0.324	14.207	0.19906	Bus ODESSA 1 :	5.268	Bus WHARTON	-0.2917	YES
8	0.324	39.346	0.55936	Bus MONAHAN	12.994	Bus WHARTON	-0.8722	YES
9	0.060	39.972	0.03815	Bus ODESSA 1 :	1.196	Bus POINT COI	-0.1645	YES
10	0.964	57.683	0.61264	Bus ODESSA 1 :	18.504	Bus POINT COI	-4.2760	YES
11	0.000	100.000	0.59650	Bus ODESSA 1 :	14.434	Bus WHARTON	-2.5257	YES

Takeaways So Far

- Modal analysis can be quickly done on a large number of signals
  - Computationally is an $O(N^3)$ process for one signal, where N is the number of sample points; it varies linearly with the number of included signals
  - The number of sample points can be automatically determined from the highest desired frequency (the Nyquist-Shannon sampling theory requires sampling at twice the highest desired frequency)
  - Determining how all the signals are manifested in the modes is quite fast!!

Getting Mode Details

- An advantage of this approach is the contribution of each mode in each signal is directly available

Modal Analysis Mode Details

Frequency (Hz) and Damping (%) 0.631 Hz, Damping = 6.082%

Transfer Results from Selected Column to Object Custom Floating Pont Field

Custom Floating Point Field 1 Transfer Results

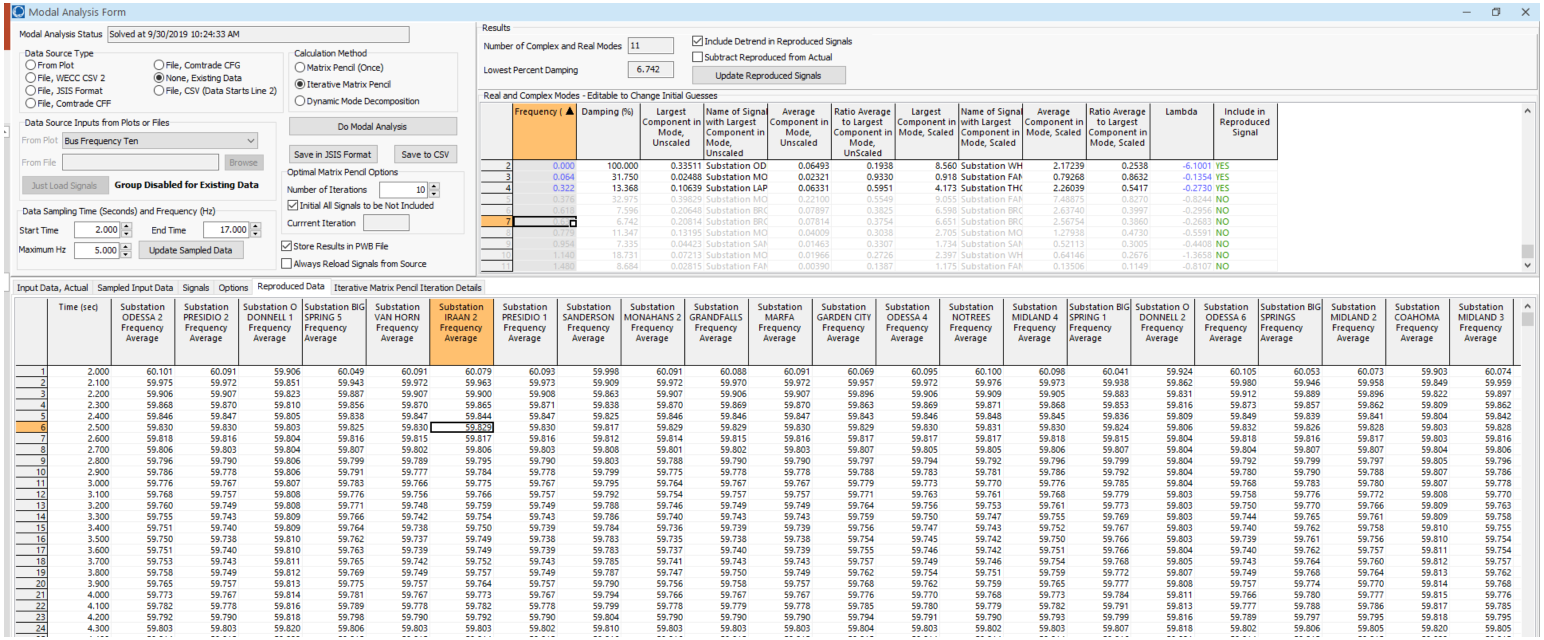
Records Set Columns f(x) Options

	Type	Name	Units	Description	Post-Detrend Standard Deviation	Angle (Deg)	Magnitude, Unscaled	Magnitude Scaled by SD	Cost Function
1	Bus	Bus BROWNSVILLE 1 0 Frequency		Frequency	0.031	176.451	0.10313	3.29203	0.0019
2	Bus	Bus BROWNSVILLE 1 1 Frequency		Frequency	0.031	176.451	0.10248	3.27853	0.0019
3	Bus	Bus BROWNSVILLE 3 0 Frequency		Frequency	0.031	176.454	0.10148	3.25747	0.0018
4	Bus	Bus BROWNSVILLE 2 0 Frequency		Frequency	0.031	176.525	0.10041	3.23684	0.0017
5	Bus	Bus OLMITO 0 Frequency		Frequency	0.031	176.456	0.10032	3.23265	0.0018
6	Bus	Bus BROWNSVILLE 2 1 Frequency		Frequency	0.031	176.522	0.09964	3.22005	0.0017
7	Bus	Bus SAN BENITO 0 Frequency		Frequency	0.031	176.452	0.09836	3.19018	0.0017
8	Bus	Bus PORT ISABEL 0 Frequency		Frequency	0.031	176.519	0.09817	3.18788	0.0016
9	Bus	Bus LOS FRESNOS 0 Frequency		Frequency	0.031	176.480	0.09601	3.13896	0.0016
10	Bus	Bus CORPUS CHRISTI 3 3 Frequency		Frequency	0.030	177.479	0.09573	3.15533	0.0013
11	Bus	Bus CORPUS CHRISTI 3 2 Frequency		Frequency	0.030	177.619	0.09533	3.14610	0.0013
12	Bus	Bus RIO HONDO 0 Frequency		Frequency	0.030	176.500	0.09462	3.10807	0.0015
13	Bus	Bus CORPUS CHRISTI 3 5 Frequency		Frequency	0.030	177.488	0.09393	3.11626	0.0013
14	Bus	Bus SAN PERLITA 0 Frequency		Frequency	0.030	176.760	0.09338	3.08711	0.0014
15	Bus	Bus SEBASTIAN 2 1 Frequency		Frequency	0.030	176.485	0.09249	3.05864	0.0014
16	Bus	Bus SEBASTIAN 2 0 Frequency		Frequency	0.030	176.500	0.09234	3.05579	0.0014
17	Bus	Bus CORPUS CHRISTI 3 4 Frequency		Frequency	0.030	177.256	0.09203	3.06646	0.0013
18	Bus	Bus SANTA ROSA 1 4 Frequency		Frequency	0.030	176.457	0.09189	3.04368	0.0014
19	Bus	Bus SANTA ROSA 1 8 Frequency		Frequency	0.030	176.462	0.09183	3.04122	0.0014
20	Bus	Bus SEBASTIAN 1 0 Frequency		Frequency	0.030	176.504	0.09153	3.03706	0.0014
21	Bus	Bus SAN PERLITA 1 Frequency		Frequency	0.030	176.588	0.09134	3.03507	0.0014
22	Bus	Bus HARLINGEN 1 0 Frequency		Frequency	0.030	176.483	0.09114	3.02757	0.0014
23	Bus	Bus CORPUS CHRISTI 1 3 Frequency		Frequency	0.030	178.815	0.09102	3.06810	0.0019
24	Bus	Bus MERCEDES 0 Frequency		Frequency	0.030	176.459	0.09095	3.02245	0.0014
25	Bus	Bus SANTA ROSA 1 6 Frequency		Frequency	0.030	176.377	0.09081	3.01773	0.0014
26	Bus	Bus SANTA ROSA 1 5 Frequency		Frequency	0.030	176.439	0.09075	3.01600	0.0014
27	Bus	Bus SANTA MARIA 0 Frequency		Frequency	0.030	176.423	0.09065	3.01479	0.0014
28	Bus	Bus HARLINGEN 2 0 Frequency		Frequency	0.030	176.455	0.09043	3.01019	0.0014
29	Bus	Bus SANTA ROSA 1 2 Frequency		Frequency	0.030	176.315	0.09034	3.00472	0.0014
30	Bus	Bus PROGRESO 0 Frequency		Frequency	0.030	176.363	0.09016	3.00188	0.0015
31	Bus	Bus SANTA ROSA 1 9 Frequency		Frequency	0.030	176.399	0.08996	2.99744	0.0014
32	Bus	Bus SANTA ROSA 1 3 Frequency		Frequency	0.030	176.399	0.08996	2.99744	0.0014
33	Bus	Bus SANTA ROSA 1 1 Frequency		Frequency	0.030	176.399	0.08996	2.99744	0.0014
34	Bus	Bus SANTA ROSA 1 7 Frequency		Frequency	0.030	176.399	0.08996	2.99744	0.0014

This slide shows the mode with the lowest damping, sorted by the signals with the largest magnitude in the mode

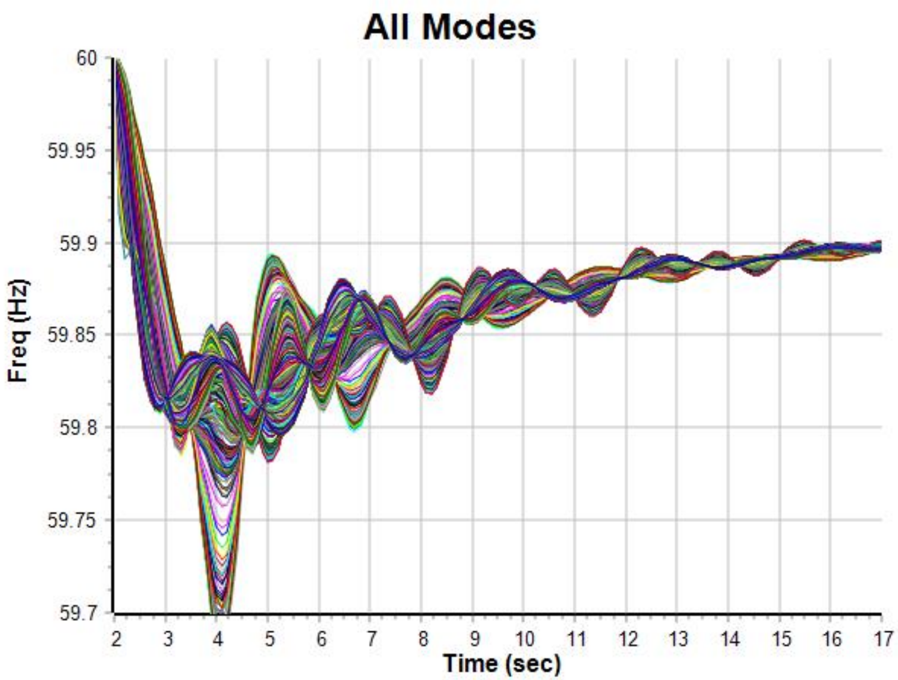
Visualizing the Some or All of the Modes

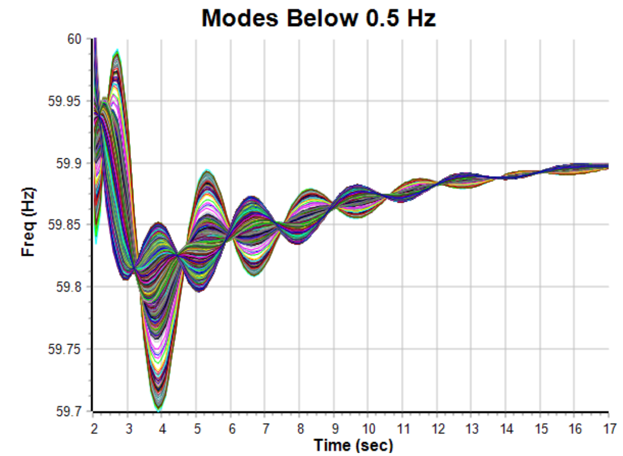
- Some or all of the modes can be shown using the **Update Reproduced Signals** option
  - Select the modes to include using the **Include in Reproduced Signal** selection

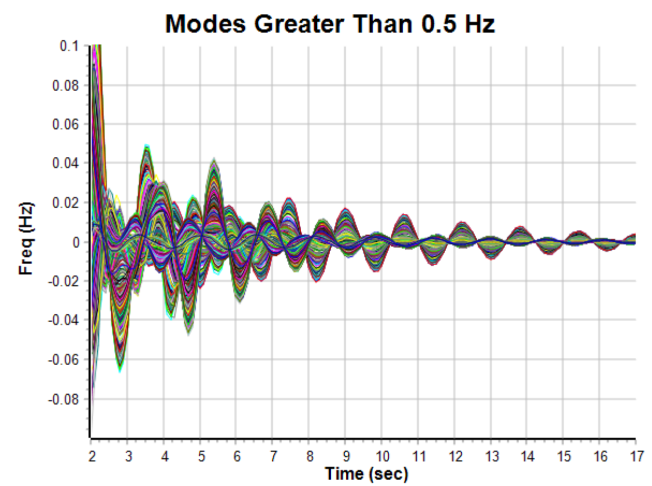


Visualizing the Some or All of the Modes

- Images show all the modes, the low frequency modes, and the high frequency modes







Visualizing the Modes

- If the grid has embedded geographic coordinates, the contributions for the mode to each signal can be readily visualized utilizing geographic data views (GDVs)

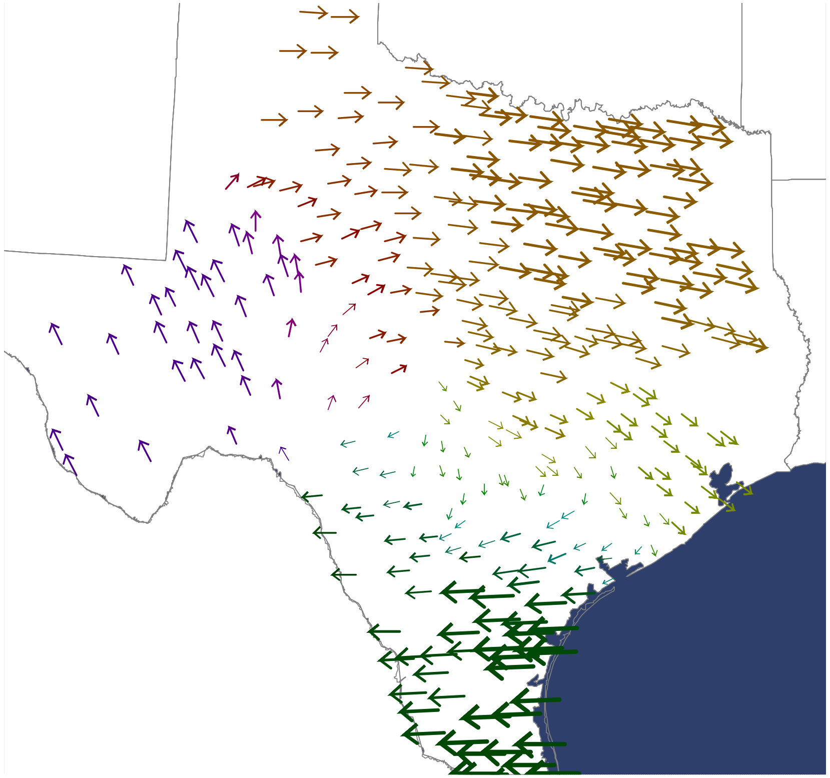


Image shows the magnitudes of the components for the 0.63 Hz mode; the display was pruned to only show some of the values

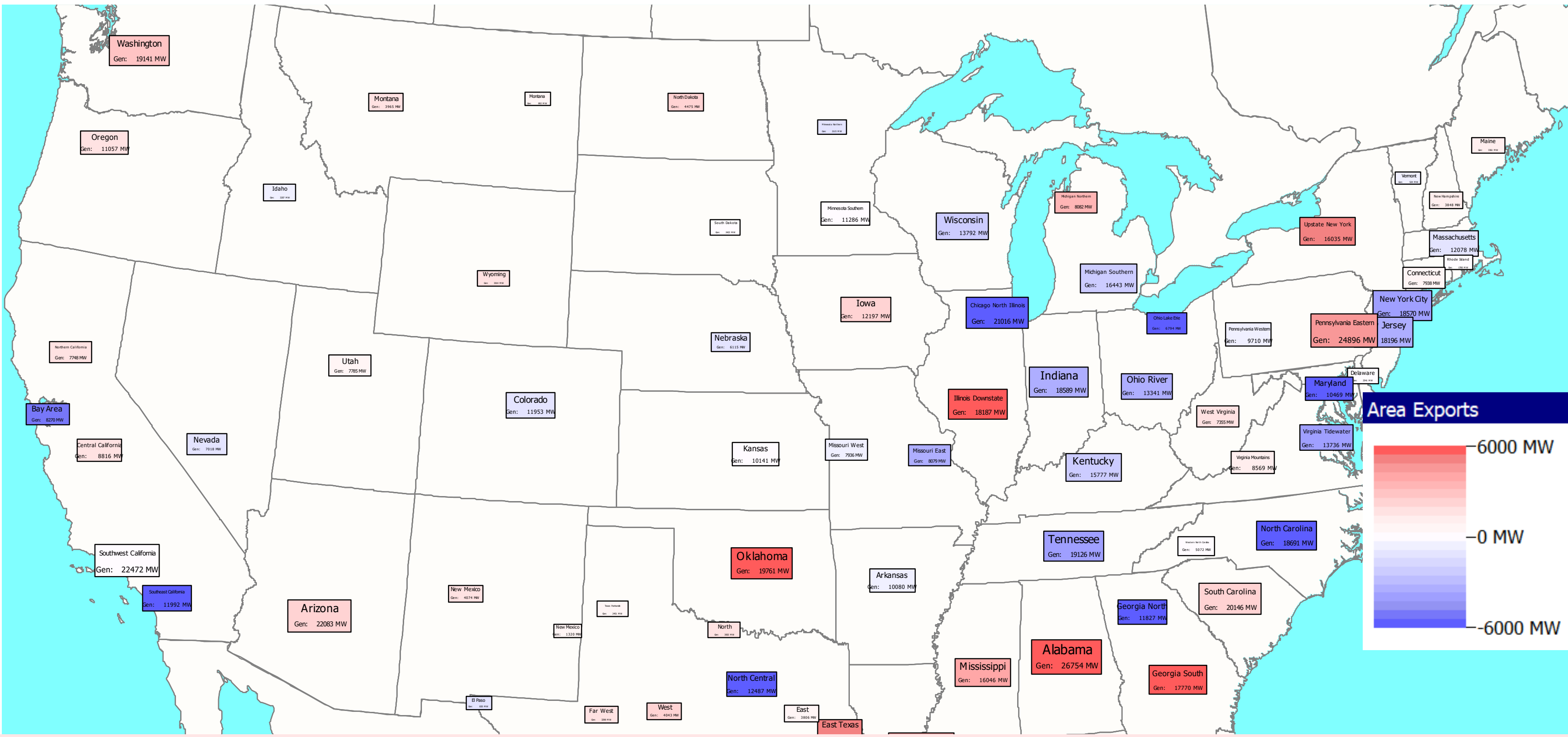
Aside: Visualizing Results Using Geographic Data Views (GDVs)

- The GDV concept arose about 13 years back as a way to auto-create oneline displays using geographic information embedded in power system models
- GDVs can be created from Model Explorer displays by right-clicking and selecting **Geographic Data View** and then either **Geographic Data View** to create a display of the selected objects or **Select Column, then Geographic Data View** for all the objects
  - As always, filters can limit the column objects
- Once defined, the GDVs are grouped based on an associated GDV Style

GDV Overview, cont.

- The GDV Style is then used to customize their appears on the displays
- The GDVs themselves are ultimately display objects that can be saved in a pwd or axd file
  - The requirement is that they also be saved with the definition for their style
  - Like other *.pwds, the GDVs can be used with multiple power systems
- The GDVs are meant to leverage the growing amount of geographic information that is embedded in power system models

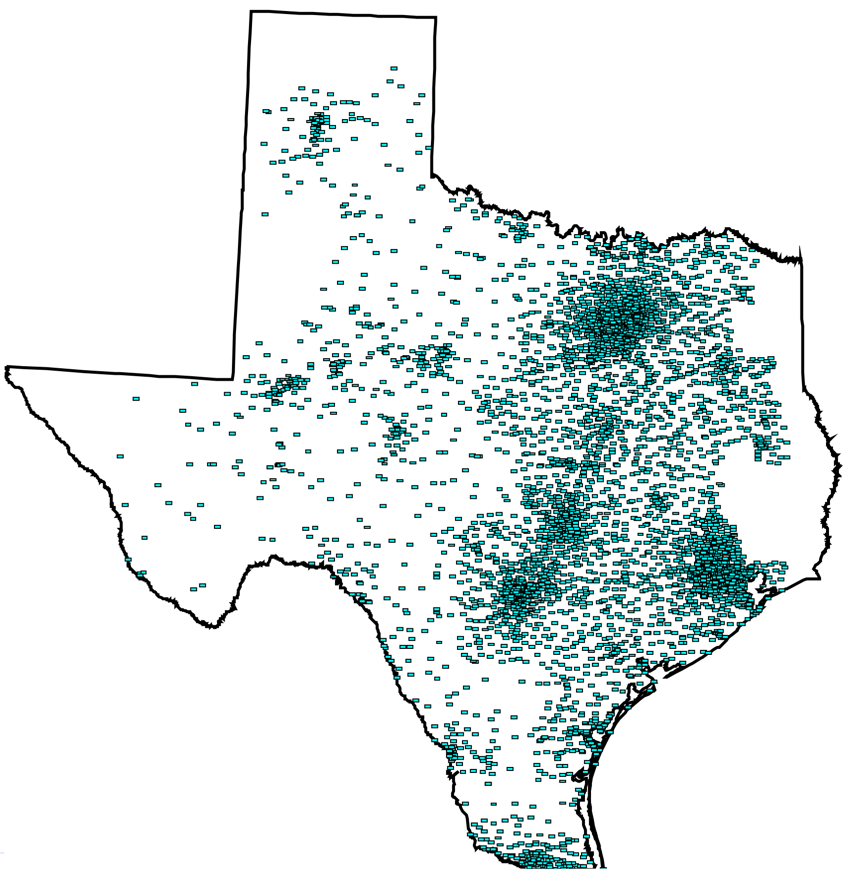
GDV Example 1

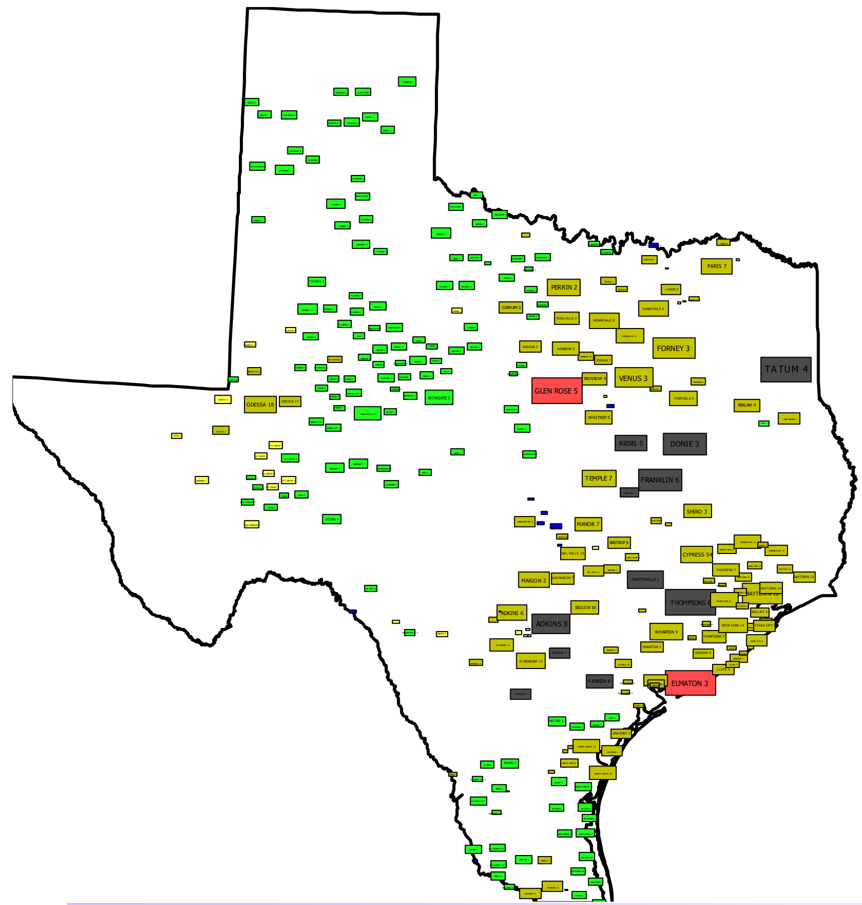


This is a classic GDV display in which the location of each GDV (shown an area here) is derived from its elements. The size is proportional to generation, color depends on its exports. Each GDV is linked, allowing access to its Area Dialog.

GDV Example 2

Left image shows the substations unscaled, and the right shows the substation GDVs sized by generation (MW), with color based on the fuel type (red: nuclear, black: coal, brown: natural gas, green: wind, yellow: solar).





Aside: Making a Frequency Movie

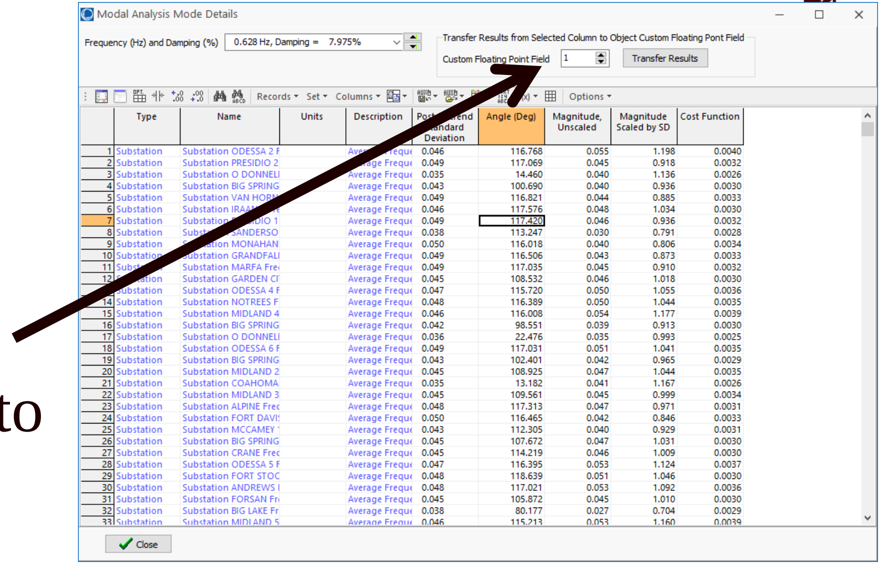
- In class demonstration of how to make a frequency movie (I am only storing every 0.25 seconds in demo)
- In **Transient Stability, Options, General** check the **Store Full Power Flow State** on Update option
- Have a oneline that can contour bus (or substation) frequency, with the **Contours, Continuously Update Contours** checked
- Once the case has been run (with the power flow state saved), select in transient stability **Results from RAM, Power Flow States**; click on **Show Power Flow Transfer Control Dialog**; make sure the jpegs are saved somewhere

Using GDVs to Visualize a Mode

- GDVs used to quickly visualize mode information
- To visualize mode magnitude and angles, we'll use the substation custom fields to store the mode values
- Rerun modal analysis using the substation average frequency field. That is,
  - Start from the **Results From RAM, Aggregations, Substation display**
  - Show just the Frequency Average field
  - Right-click to select "Modal Analysis All Columns" to show the **Modal Analysis Form**
  - Select the Iterative Matrix Pencil method and click on **Do Modal Analysis**; view the **Mode Details** dialog for 0.63 Hz

Visualizing Mode Magnitude and Angle Components

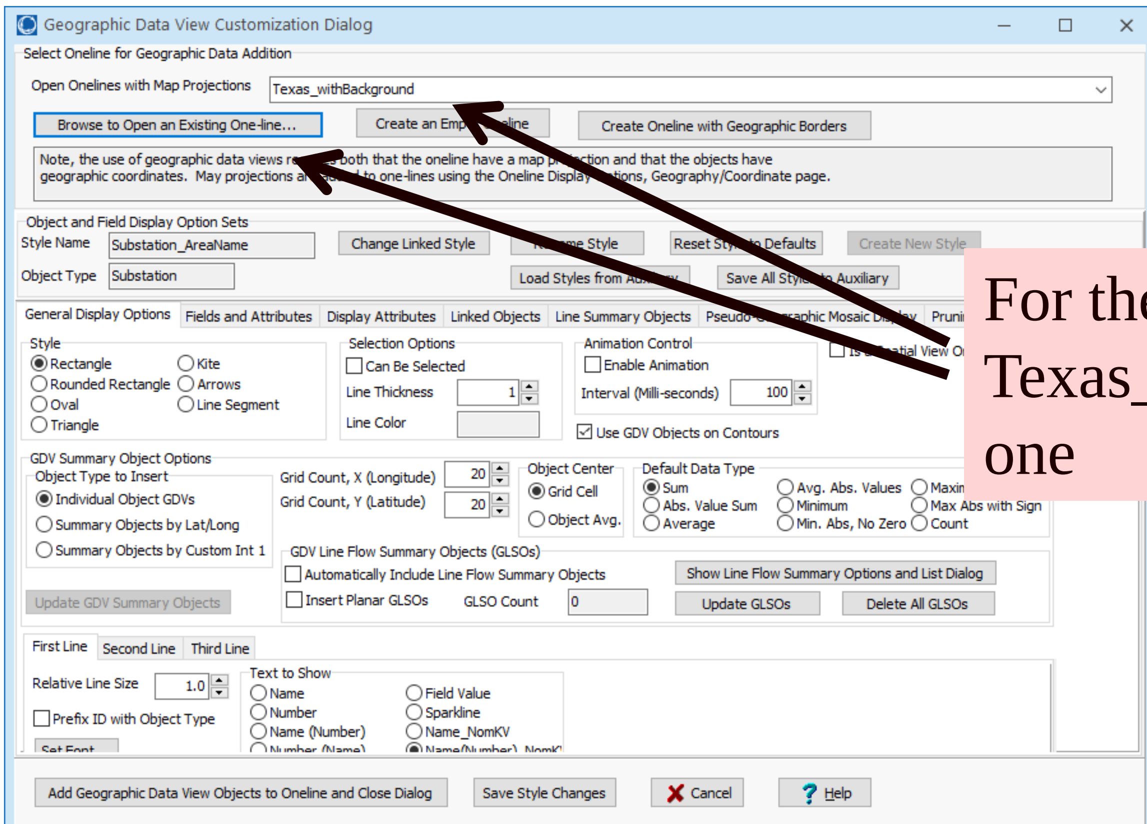
- We’ll use the custom fields to tell the substation objects about this mode’s data
  - Select the Angle field, set the Custom **Floating Point** Field to 1; click Transfer Results
  - Repeat, except click on the Magnitude Unscaled field and set the Custom Floating field to 2



- Then we’ll create a new GDV display using the **Texas_withBackground** oneline display (the customizations are on the next slides)

Creating the GDV Display

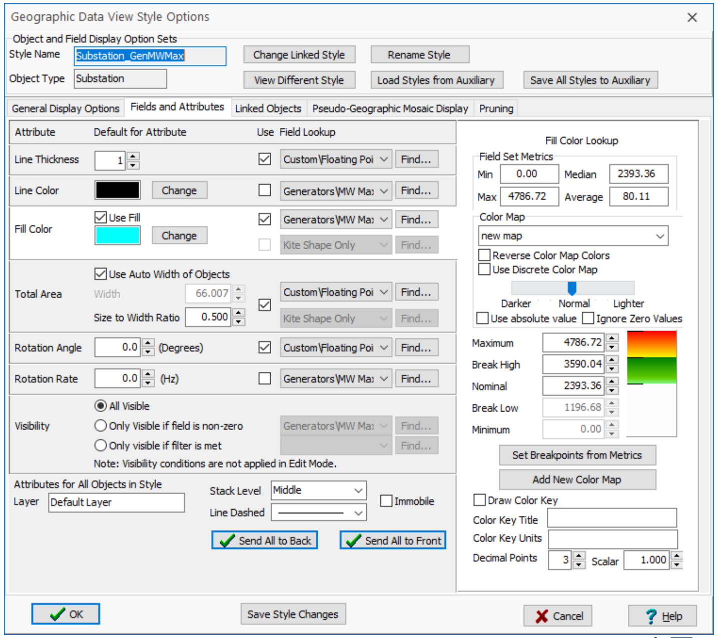
- On the **Case Information, Aggregation, Substations,** select **Geographic Data View, Select Column, Then Geographic Data View**



For the One-Line, pick the Texas_withBackground one

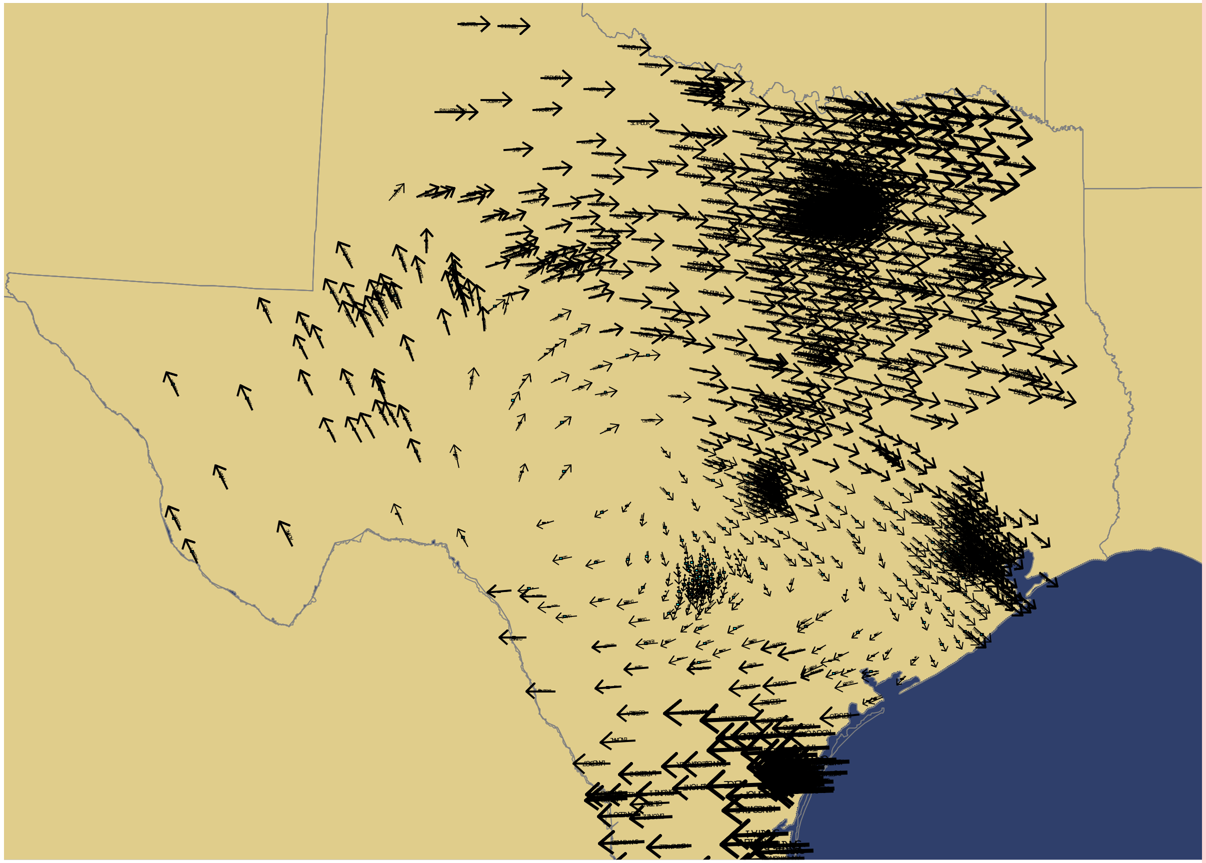
GDV Visualization of Mode Magnitude and Angle Components

- Set the GDV Style as
  - On the **General Display Options** page set the **Style** to Arrows and the **Text to Show** field to None.
  - On the **Fields and Attributes** page
    - Total Area uses the Custom Float 2 field (magnitude); a ballpark largest size should be 50000.
    - Rotation Angle uses the Custom Float 1 field (angle)
    - Line Thickness uses the Custom Float 2 field (magnitude)



- Once a oneline has been setup, it can be saved for repeated use
- Save oneline as **TSGC_2000_Modes**

Visualization of 0.63 Hz Mode



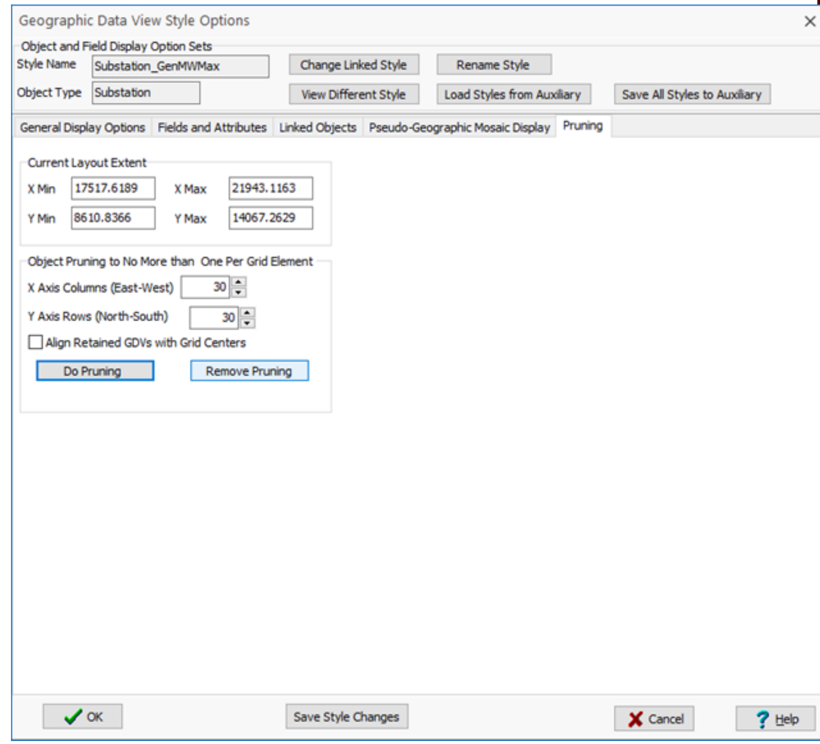
In this display the arrows show the magnitude and angle (direction) for the mode at each substation.

However, the problem is there are too many arrows!

The solution it so dynamically prune the display using the GDV Options, Pruning command

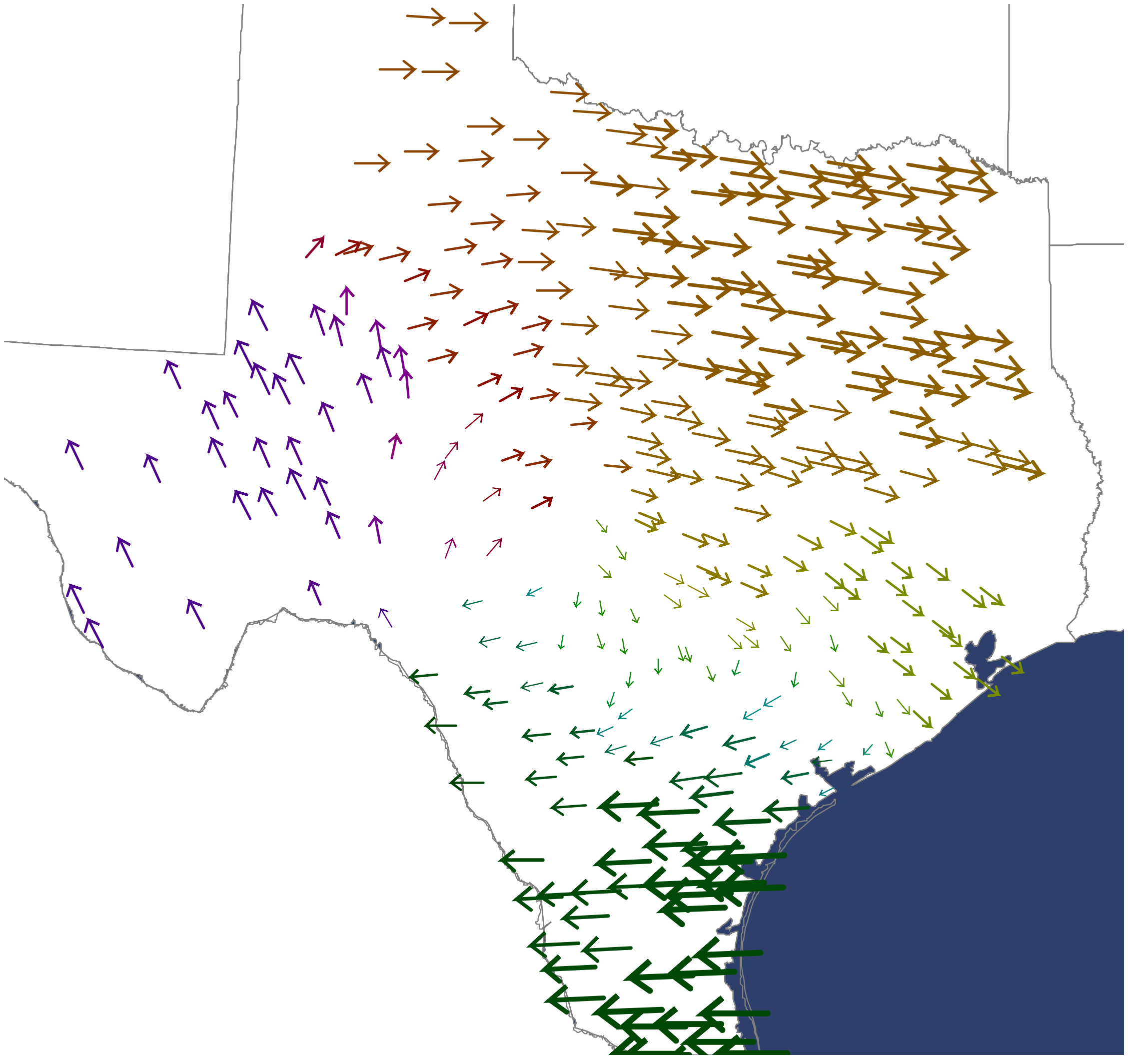
GDV Display Pruning

- This page allows GDVs to be selectively displayed
- Select **Do Pruning** to modify the oneline so an invisible grid is added to the display and only one GDV arrow is visible in each grid area



- I also added some color, using a circular color map to highlight the angles

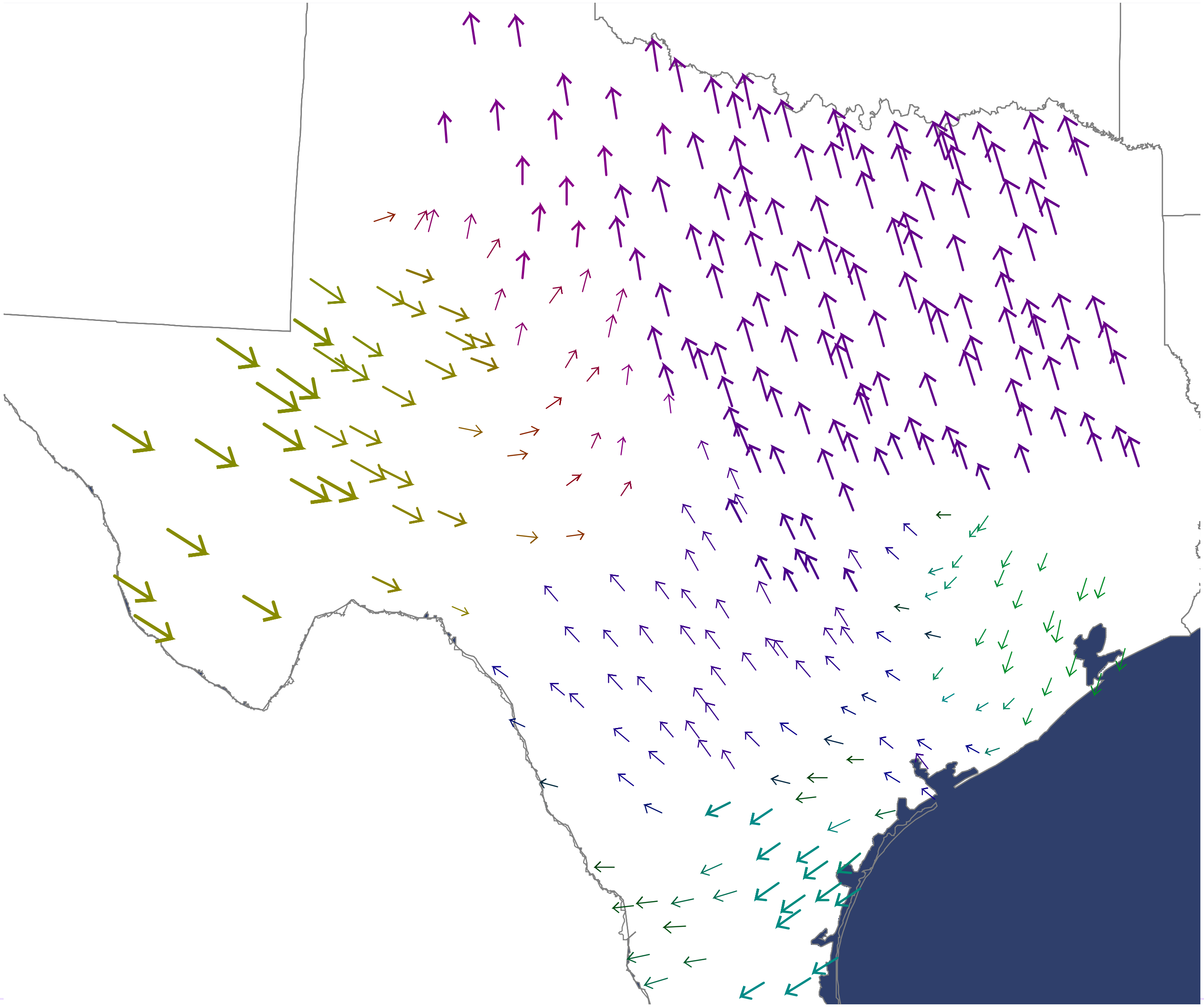
Visualization of 0.63 Hz Mode



Again save the oneline; it can then be used to quickly visualize the other modes

To show other modes, just go to the Mode Details dialog for a different frequency and again transfer the angle and magnitude

Visualization of 0.76 Hz Mode



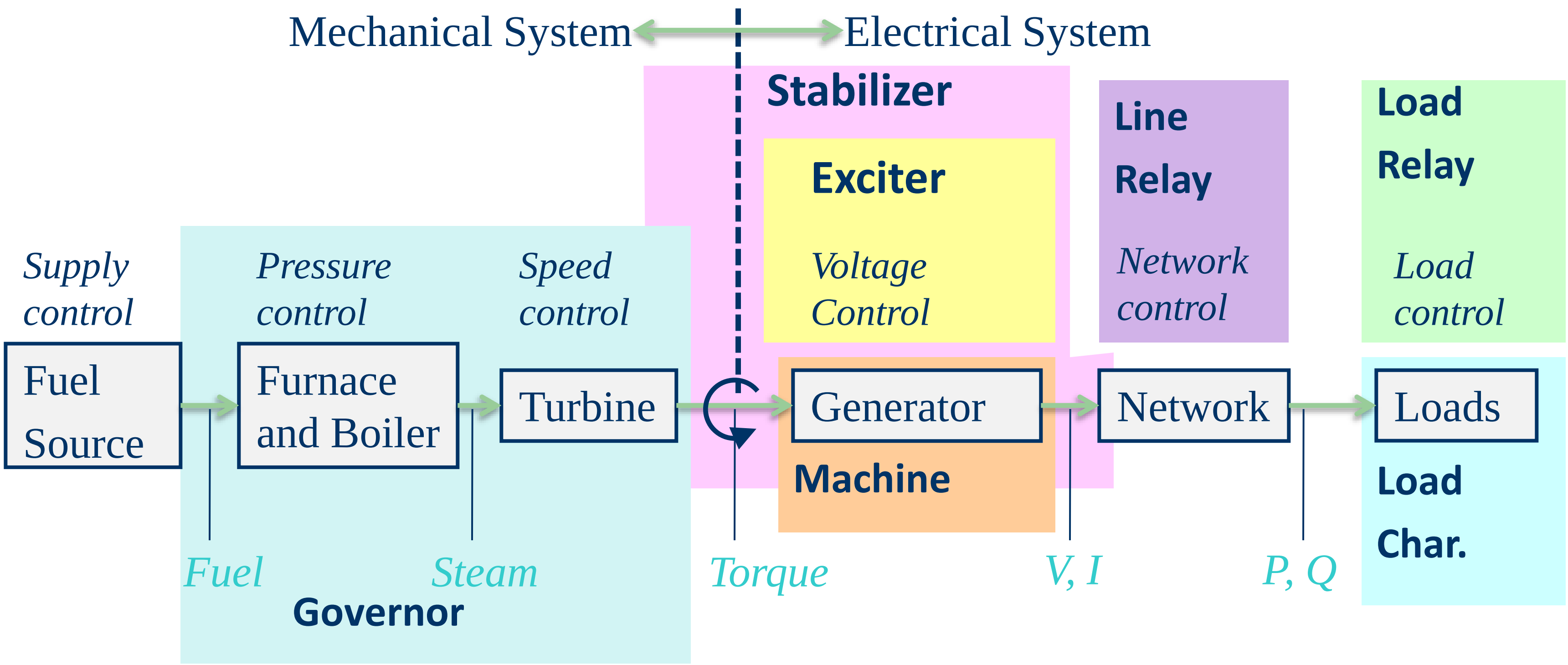
Damping Oscillations: Power System Stabilizers (PSSs)

- A PSS adds a signal to the excitation system to improve the generator's damping
  - A common signal is proportional to the generator's speed; other inputs, such as like power, voltage or acceleration, can be used
  - The Signal is usually measured locally (e.g. from the shaft)
- Both local modes and inter-area modes can be damped.
- Regular tuning of PSSs is important

Stabilizer References

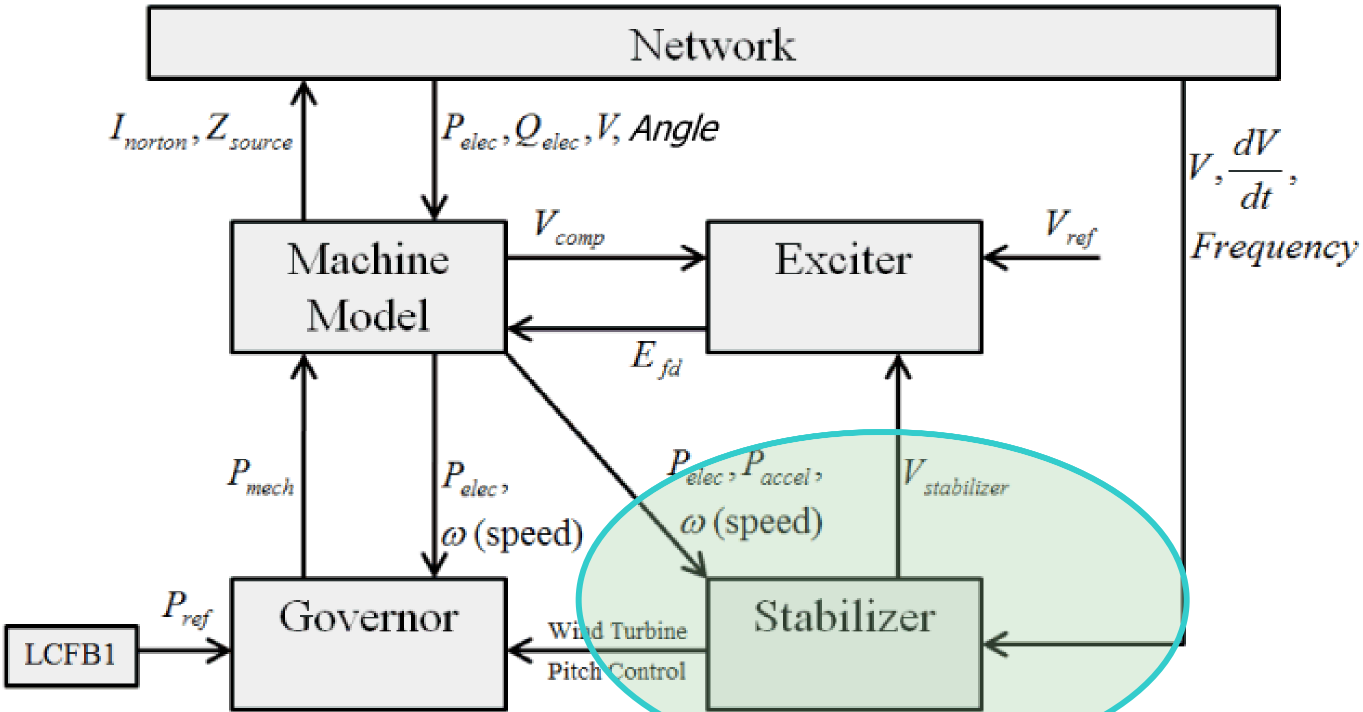
- A few references on power system stabilizers
  - E. V. Larsen and D. A. Swann, "Applying Power System Stabilizers Part I: General Concepts," in IEEE Transactions on Power Apparatus and Systems, vol.100, no. 6, pp. 3017-3024, June 1981.
  - E. V. Larsen and D. A. Swann, "Applying Power System Stabilizers Part II: Performance Objectives and Tuning Concepts," in IEEE Transactions on Power Apparatus and Systems, vol.100, no. 6, pp. 3025-3033, June 1981.
  - E. V. Larsen and D. A. Swann, "Applying Power System Stabilizers Part III: Practical Considerations," in IEEE Transactions on Power Apparatus and Systems, vol.100, no. 6, pp. 3034-3046, June 1981.
  - *Power System Coherency and Model Reduction*, Joe Chow Editor, Springer, 2013

Dynamic Models in the Physical Structure



P. Sauer and M. Pai, *Power System Dynamics and Stability*, Stipes Publishing, 2006.

Power System Stabilizer (PSS) Models



P_{elec} = Electrical Power

Q_{elec} = Electrical Reactive Power

V = Voltage at Terminal Bus

$\frac{dV}{dt}$ = Derivate of Voltage

V_{comp} = Compensated Voltage

P_{mech} = Mechanical Power

ω(speed) = Rotor Speed (often it's deviation from nominal speed)

P_{accel} = Accelerating Power

$V_{stabilizer}$ = Output of Stabilizer

V_{ref} = Exciter Control Setpoint (determined during initialization)

P_{ref} = Governor Control Setpoint (determined during initialization)

Classic Block Diagram of a System with a PSS

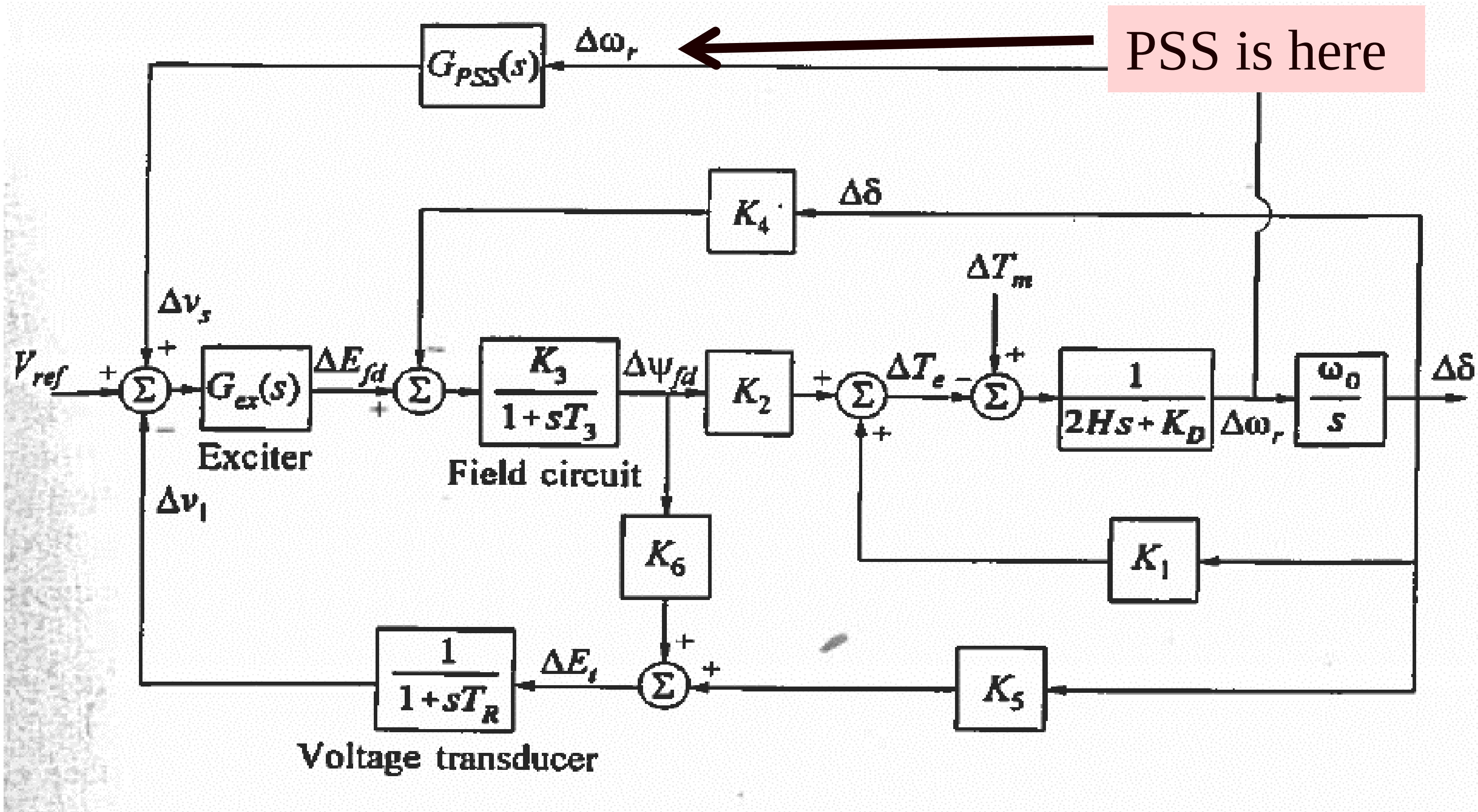
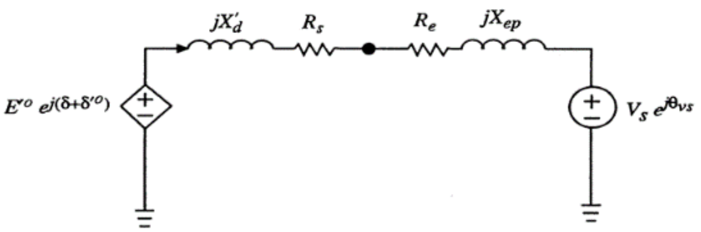


Figure 12.13 Block diagram representation with AVR and PSS

Image Source: Kundur, *Power System Stability and Control*

PSS Basics

- Stabilizers can be motivated by considering a classical model supplying an infinite bus



$$\frac{d\delta}{\mathrm{dt}} = \omega - \omega_s = \Delta\omega$$

$$\frac{2H}{\omega_0}\frac{d\Delta\omega}{dt} = T_M^0 - \frac{E'V_s}{X'_d + X_{ep}}\sin(\delta) - D\Delta\omega$$

- Assume internal voltage has an additional component

$$E' = E'_{org} + K\Delta\omega$$

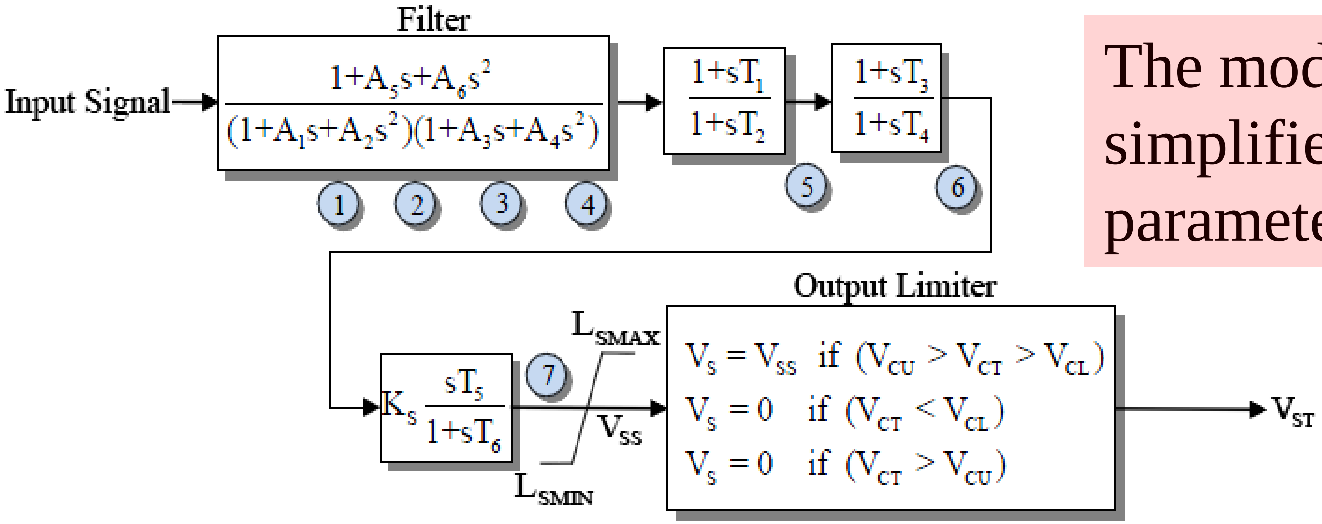
- This can add additional damping if sin(δ) is positive
- In a real system there is delay, which requires compensation

PSS Focus Here

- Fully considering power system stabilizers can get quite involved
- Here we'll just focus on covering the basics, and doing a simple PSS design. The goal is providing insight and tools that can help power system engineers understand the PSS models, determine whether there is likely bad data, understand the basic functionality, and do simple planning level design

Example PSS

- An example single input stabilizer is shown below (IEEEST)
  - The input is usually the generator shaft speed deviation, but it could also be the bus frequency deviation, generator electric power or voltage magnitude



The model can be simplified by setting parameters to zero

V_{ST} is an input into the exciter